Instructional Design: Development, implementation and evaluation of a teaching sequence about plant nutrition in Saudi

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I confirm that the work submitted is my own and that appropriate credit has been given where reference has been made to the work of others

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ABSTRACT

The aim of this study was to design, implement and evaluate a teaching sequence about plant nutrition for male Saudi students aged 15-16. Considering the Saudi context, conducting a study related to developing instructional materials is likely to be beneficial as the Ministry of Education is currently reforming science education, including developing new science textbooks. The choice to target plant nutrition was influenced by the significance of this topic in school biology and the widespread misunderstandings that students hold about it.

A case study methodology employing a design research approach was used, involving four teachers and 131 students (from two schools). A design model was used to design the teaching sequence that brings together, using specific design tools, theoretical perspectives on learning and teaching, and empirical findings on students' ideas about plant nutrition to inform specific decisions about teaching plant nutrition in the Saudi context. The resulting design was evaluated using an evaluation model that measures the match between what was intended from teachers and students and what they actually did, and what was expected from students in terms of learning and what they actually learnt. Data were collected using videos, written probes, interviews and classroom written work.

Findings from the evaluation suggest that the sequence helped students to acquire factual knowledge relating to photosynthesis, as well as develop a conceptual understanding of the nature of plant food and the source of extra biomass. However, it was less effective with regard to promoting long-term retention of conceptual understanding. This limited effectiveness may be due to overlooking the relationships between photosynthesis and respiration, food and energy in the design, and providing a relatively limited focus on the construction and practice of scientific explanations. Based on evaluation results, some revisions were identified and a set of guidelines for teaching plant nutrition in Saudi schools was developed. Findings from interviews with teachers and students point out that both the teachers and students appreciated the sequence and associated pedagogic strategies, although these differed considerably from usual practice.

Some general implications for designing and evaluating teaching sequences are proposed. In addition, specific implications for teaching scientific concepts in the Saudi context as part of a reform of science education are highlighted. Finally, suggestions for future research are identified.

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CHAPTER 1: INTRODUCTION

This chapter will introduce my study, beginning with the rationale for conducting a design study and the reason for targeting plant nutrition. It then presents the research aims and emerging research questions, followed by a brief section focusing on the choice of research method. Finally, a summary of the forthcoming chapters is outlined.

CHAPTER 1: Introduction

1.1 Introduction

This research describes a case study designed to develop a teaching sequence regarding plant nutrition for Saudi male students aged 15-16 in order to improve their understanding of the topic.

The study is conducted by employing characteristics of design studies that comprise the processes of designing, implementing and evaluating the teaching sequence. When designing the teaching sequence, I used a particular design model that brings together, using specific design tools, theoretical perspectives on learning and empirical findings on students' ideas about plant nutrition to inform specific decisions about teaching plant nutrition in the Saudi context. The resulting design is implemented and assessed using an evaluation model that measures the match between what was intended from teachers and students and what they actually did, and what was expected from students in terms of learning and what they actually learnt. Data are collected using videos, written probes, interviews and classroom work. Like other design studies, in addition to the resulting teaching sequence, some possible revisions are suggested to improve the original design, and a set of guidelines for teaching plant nutrition in Saudi are proposed. Acknowledging the specific context of this study, I also discuss the possibility of using the guidelines to teach plant nutrition in other contexts.

1.2 Rationale for the study

Compelling evidence from empirical research shows that students' ideas about the natural world differ significantly from the scientific view (see a bibliography compiled by Duit, 2010). In biology, for example, students think that soil, water, minerals and even air are sources of food and biomass, while the scientific view is that plants make their own food through photosynthesis. Research suggests (Driver et al., 1994a; Wandersee et al., 1994) that such ideas are not only resistant to change, but also stand in the way of the students learning new views of school science. Therefore, unless teaching considers them, it is unlikely that students will accept the new scientific concepts (Duit and Treagust, 2003). Given the effect of students' ideas, and the extensive studies that have investigated students with regard to many topics, calls have been made to draw upon theoretical perspectives on learning and empirical findings on students' ideas to design domain-specific teaching sequences (Driver and Erickson, 1983). However, according to Leach and Scott (2002) and Leach et al. (2009), there are very few examples in the science education literature of such design studies where the teaching sequence is designed and evaluated and its rationale and specific design decisions are made explicit.

Conducting design studies could be beneficial, in particular, for improving science education in the Saudi context. From my experience of 15 years working in science education as a biology teacher, science education supervisor and an author of science textbooks, science is mainly taught in schools through conventional manners that promote the recall of facts at the expense of improving conceptual understanding. Furthermore, science textbooks impose such an approach, since a large proportion of their content is scientific definitions and facts rather than explanations. Thus, it is not surprising that eighth grade Saudi students were placed at the bottom of the TIMSS 2007 (The Trends in International Mathematics and Science Study, 2007) about 100 points below the average score of 500 (Martin et al., 2008).

On the other hand, the Ministry of Education is dependent on others when developing science textbooks. For example, in the early seventies, a team of science education researchers from Ohio University in the USA and the American University in Beirut (Lebanon) was contracted to provide science textbooks for all school years; these textbooks were used for about 22 years with minor successive revisions (Alsadaawi, 2007). Furthermore, in 2007, the Ministry of Education announced a plan for reforming science and math education including the adoption and adaption of international science textbooks (Ministry of Education, 2007). While the ultimate aim should be to develop our own textbooks, the process of selecting and adapting instructional materials would be more accurate and professional if it were enhanced by an understanding of design, implementation and evaluation of science instructional materials and the way in which Saudi teachers and students respond to them.

However, there is a shortage of studies of this kind in the Saudi context. Despite the fact that postgraduate students in Masters' programmes conduct most educational research concerning curriculum and instruction, Alkathiri (2002) found, in his analysis of 240 dissertations submitted in the period 1983-2002 in King Saud University, the largest Saudi university, that designing instructional materials was researched in only four dissertations.

1.3 The reason for targeting plant nutrition

The choice of targeting the topic of plant nutrition can be justified on the grounds of its significance, difficulty, the availability of empirical findings on students' ideas and relevance to the Saudi context. In terms of its significance, photosynthesis is "…the most important biochemical process on earth" (Arnon, 1982, cited in Wood-Robinson, 1991, p.123). This importance is a result of the fact that photosynthesis acts "…as a bridge between the living world and the non-living world in terms of energy flow and matter cycling" (Lin & Hu, 2003, p.1531). Therefore, a basic understanding of how the world functions as an ecosystem is crucially dependent upon an understanding of photosynthesis and plant nutrition (Eisen & Stavy, 1988). Following this importance, photosynthesis and plant nutrition is included in every school syllabus, is introduced through different contexts (e.g. ecology and chemistry) and, subsequently, is a revisited topic throughout school years (Haslam & Treagust, 1987).

In contrast, photosynthesis has been identified as one of the most difficult topics for students studying biology (Simpson & Arnold, 1982a; Waheed & Lucas, 1992). In fact, some students leave compulsory education to attend university and still think that plants take their food from the environment (Boyes & Stanisstreet, 1991). Hence, biology education researchers paid specific attention to investigating students' understanding of photosynthesis and plant nutrition. According to Wood-Robinson (1991, p.123), "…it is the most fully researched aspect of children's understandings of plants and their physiology". The availability of empirical findings encouraged me to draw upon them to inform designing a teaching sequence about plant nutrition with the intention of improving students' understanding.

In terms of relevance to the Saudi curriculum, the topic is first introduced in Year 10 and is revisited in Year 11 with more technical details. In both grades, the focus is on plant nutrition rather than photosynthesis; hence, plant nutrition is selected to be the focus of the teaching sequence.

1.4 Aims of the study and research questions

Considering the rationale for conducting a study concerning the design of a domain-specific teaching sequence, the need of instructional design studies in the Saudi context and the choice of targeting plant nutrition, the key aim of this study is to develop a teaching sequence about plant nutrition for the Saudi context. I used the Leeds Design Model (Leach et al., 2009) to guide my thoughts and actions when designing the sequence, in order to articulate the rationale of the design and provide detailed justifications of the design decisions. I discuss my reasons for using this particular model in section 2.4.1.4. The resulting design is then implemented and evaluated. In addition, due to the novelty of the designed teaching in the Saudi context, I was interested in exploring the perceptions of Saudi teachers and students with regard to the sequence.

To this end, three secondary aims and three questions emerged from the key aim set out above, as follows:

- **Research aim 1**: To use the Leeds Model to design a teaching sequence about plant nutrition for male Saudi school students aged 15-16.

Although no research questions emerge from this aim, developing the teaching sequence constitutes an essential step to be able to follow the other research aims.

- **Research aim 2:** To determine the effectiveness of the teaching sequence in terms of meeting its design intentions and achieving the expected learning outcomes.

The following two research questions emerge from this aim:

1. *To what extent was the planned design implemented as intended?*
2. *To what extent did the students develop the desired learning outcomes?*

- **Research aim 3:** To determine how the teaching sequence and associated teaching practices were perceived by Saudi teachers and students.

The following question emerges from this aim:

3. *How did the teachers and students respond to the key conceptual and pedagogical aspects of the teaching sequence?*

1.5 The choice of research method

Given the research aims and questions listed above, there is a need to employ a research method that enables me to collect evidence about the implementation of the teaching sequence in the classroom, students' learning outcomes and teachers and students' perceptions. Yin (2003) advises using case study research when both process and outcomes are sought in the study, both of which feature in my analysis. Furthermore, within the case study I employ an approach that is usually used in design studies when a given design goes through a process of design, implementation and evaluation with the purpose of producing tangible instructional materials and ending with guidelines for teaching a specific topic (Gorard and Taylor, 2004).

1.6 A summary of the forthcoming chapters

Following this introductory chapter, the thesis is divided into eight chapters. Chapter 2 begins by reviewing studies which focus on students' understanding of photosynthesis and plant nutrition, highlighting issues related to the specific conceptual difficulties that students face. It then goes on to underline issues with regard to the difficulties of drawing upon such findings to inform teaching, and the promise of design studies to address these difficulties. Hence, a review of the general literature on design studies in education is conducted, followed by an outline of how design studies have been used in science education, which leads on to the adoption of a design model to use in my study. The chapter concludes by presenting the aims of the research and emerging questions.

Chapter 3 addresses the first aim of my research which concerns the development of a teaching sequence about plant nutrition. The sequence is presented in terms of the rationale of the design (i.e. the Design Brief) and how this rationale was embodied into instructional materials to be used by the teachers (i.e. the Worked Example). Because the topic of plant nutrition has been targeted by several researchers and some teaching sequences are available, I chose a sequence that was developed by Hind et al. (n.d.) and made some modifications and improvements to meet my intentions. Presenting the teaching sequence early in the thesis will make the nature of the sequence and intended outcomes clear before setting out the methodology.

The methodology is presented in Chapter 4, starting with an explanation of how the research questions are addressed. Next, the research strategy is justified and descriptions provided of the three phases of design, implementation and evaluation. In addition, data collection techniques and analysis approaches are outlined and described. The chapter concludes with a discussion of the quality of research and ethical issues.

In the subsequent chapters (Chapters 5, 6 and 7), the gathered data and findings are presented in relation to the three research questions. Chapter 5 concerns the first question that is intended to establish the match between what is planned and what is implemented using findings from videos and collected classroom work. Chapter 6 focuses on research question 2 and seeks to establish whether students attained the desired learning outcomes using findings from students' responses to three written probes. Then, Chapter 7 presents findings from the interviews to ascertain how the teachers and students responded to the teaching sequence, which answers research question 3. Tables and figures are used to clarify the text when they are thought to be beneficial and all findings are triangulated, when appropriate.

Chapter 8 features a discussion of the findings that are presented in the previous three chapters. It starts with a summary of the key findings linked to the three research questions. Since this study is a design study, the results of the findings in terms of refining the teaching sequence and suggesting domain-specific guidelines for teaching plant nutrition in the Saudi context are presented in two sections. Finally, some reflections concerning the strengths and limitations of the design and evaluation models that were used in this study are discussed.

The last chapter (Chapter 9) draws general conclusions from the study, highlights contributions and limitations, suggests some implications, and concludes by underlying the lessons that I learnt from conducting a design study and how these lessons can be linked to my practice of developing instructional materials in Saudi.

CHAPTER 2: LITERATURE REVIEW

This chapter comprises a literature review related to three areas. Firstly, students' ideas of plant nutrition with a focus on the nature of plant food, sources of biomass and the photosynthetic process. Secondly, design studies as a research approach that meet the needs of the development of teaching sequences. Thirdly, the chapter describes three design models that have been proposed in science education, and highlights issues about the implementation and evaluation of teaching sequences. The chapter concludes by setting out the research aims and emerging questions.

2 CHAPTER 2: Literature review

2.1 Introduction

The purpose of this chapter is to discuss the relevant literature on students' ideas of plant nutrition and how to draw on this literature to develop domain-specific teaching sequences to improve students' learning and to highlight issues that should considered when implementing and evaluating teaching sequences.

The first section (2.2) reviews studies concerning students' ideas of plant nutrition. After presenting a conceptual analysis of the topic as introduced in the Saudi biology textbook, it focuses on how students think about plant food, sources of extra biomass and their views about photosynthesis. Within this review, I underline possible reasons why students develop such views. Then I highlight challenges faced by researchers when attempting to draw upon these findings to inform the design of teaching sequences, and how they respond to these challenges by creating design models and tools.

Hence, the second section (2.3) describes design studies as a research approach that science teaching designers, and designers from other fields, employ to develop and evaluate their designs. The main characteristics of this approach are highlighted, as well as key critiques.

Then, the third section (2.4) describes three design models used to develop teaching sequences in the field of science education. The descriptions follow their theoretical underpinnings, the design tools used and intended products, and then comparisons are made between the three models with the intention of adopting one of them. Finally, issues relating to the implementation and evaluation of teaching sequences in general are discussed.

The final section (2.5) concludes with emerging issues from the literature and sets out the research aims and questions.

2.2 Students' conceptions about plant nutrition

The purpose of this section is to review studies concerning students' ideas of plant nutrition. Since the research in this area is very wide ranging with a variety of aspects, this section begins by presenting a conceptual analysis of the contents of the Saudi biology textbook used by Grade 10 students in order to limit the review to the key ideas to be taught. Then, an overview of the research conducted in this area with regard to plant food, sources of biomass and the photosynthetic process follows. It finally concludes with a summary and emerging issues.

2.2.1 Conceptual analysis of the topic of plant nutrition

A conceptual analysis (for further details, see section 3.2.2) of the textbook reveals that it emphasises a disciplined knowledge focusing on teaching facts and definitions at the expense of developing explanations. In addition, the focus is on the molecular level of photosynthesis (light/dark reactions) with a brief mention of glucose as a source for energy, whereas using glucose to assimilate plant biomass is totally ignored. Moreover, the content contains misleading sentences about the requirements involved in photosynthesis (see section 3.2.2). Therefore, it was insufficient to rely only on the textbook as a source for the key ideas to be taught.

To fill this gap, it was necessary to turn to existing teaching schemes about plant nutrition (Oldham et al., 1985; Roth and Anderson, 1987; Hind et al., n.d.) in order to augment the textbook so as to compile a set of ideas that together constitute a comprehensive view of plant nutrition for secondary school students in Saudi. To ensure that the resulting ideas cover all the sub-concepts, Gagne's notion of task analysis (1974) is employed to break the key ideas into their constituent pieces (Appendix B). The resulting key ideas are:

- ***Photosynthesis***: carbon dioxide combines with water using light energy, which is trapped by chloroplasts, to produce glucose as a main product and oxygen as a by-product. Photosynthesis takes place in chloroplasts that are located in leaves. It is described at a molecular level by the equation: $6\ H_2O + 6\ CO_2 \rightarrow 6\ O_2 + C_6H_{12}O_6$
- ***Plants exploit glucose in two ways*:**
  - **As a source for energy:** glucose is used as substrate in respiration from which energy is librated to carry out biochemical functions.
  - **To assimilate plant biomass:** some of the glucose is converted into other complex chemicals such as cellulose, proteins and fats, which make up the plant biomass, with some minerals absorbed from the soil.

The next section identifies students' ideas as a result of reviewing empirical studies of students' views about plant nutrition and photosynthesis. The following review is constructed around the key ideas identified above.

2.2.2 Overview of the research

According to Wood-Robinson (1991), the topic of plant nutrition "…is the most fully researched aspect of children's understandings of plants and their physiology" (p.123). Indeed, students' ideas of plant nutrition have been explored with different conceptual foci across students' ages using several techniques.

In terms of the conceptual focus, most of the early research focuses directly on documenting students' understanding in terms of the mechanism and importance of photosynthesis, relationships between photosynthesis and respiration/metabolism, and plant nutrition and growth (i.e. the nature of plant food and the sources of biomass). Examples of studies that represent this focus are Simpson & Arnold (1982, a & b), Wandersee (1983), Bell (1984), Haslam & Treagust (1987), Eisen & Stavy (1988), Boyes & Stanisstreet (1991) and Ozay et al. (2003). On the other hand, researchers have also investigated students' understanding of plant nutrition and photosynthesis within an ecological focus in terms of energy flow (Adeniyi, 1985; Waheed and Lucas, 1992; Lin & Hu, 2003; Carlsson, 2002a,b), cycling of matter between organisms (Leach et al., 1996 a; Lin & Hu, 2003; Carlsson, 2002a,b), and interdependency of organisms in ecosystems (Leach et al., 1996b). Thus, a recent study investigated students' understanding by bringing the two foci together (Marmaroti & Galanopoulou, 2006).

With regard to the age ranges that have been sampled, some researchers targeted students across different ages between 5-16 (Wandersee, 1983; Bell, 1984; Haslam & Treagust,1987; Eisen & Stavy,1988; Leach et al., 1996a), others focus only on high school students (Simpson & Arnold , 1982a,b; Adeniyi, 1985; Waheed and Lucas, 1992; Lin & Hu, 2003; Ozay et al., 2003; Marmaroti & Galanopoulou, 2006), while a few research university students (Carlsson, 2002a,b) or student teachers (Boyes & Stanisstreet, 1991). It should be noted that school teachers' knowledge of plant nutrition has not attracted attention like that of school students. Therefore, it may be useful to investigate teachers' understanding, since there is evidence that even practicing teachers who are specialists in their subjects may harbour misunderstandings about the natural world (Sanders 1993; Yip, 1998).

The techniques used by researchers to probe students' understanding also vary. While paper-and-pencil is the most frequently used technique (Wandersee, 1983; Haslam and Treagust, 1987; Eisen and Stavy, 1988; Boyes and Stanisstreet, 1991; Waheed and Lucas, 1992; Lin and Hu, 2003; Ozay et al., 2003; Marmaroti and Calanopulou, 2006), some use a combined technique of paper-and-pencil and interviews (Simpson and Arnold, 1982a,b; Adeniyi, 1985; Bell, 1984; 1993; Leach et al., 1996), and a few use only interviews (Carlson, 2002a,b). Most of the researchers use conceptually-framed probes that investigate students' understanding in the context of school science, focusing, for example, on facts and definitions (Simpson and Arnold, 1982a,b; Adeniyi, 1985; Haslam and Treagust, 1987; Eisen and Stavy, 1988; Boyes and Stanisstreet, 1991; Lin and Hu, 2003; Ozay et al., 2003; Marmaroti and Calanopulou, 2006). Others use phenomenologically-framed probes that explore students' understanding based on an event or phenomenon without necessarily referring to school science with the intention of allowing students to use their own language (Bell, 1984; Leach et al., 1996; Carlsson, 2002), and a few use a mix of the two approaches (Wandersee, 1983; Waheed and Lucas, 1992).

In addition to these studies, some researchers bring the empirical findings together after reviewing studies, thus drawing out some implications for biology teaching (Wood-Robinson, 1991; Driver et al., 1994a).

This variation in researching students' understanding can show, on one hand, how widely the topic has been researched and, on the other, how established are the findings in this area of biology. Findings derived from these studies are presented below with regard to "The nature of plant food", "Sources of biomass" and “The photosynthetic process”.

2.2.3 The nature of plant food

Several studies found that high school students believe that plants obtain their food from external sources (Wood-Robinson, 1991). For example, using a set of multiple-choice items to probe the knowledge of Scottish students aged 12-14 years, Arnold and Simpson (1982a) found that the majority believe that plants obtain food from the soil. This is also confirmed by Wandersee (1983) who conducted an across-age survey to investigate American students’ understanding of the role of the soil with regard to plants. In addition, Driver et al. (1984) presented English students aged 15 years with three written probes and conclude that one of the main alternative ideas that students have is that “…plants obtain food from the environment…[*and*] food for plants is anything taken in from the outside” (p.14).

The idea that plants suck up their food from the soil (this food might include water, minerals and/or fertilisers) has been confirmed in several studies with students from Australia (Haslam and Treagust, 1987), Israel (Eisen and Stavy, 1988) New Zealand (Barker and Carr, 1989) and Turkey (Ozay et al., 2003). Interestingly, students often draw an analogy between the mouth in animals and roots in plants (Bell, 1984; Wandersee, 1983; Adeniyi, 1985; Marmaroti & Galanopoulou, 2006). In addition to the types of food mentioned above, Wandersee (1983) and Bell (1984) found that some students aged 14-15 consider air, whether taken in through roots or leaves, to be food for plants. Yet, in some cases prior to learning plant nutrition, even light was regarded by high school students to be food for plants (Wandersee, 1983, Tamir, 1989).

Across the studies, little evidence suggests that students are aware that plants make food internally (Driver et al., 1994a). In addition, even after learning plant nutrition, although students regard glucose to be a source for plant food, they simultaneously advance the idea that plants take in food from the soil (Simpson & Arnold, 1982a; Bell, 1984;).

It seems that the continuity of these erroneous views of plant food is due to an improper understanding of the concept of food, which is a pre-requisite to understanding the nature of plant food (Simpson & Arnold, 1982a). While scientists often use the term "food" to refer to a chemical substrate in respiration from which energy is liberated to carry out biochemical functions (Wood-Robinson, 1991), students think that food is important because it keeps us alive and healthy (Wandersee, 1983; Bell, 1984, Marmaroti & Galanopoulou, 2006). Wandersee (1983) confirms this view of the function of food at the university level as well. In line with this view, Simpson and Arnold (1982a) found that students aged 11-14 tend to classify food according to how edible it is considered to be, irrespective of the energy it supplies.

In addition to the problem of how students conceptualise food, it also seems that the word "food" is problematic, as it is used in science lessons with a variety of meanings. For example, in human nutrition lessons, students learn that food provides both nutrients and the energy that humans need to function, whereas in plant nutrition lessons glucose produced in photosynthesis is regarded as the only food for plants, yet in the ecological context food includes all nutrients that are cycled back and forth between non-living and living systems (Barker and Carr, 1989; Hogan, 1996).

2.2.4 Sources of biomass

Students' understanding of the "Sources of biomass" has not received as much attention as "The nature of plant food". Yet, similar to the beliefs documented in terms of plant food, students at different ages think that biomass increases due to nutrients taken in from the soil (Wood-Robinson, 1991; Driver et al., 1994a).

For instance, Wandersee (1983), in a cross-age study, presents 1405 American students with a picture that represents Helmont's experiment, attempting to probe students' understanding of the role of the soil. Although most students did not provide a causal explanation for their answers, about one third of the students aged 14-16 thought that soil would lose weight "*…because when the plant grew it was taking all its food out of the soil*" (Wandersee, 1983, p. 464). In line with Wandersee, Bell (1984) found that a fifth of a sample of English students aged 15-16 years referred to the soil as a source for plant growth. In addition, Stavy et al. (1987) researched Israeli students aged 13-15 years and found that, despite knowing that carbon dioxide is absorbed and involved in photosynthesis, students did not mention its effect on the increase of weight.

So, one may wonder of the barriers that prevent students from applying their knowledge of photosynthesis to account for plant growth. This is discussed in the next sub-section with regard to students' understanding of the photosynthetic process.

2.2.5 The photosynthetic process

Although photosynthesis is a revisited topic in school science, it seems that many students continue to hold ideas, as mentioned above, that are inconsistent with the school science conceptualisation of photosynthesis. So, in the first instance, how do students conceptualise photosynthesis? In addition, to what extent do they understand the mechanism of photosynthesis?

Firstly, the term "photosynthesis" is a purely abstract scientific term that it is unlikely to come from experiences derived from everyday observations. Rather, it is mostly encountered in science lessons, museums visits and/or documentary scientific videos. In the case of an abstract concept like photosynthesis, some researchers suggest that most of students' misunderstandings result from incomplete views that were constructed during biology lessons, derived from textbooks and/or learnt in out-of-school learning situations (Yip, 1998).

In terms of students' misconceptions about photosynthesis, one of the ideas that students possess is considering photosynthesis to be plant respiration (Driver et al., 1994a). Stavy et al. (1987) found that about two thirds (*n*= 33) of their sample of 13-15 years old students think of photosynthesis as a type of plant respiration. Moreover, it seems that there is widespread confusion amongst students of different ages regarding photosynthesis and respiration in terms of their roles, reactants and products, and the times at which they occur (Wandersee, 1983; Stavy et al., 1987; Wood-Robinson, 1991).

In line with the view which considers photosynthesis to be a process involving only the gas phase, American students aged 11-14 in Wandersee's study (1983) regarded photosynthesis as a process which is meant to balance oxygen in ecosystems, irrespective of food-making characteristics. As a result of this view, Roth and Anderson (1987) indicate that students might also hold an anthropocentric view that considers the purpose of photosynthesis is to supply oxygen for other organisms.

When it came to relating photosynthesis to food and energy, it is revealed that some students might also regard photosynthesis itself as a substance rather than a process (Bell, 1984). It seems that, although photosynthesis is a revisited topic, students tend to correctly memorise the technical terms encompassed in the equation of photosynthesis without appreciating what photosynthesis is or its purpose (Simpson and Arnold, 1982a; Wandersee, 1983).

To underline the conceptual problems related to learning photosynthesis, Wandersee (1983) concludes that students have particular difficulties with the requirements involved in photosynthesis, i.e. carbon dioxide, water and light energy. Despite knowing that carbon dioxide, water, air and light are important for plants, students very often do not have a functional awareness of why they are important or why they are required in photosynthesis (Ozay & Oztas, 2003). In addition to difficulties with the requirements, students also have problems appreciating the fact that the physical mechanism of photosynthesis is a chemical reaction (Barker and Carr, 1989b).

In terms of carbon dioxide, Bell (1984) reported that about two thirds (*n*=300) of the surveyed English students aged 15 years did not mention that plants take in carbon dioxide. In addition, even with regard to university students, Eisen and Stavy (1988) found few students who were aware of the role of carbon dioxide in photosynthesis and that the increase in biomass mainly comes from it. In addition, Stavy et al. (1987) mention that, despite knowing that carbon dioxide is absorbed, students find it hard to believe that biomass increases as a result of the incorporation of a mere gas. This also is confirmed by Wandersee (1983), who concludes in his across-ages study that appreciating "…the importance of carbon dioxide as the main source of raw materials for photosynthesis was one of the least improved aspects of photosynthesis" (p.479).

In addition, Leach et al. (1996a) indicate that it is difficult for students to grasp that an invisible gas, in this case carbon dioxide, can contribute to food making and the increase in biomass. It seems that students, in the first instance, have a problem with the concept of gas (Séré, 1986). On the other hand, students also have problems with the concept of matter (Nussbaum, 1985). For example, studies that investigated students' knowledge of matter revealed that students consider matter to be something concrete and solid and therefore believe that gas is not a form of matter, as it appears to weigh nothing and, therefore, cannot contribute to forming other things (Stavy, 1988, 1990). It seems that students lack the prerequisite concept that gas has mass. However, in order to make photosynthesis a plausible explanation, this pre-requisite must first be addressed.

The role of water was also regarded by Wandersee (1983) to be one of the problematic aspects of photosynthesis. Indeed, water is regarded, as mentioned previously, by students of different ages as food for plants. In this respect, Wood-Robinson (1991) indicates that observing the consequence of drought on plants makes the conclusion that plants grow because they are watered inevitable. In addition, students might misunderstand the canal through which plants absorb water. While most students know that water is absorbed through the roots, Barker and Carr (1989) mention that some students might think that water is absorbed through the leaves.

In terms of the role of light in photosynthesis, students know that light is important for plants and that plants die if they are left in the dark (Wood-Robinson, 1991). However, they are unable to provide a scientific explanation as to why light is important (B. Bell, 1984; Wandersee, 1983). Instead, as mentioned by Roth (1985), students tend to hold the view that light is food on its own, or that plants need it to live, grow and be healthy and green. Therefore, students might think that plants die in the dark as a result of illness caused by the absence of light rather than the inability to make food. In addition, students might confuse heat with light. Barker and Carr (1989) reveal that some students aged 13-15 think that solar heat can be absorbed by leaves and used in photosynthesis. Even if students recognise that light is needed in photosynthesis, they consider light to be an equivalent of carbon dioxide and water rather than a source of energy. This confusion over the nature of light energy might be due to the misunderstanding mentioned by Driver et al. (1994a) that students tend to think that light made is of molecules, so treat it in a similar way to carbon dioxide and water. Another conceptual difficulty in this respect is energy conservation. Barak et al. (1997) reveal that students, even those who were in the final year of high school, found it difficult to apply the concept of energy conservation in a biology context such as converting light energy into chemical energy in photosynthesis.

Thus, students have difficulties with the role of chlorophyll in relation to plants in general or to its function as an energy converter. When Wandersee (1983) asked students about the loss of green colours in leaves during autumn, only about a quarter of students (aged 11-18) indicated chlorophyll by name. In terms of the role of chlorophyll, Arnold and Simpson (1982a) found that about 40% of their sample (n=627) of students aged 15-16 who followed an advanced biology course failed to determine the role of chlorophyll. In addition, some students in Wandersee's study (1983) went as far as to regard chlorophyll as food for plants. It also appears that chloroplasts are associated with several different notions in students' minds. As indicated by Bell and Brook (1984), students have a limited understanding of the relationship between chlorophyll, colour, light and energy, despite being able to correctly name chlorophyll. This is in line with Wandersee's findings (1983) that only half (n=393) of students aged 15-16 years were able to link chlorophyll to energy.

With regard to the mechanism of photosynthesis, students are taught that carbon dioxide combines with water to form glucose. However, they have difficulties in appreciating that a solid substance (sugar) can be produced by combining liquid (water) with gas (carbon dioxide) (Driver et al., 1994a). It seems that students lack the prerequisite concept related to the cycling of matter (Arnold and Simpson, 1982a). In addition, according to Leach et al. (1996a), this problem is apparent in both young and old students, although the latter might use scientific terms in their answers. Driver et al. (1994a) point out that applying the cycling of matter appears more difficult in a biology context. This is also observed by Lavender and Anderson (1982), indicating that students have difficulty in recognising that a *chemical change* occurs in photosynthesis whereby plants combine carbon dioxide with water to produce glucose and oxygen.

2.2.6 Summary and emerging issues from research on students' ideas of plant nutrition

In this section some of the empirical studies related to students' knowledge of plant nutrition have been reviewed. Two main findings can be highlighted from this review. Firstly, students hold a range of views about the nature of plant food, sources of biomass and the photosynthetic process. It is likely that students attend a plant nutrition lesson with the following preconceptions:

- *Sources of plant food:* Students believe that plants take in ready-made food from their surroundings. Examples of this food include water, minerals, fertilisers and maybe light and air. Although they might refer to plants making food internally, they might also believe that plants suck nutrients up from the soil as food. It seems that students retain a model of plant nutrition similar to that of animals' feeding, in which roots function as a mouth.

- *Plant biomass*: students ascribe plant growth and the increase of biomass to nutrients taken in from the soil, mainly water. In particular, they find it difficult to believe that plants' mass mainly comes from the incorporation of carbon dioxide.

- *The nature of photosynthesis*: students might see photosynthesis as a type of respiration or they may confuse photosynthesis with respiration in terms of purpose, outcomes and time of occurrence. Moreover, roles of carbon dioxide and light energy appear to be challenging for students to appreciate.

The second key finding concerns the causes of these misunderstandings. It seems that these misunderstandings are caused by a lack of proper understanding of some pre-requisite concepts, which are:

- *Concept of food:* while the scientific conception rests on using food as a source for energy and biomass, students tend to conceptualise food as elements that are edible, digestible, or absorbable, in the case of plants.

- *Concept of gas*: although the scientific view is that gas (e.g. carbon dioxide) has mass and can contribute to forming other substances, students think of carbon dioxide as a weightless gas, which cannot contribute to forming glucose.

- *Cycling of matter*: while matter is conserved and can be cycled into different forms, students find it difficult to believe that solids like glucose or mass can be produced from combining gas (carbon dioxide) with liquid (water).

Given, on one hand, the importance of understanding plant nutrition in biology as a basis for future learning (Stavy et al., 1987), and, on the other, the conceptual difficulties associated with learning this topic, it maybe feasible to develop a teaching sequence for the purpose of addressing these difficulties and improving students' learning with regard to plant nutrition. So, the question is: how is it possible to develop a sequence that fulfils this purpose?

The findings I have presented above are useful to indicate students' likely starting points and possible difficulties with learning about plant nutrition. In addition, the literature on learning in general contains hints and guidance on how to teach, taking into account students' likely starting points. For example, one of the most cited pieces of guidance in this respect is the call by Ausubel to consider students' existing knowledge; he stresses that "*The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly*" (Ausubel, 1968; Epigraph). While this call asserts the importance of considering students' existing knowledge and does refer to teaching, it does not offer guidance on how teaching can be planned in a way that addresses the difficulties that students have with regard, for example, to conceptualising food or the ways they see gas and matter. Indeed, assistance about that departure from "…what the learner already knows" to "…teach him accordingly" seems to be missing.

Another source of guidance can be also found in the literature related to conceptual change (i.e. "…the development of students' pre-instructional conceptions towards the intended science concepts", Duit and Treagust, 2003, p.671). Scott, Asoko and Driver (1992), for example, conducted a literature review regarding teaching strategies that can be used in guiding students from their existing knowledge towards the science view. Their review results in two main strategies, which they find are widely used in conceptual change studies. The first strategy involves making the student's ideas explicit and then setting a conflict in order to help students recognise the limitations of everyday ideas. Then the attempt to resolve the conflict constitutes the first step in the journey towards learning the scientific view. The other strategy involves building on students' existing conceptions and extending them towards the scientific view by means of using analogies. While these two strategies can be effective in general, it is essential that questions like "Which science concepts can these strategies help?", "When should these strategies be used in teaching?", and "How should they be used within a specific context?" should be answered when planning teaching, but they cannot be answered from general principles. In my view, both examples of guidance can be valuable in providing general principles for planning teaching, but fall short of providing specifications of the decisions related to teaching and learning specific aspects of content.

In an attempt to determine the required specifications, Leach and Scott (2008) distinguish between two levels of guidance needed to inform instruction. The first is *a large grain size* level of detail that can be translated into general attributes to improve teaching and learning, like the two examples mentioned above. The second type of specification is *a fine grain size* level of detail that aims to provide content-specific guidance on teaching a given topic or set of concepts.

In other words, the knowledge that students' ideas about plant nutrition have an effect on their understanding of the fact that glucose is produced in photosynthesis should be complemented by an awareness of the specific challenges involved in teaching and learning photosynthesis, and assistance for the teacher to deal with these challenges. Developing such specifications requires an integral approach that takes into account what students already know, clarifies the knowledge to be taught and afterwards develops examples of content-specific practices (Lijnse, 2000, Leach et al., 2009). Then, teachers can use these examples when teaching specific content.

In order to arrive at such domain-specific teaching sequences, science education researchers have been engaged in creating their design models and tools, and employing a design research approach that fulfils their purposes. They usually develop instructional materials and a set of domain-specific guidelines for teaching a given topic.

The next section presents an overview of the general literature on design studies in education, and then the successive section goes on to consider how design studies have been used to develop the intended products in science education.

2.3 Design studies

Design studies have been gaining attention from researchers in education. This is reflected in special issues of journals (e.g. (*Educational Researcher* 32(1), 2003; *Journal of the Learning Sciences* 13(1), 2004; *International Journal of Science Education* 26(5) 2004) and books (e.g. van den Akker et al., 2006; Kelly et al., 2008) that have been dedicated to discussion of theory and methodology related to conducting design studies in general or, more specifically, in science education.

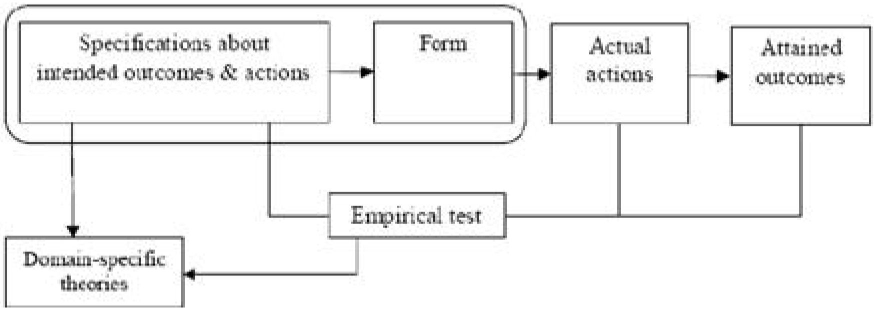
Design researchers use different labels to name their research. Examples of these labels include “design experiments” (Brown, 1992), “teaching experiments” (Brown and Clement, 1992), “learning environments” (Collins et al., 1994), and “developmental research” (Lijnse, 1995). Rather than adopting one of these labels, I prefer to follow Confrey (2006) and use the term “design studies” as an umbrella that encompasses different labels and reflects the design characteristic, while it avoids confusing this research approach with traditional experimentation.

Design studies can be seen more as *approaches* to conducting research that is concerned with developing and testing teaching/learning methods, instructional materials and/or software tools (Collins et al., 2004; Gorard and Taylor, 2004). Although there is no consensus on the definition, Barab (2006) attempts to capture its nature and purposes by defining it as:

> *…the close study of a single learning environment, usually as it passes through multiple iterations and as it occurs in naturalistic contexts, to develop new theories, artefacts, and practices that can be generalized to other schools and classrooms (*p.153*).*

As shown in Figure 2.1, design studies start by specifying the intended outcomes and actions, and then embody these specifications into a form (e.g. teaching sequence or software) for the purpose of influencing practice (Gorard and Taylor, 2004). Applying this model to teaching and learning specific content, the design intentions might include specifications of intended outcomes, planned-for teachers’ actions, desirable engagements and planned-for contextual conditions. These specifications are usually shaped and informed by theories of teaching and learning, and constitute, in themselves, initial hypotheses that can be generalised into different contexts.

Figure 2.1: General Design Model (based on Gorard and Taylor, 2004)



The designer then takes the form to natural settings to test its workability. The purpose of this validation differs, however, from traditional experimentation. It goes beyond finding out whether the designed intervention is better or worse than usual practice and delves into what happens when this intervention is used. After testing the product in natural settings and matching the actual actions and attained outcomes to the intended actions and outcomes, designers usually introduce revisions to improve the form, develop specific guidelines about effective approaches of teaching and learning a specific content and guidelines for situations when these approaches do or do not work. A combination of these two kinds of guidelines contributes to building a practical theory, or "humble theory" in the words of Cobb et al. (2003), that can be used by teachers and students in classrooms. It should be noted that developing a design is not a linear process, as this general model might suggest. Rather, developing a design involves creative thinking and consideration of multiple factors (Confrey, 2006). Moreover, this model only shows one cycle of developing an intervention, while in practice the design process is iterative in the sense it involves designing, testing, redesigning and so on until the product reaches a "good enough" level to be used by practitioners (Lijnse, 2000).

2.3.1 Characteristics of design studies

The general model presented above reflects three characteristics of design studies, namely, design activity, grand theory and domain-specific theory, using multiple methods to gather multiple data sets (Gorard and Taylor 2004; van den Akker et al., 2006).

2.3.1.1 Design activity

Some researchers draw an analogy with engineering to illustrate the design nature embedded in this approach. Cobb et al. (2003), for example, stress this characteristic, stating that:

> *Engineering particular forms of learning and systematically studying those forms of learning within the context defined by the means of supporting them. This designed*

> *context is subject to test and revision, and the successive iterations that result play a role similar to that of systematic variation in experiment.* (p. 9)

The products could be a material (e.g. teaching intervention) that embodies the designer's theoretical intentions, accompanied by ways of achieving them. Thus, there is another product, namely the embodied theories (see next section). Both products go through an evaluation. However, unlike traditional experimentation, measuring the output is not the end goal in design studies and the evaluation cannot be limited to a laboratory setting (Brown, 1992; van den Akker et al., 2006). Rather, the products should be evaluated in natural settings (e.g. classrooms) for the purpose of improving them and understanding "how" and "why" they work in practice in order to develop practical and tested solutions to approach certain problems. Some researchers describe the process of designing as a "*coevolutionary process*" in order to assert that the resulting design is a product of the interplay between the embodied theory, improvements inspired by testing the product in practice and the environment in which the testing takes place (Jacobson and Riemann, 2010). Hence, they use the label "learning environment" to denote their research.

2.3.1.2 Grand theory and domain-specific theory

In an attempt to signify the place of theory in design studies, diSessa and Cobb (2004) refer to "grand theories" (e.g. Piaget or Vygotsky's theories) that contribute to shaping the researcher's theoretical position and provide general principles that guide developing and testing the design. On the other hand, they also point to "domain-specific instructional theories", which are framed by "grand theory", but are more practical since they "…embody testable conjectures about both learning processes and the means of engineering them" (p.83). According to Cobb et al. (2003), the production of these domain-specific theories is expected as a result of conducting design studies. To this end, with regard to design studies, theory can be seen from two ends: as an input (i.e. general theoretical perspectives on learning) and an output (i.e. specific practical theories for teaching and learning specific theoretical content or skills).

However, as previously mentioned, utilising a grand theory or general principles about learning and teaching to generate domain-specific theories about teaching is not a straightforward task. Rather, alongside the creative process, it involves using particular design models and tools so as to subdue the grand theories and contextualise them to serve specific purposes. This, in turn, entails making decisions about the content and how it can be sequenced and approached. These decisions must be made explicit through coherent articulation and justification. Gorard and Taylor (2004) stress this requirement in design studies, stating that:

> *...unless that structure is made explicit, and the propositional framework upon which the design rests laid bare, it does not constitute a test of that theory, and therefore contributes little to the broader body of disciplined knowledge about teaching, learning, or anything else* (p. 107).

After making the rationale of the design explicit, the designer takes the design to natural settings to test if it works. Design researchers use several methods to gather different types of data.

2.3.1.3 Using different methods to gather multiple data sets

The nature of the classroom and the desired outcomes from design studies necessitate employing different methods to gather different data. According to Gorard and Taylor (2004), design studies: look at many dependent variables, allow participants to interact, develop profiles rather than hypotheses, consider the context of and seek to understand the actual implementation, measure the impact and come up with possible revisions and guidelines for practice. In order to complete these tasks, design researchers employ combined methods derived from quantitative as well as qualitative traditions (see section 2.2.3.2).

Despite these advantageous characteristics, some critiques have been made against design studies. The next sub-section underlines some of these critiques and explains how to minimise their effect.

2.3.2 Critiques of design studies

Like any research approach, some critiques have been levelled against design studies. It seems that the critiques concern the importance of ensuring that the final claims rest on solid empirical findings. For example, there is a concern that studies conducted according to this approach are not always sufficiently tested. Without evaluating the design, Gorard and Taylor (2004) wonder how design researchers can "…persuade others that they have successfully eliminated rival explanations" (p. 107). In my view, this critique concerns how design studies are evaluated rather than the conduction of design studies. Indeed, the claims drawn from the research regarding domain-specific theories must be supported by evidence generated by using accurate measurement. The importance of evaluation is elaborated below (see section 2.4.3).

Another critique introduced by Millar et al. (2006, p.19) is that "Design experiment(s) are likely to be more open to interpretation – and hence may be less likely to persuade people to change practices". In my view, this openness reflects the complex and uncontrolled nature of the classroom and can apply to any qualitative study conducted in such settings. It may also apply to quantitative studies when the effect of a certain pedagogic technique is determined by “guess work”. However, techniques in design studies can overcome this challenge by collecting multiple sets of data and achieving triangulation, which might make the researcher more confident about final conclusions.

Related to this issue is the concern mentioned by Barab and Squire (2004) that researchers can be biased when selecting evidence that proves certain views or when they only report observations that support their claims. While this applies to any research, the researcher has to ensure that provided descriptions represent all possibilities, even those that challenge their final conclusions. Moreover, the researcher might ask an external checker to randomly review the descriptions against the original transcriptions. Another suggestion proposed by Brown (1992) is to make the obtained raw data available to others. In addition, researchers in design studies can conduct a self-evaluation, drawing on standards usually used in meta-evaluation reports. According to Stufflebeam (2000), meta-evaluation (i.e. an evaluation of evaluation) can be used to determine the merit of the evaluation by reviewing the extent to which it meets the requirement of sound practice.

Moreover, a critique raised by advocates of randomised controlled trials is the limited generalisability of findings from design studies, as they are specifically designed for, and tested in, a certain context (Gorard and Taylor, 2004). While acknowledging that this is a characteristic of design studies, there is no reason to believe that the designed teaching, for example, cannot be used in different contexts with the possibility of replicating similar effects. In this respect, Gorard and Taylor (2004) indicate that the produced solutions "…can be 'transported' to any working environment where others might determine the final product within their particular context" (p.101). Yet, it is the responsibility of designers in the first instance to provide base data in order to help others to make such a judgement (Guba and Lincoln, 1985).

However, transporting instructional solutions requires, amongst other things, that design researchers explicitly articulate the rationale of the design to enable others to draw upon their work and to make necessary modifications to meet their local needs. This study will show an example of this articulation (see Chapter 3 and Appendix A) and result in domain-specific guidelines that others can use in different contexts (see section 8.4).

In the next section, three design models in the field of science education that concern the development of teaching sequences with explicit rationale are reviewed. Comparisons between these three models are then made for the purpose of adopting one of them in my study.

2.4 Developing science teaching sequences

As previously mentioned, insights at a large grain size cannot *alone* meet the need for the development of subject-specific practices that address teaching specific topics. This is simply because they do not offer guidance with regard to how to approach specific content for the purpose of supporting learning. Therefore, science education researchers start conducting design studies and creating specific design models and tools that integrate insights on learning, findings about students' ideas and teachers' professional insights in order to develop teaching sequences that are "…theoretically and empirically informed at both large and fine grain size" (Leach et al., 2009, p.4).

I intentionally prefer to use the word "developing" rather than "designing" in the title of this section to stress that this activity goes through processes of design, implementation and evaluation. Designing a product without testing it in practice does not reflect the nature of design research. The designed teaching should go through an iterative process of implementation, evaluation and revision until it reaches a good enough level to be recommended to teachers (Lijnse and Klaassen, 2004).

This section is structured to describe the three phases of developing teaching sequences. While the review of the design phase is based on literature in the area of science education, reviews of implementation and evaluation phases draw upon wider literature related to design and evaluation studies in education.

2.4.1 Designing teaching sequences

Bridging from the empirical findings on students' ideas, science education researchers call for teaching sequences informed by these findings to be designed in order to guide practice in classrooms (Driver and Erickson, 1983). However, amongst initiatives directed to produce such teaching sequences, only a few propose systemically-framed design models that explicitly specify the theoretical underpinnings and procedural processes involved in developing the desired sequence. In science education, three design models are prominent as they are constantly used and improved through national projects, as well as doctoral studies, in three European countries. In the Netherlands, the Developmental Research model is proposed by Lijnse and Klaassen (2004), in Germany the Educational Reconstruction model is proposed by Duit, Gropengieber and Kattmann (2005) and in England a model is proposed by Leeds Design Group (hereafter the Leeds Model) (Leach Ametller and Scott, 2009; Ametller Leach and Scott, 2007). The sub-sections below review each model and underline its main characteristics and components.

2.4.1.1 Developmental Research

This model was first proposed by Lijnse (1995) as a response to the lack of practical guidance that perspectives on learning can offer with regard to teaching specific content. It subsequently underwent further developments and clarifications through successive publications (Lijnse, 2000 & 2005; Lijnse and Klaassen, 2004). The model is reviewed below with regard to its theoretical underpinnings and its use of the problem posing approach as a design tool and to develop the scenario.

- **Theoretical underpinnings**

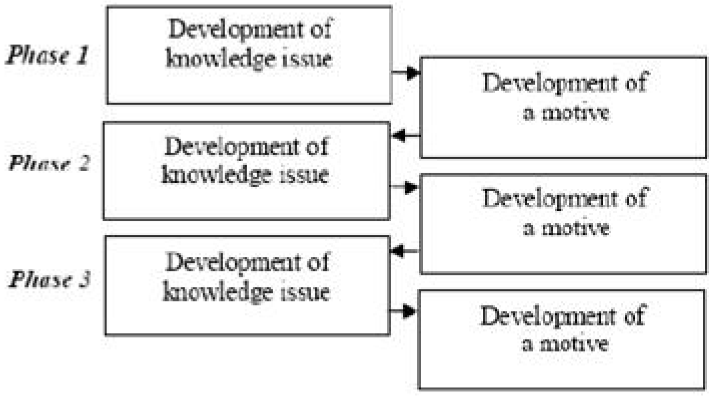
The model adopts the constructivist view that the ideas that students already hold affect their learning with regard to new scientific concepts and, therefore, should be taken into account when planning teaching. The authors utilise findings on students' ideas in informing designed teaching through a specific approach. Students' ideas are considered to be correct, to some extent, rather than obstacles if they are properly interpreted. In other words, designers can find shared ground between scientific views and students' ideas and use it as a starting point. Therefore, rather than replacing students' ideas, the purpose is to help students see and use new approaches when thinking about the natural world, which can be *added* to already existing everyday ideas (Lijnse and Klaassen, 2004). However, the authors argue that this process is not straightforward. Rather, it requires the learner to be "willing" to add the scientific view. In order to create this "will", students must make sense of what they are learning or doing so they can accommodate the new knowledge. To embody this view, the authors propose using the *problem posing* approach as a design tool, and then developing a *scenario* of teaching to be used by both teachers in the classroom and the researcher to evaluate the implemented teaching.

- **Using the problem posing approach as a design tool**

The purpose behind the "problem posing" approach is to help students "…see the point of extending their existing knowledge" (Lijnse and Klaassen, 2004, p. 539). In developing the teaching sequence using the problem posing approach, the authors suggest conducting a didactical analysis of empirical studies on students' ideas with the purpose of designing a conceptual teaching pathway that consists of several steps.

As simplified in Figure 2.2, the problem posing approach goes through a series of linked phases (usually 5-6 phases). Each phase combines an issue of knowledge to be addressed in the teaching in order to help students make sense of the raised issue of knowledge. Depending on the targeted content, each phase addresses a specific purpose, whether to start with a motivation for learning the whole topic, to raise a question, plan an investigation, encourage applications, ask for reflections or bridge to further theoretical knowledge.

Figure 2.2: Problem Posing approach



While these motives work as local motives for learning a specific aspect of the content, Lijnse (2005) explains that there is still a global motive that should be created in order to put the whole teaching sequence into functional contexts that help students to see the reasons for learning science. These global motives can be practical (to cope with everyday needs), theoretical (to understand nature), technical (to design products) or societal (to link science to society).

- **Developing the scenario**

After developing the problem posing stage, the model considers developing teaching/learning activities accompanied by a "…scenario that predicts and theoretically justifies in detail the teaching–learning process as it is expected to take place and why it is expected to happen in that way" (Lijnse and Klaassen, 2004, p.540). In other words, the scenario specifies the content to be taught in relation to the teaching activities and how they would be perceived by students, as well as how the teacher enacts these activities as intended by the designers. Alongside using the scenario to prepare teachers to implement the design, the act of making the design intentions explicit guides the researcher in observing the implementation and, therefore, testing the workability of the design. Development of the teaching/learning activities and the scenario undergoes cyclic evaluations until it becomes ready to be used in practice. Results from students' learning, as well as teachers' enactments, inform refinement of the design to make it more effective.

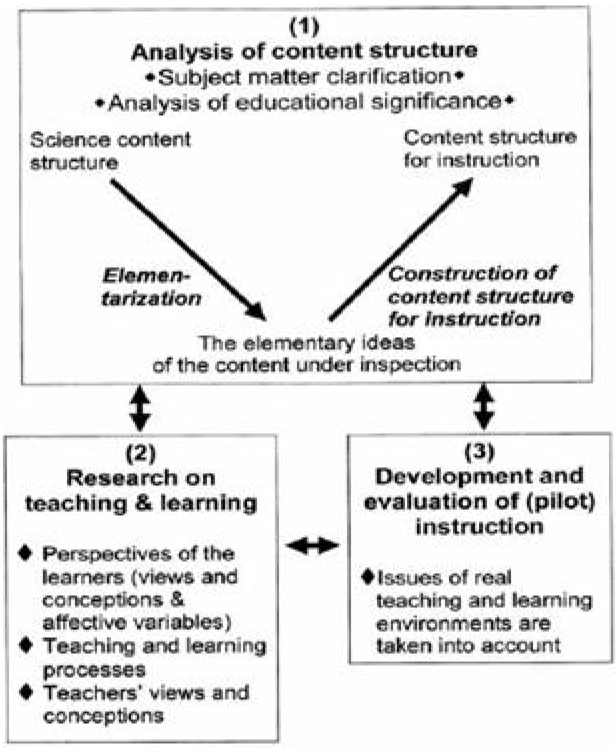
2.4.1.2 Educational Reconstructions

In an attempt to link theory to practice, Duit, Gropengieber and Kattmann (2005) introduce a design model for the development of learning and teaching sequences with the purpose of promoting the learning of a particular aspect of school science. According to Duit (2007), in addition to designing teaching situations, the model can also be used as a theoretical framework for planning teacher education or researching students' conceptions. This model is reviewed from the authors' published work (Duit, Gropengieber and Kattmann, 2005; Duit, 2007) in order to underline its theoretical underpinnings and the three steps of development of teaching (i.e. analysis of content, reviewing research on teaching and learning and development and evaluation of instruction).

- **Theoretical perspectives**

The model rests on the German Didaktik that emphasises the importance of transforming the content (or elmentarisation in the authors' terms) of a certain topic into a more simplified form that is specifically prepared for instruction. This transformation puts the content into a context that makes it more meaningful and accessible for the learners (Duit, 2007). On the other hand, the model utilises a perspective on learning in which learners actively reconstruct their existing knowledge to accommodate the new scientific concepts. Furthermore, alongside consideration of the epistemic dimension of students' ideas, the model takes into account social and ethical implications.

Figure 2.3: The Model of Educational Reconstruction (Duit, 2007)



As shown in Figure 2.3, the model consists of three components, as follows:

(1) Analysis of content structure: this component includes processes of clarifying and analysing the educational significance of the content at hand by reviewing two sources.

Firstly, the content presented in the leading science textbook of the targeted topic and publications of the historical development of the topic is reviewed. However, since textbooks often present scientific concepts though an abstract view, other learning papers are used as a secondary source to complement the ideas presented in the textbook with the purpose of simplifying the content for teaching and learning. To this end, the identified key ideas will not be limited to the epistemic view, but will also consider the ethical, social and environmental aspects of the content.

(2) Research on teaching and learning: this component encompasses reviewing empirical findings concerning students' perspectives about the topic at hand. The term "perspectives" is intentionally used as it goes beyond students' (pre)conceptions that are well-documented in the literature to include interests, motivations and attitudes that might affect their learning of the key ideas. In addition, this step might also include identifying the potential language difficulties that students may face when attempting to learn the content, as well as studies directed to explore teachers' views and conceptions.

(3) Development and evaluation of instruction: the outcomes of first and second components guide the design of learning environments and the selection of appropriate teaching/learning activities that meet students' specific needs and abilities. The designed teaching should then be piloted and evaluated using several methods like questionnaires, interviews and videos. The evaluation results inform revisions to the original design, as well as yielding empirical findings about students' understanding.

2.4.1.3 The Leeds Model

The model started with a perspective on learning (Driver et al., 1994b; Leach and Scott, 2003), together with design tools (Learning Demand, Leach and Scott, 2002; Communicative Approach, Mortimer and Scott, 2003); these were brought together and used in examples to design science teaching sequences in physics, chemistry and biology (Leach et al., 2006). The model went further in theorising and describing the design process in subsequent publications (Ametller et al., 2007; Leach et al., 2009).

In reviewing the Leeds Model, this section begins by underlining the theoretical underpinnings and describing the proposed design tools and intended products.

- **Perspectives on learning**

The model brings together insights from Vygotsky's theory on meaning making and individual perspectives on learning to develop a social constructivist perspective directed towards learning and teaching scientific concepts in classrooms (Driver et al., 1994b; Leach and Scott, 2003). Central to the adopted perspective is the Vygotskian view of learning as a passage from the social plane to individual understanding (Vygotsky, 1986). In other words, new ideas are first introduced in the social plane by other knowledgeable people (e.g. parents, teachers), and the individual actively tries to make personal sense of what is going on by relating it to his/her existing knowledge, while receiving support from others.

Furthermore, learning science is conceptualised as developing a new way of talking about the natural world that differs from the talk used in everyday contexts (Leach and Scott, 2003). In this regard, the model draws upon the work of Wertsch (1991) who employs Bakhtin's notion (1981) that specific communities utilize different social languages for particular purposes. For example, in the context of science, there is a scientific social language that represents a particular way of thinking using certain conceptual models to explain the natural world. This is different, though, from the social language of everyday ways of talking about the natural world. Making distinctions between the two social languages provides the learner with a toolkit that helps in moving between different "…ways of talking and thinking about phenomena according to context, recognising the appropriateness, power and limitations of each" (Leach and Scott, 2003, p.101). To this end, everyday concepts are no longer seen as absolute erroneous views that must be abandoned, often emphasised by individual perspectives of learning science. Rather, everyday ideas still better serve the need for communication with other people. Fertilisers, for example, may be considered to be "plant food" when referred to in a local shop, while in the science classroom glucose is the only source of energy and biomass in the context of plant nutrition (Scott et al., 2007).

In this sense, learning science is conceptualised as "learning to talk science" (Lemke, 1990, p.1), or becoming able to talk about natural phenomena in new ways. However, it is evident from research on students' ideas that the difficulties that students encounter when trying to make sense of and use the social language of science (see, for instance, the mentioned examples of students' ideas of plant nutrition). In appreciation of these difficulties, Leach and Scott (2003) use the notion of internalisation to stress the role of individuals in *re-constructing* their views using talk and activities introduced in the social plane and then *re-organising* their existing views accordingly. Of course, the teacher also plays a crucial role in supporting learning.

In order to use these theoretical perspectives to inform decisions about teaching and learning given content, the authors propose using specific design tools to specify the social language of science, the everyday social language students bring to the science lesson, the specific difficulties they encounter in learning the social language of science, and how to support them through verbal interactions. The next sub-section describes these tools and the procedure for developing the teaching.

- **Design tools**

The authors propose using two design tools: the Learning Demand (Leach and Scott, 2002) and the Communicative Approach (Mortimer and Scott, 2003) to inform designing a given teaching sequence.

Learning Demand: the purpose of the Learning Demand is to identify '…more precisely the intellectual task faced by the learners in coming to understand the scientific account of a given topic' (Leach et al., 2009, p.44). The learning demands can be identified through three steps. The first starts by analysing the curriculum and related official documents (e.g. textbooks) in order to determine the key ideas to be taught. The second step concerns identifying students' common ways of thinking and talking about phenomena under consideration with relation to the key science ideas identified in the previous step. Identifying students' ideas requires a literature review of empirical studies concerning the content at hand to be conducted. By way of comparing the gap between scientific ideas and students' way of thinking, certain specific differences can be recognised and attributed to ontological, epistemological or conceptual origins, as follows:

- A conceptual learning demand appears when students apply everyday discussion to explain scientific phenomenon (e.g. food for plants is anything that plants suck up from the soil through the roots).
- An epistemological learning demand arises when students limit their conceptual understanding to a certain context (e.g. cycling of matter can be explained in the physical world, but not in living systems).
- An ontological learning demand appears when students consider an object in a way that differs from reality (e.g. food is perceived based on its edibility rather than being seen as a substrate from which energy is librated in respiration).

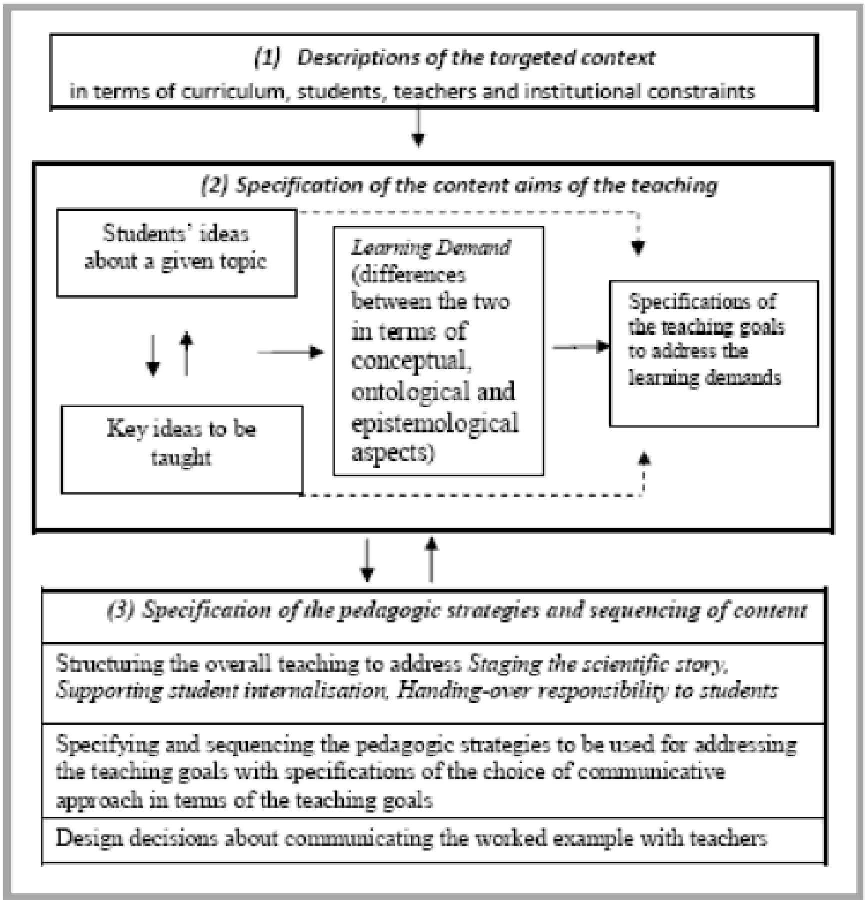
Then, by way of considering the nature of the differences between everyday ideas and scientific views, a set of teaching goals emerges to address these differences. As the authors assert (Leach et al., 2009), drawing out the teaching goals is not a linear procedure as it might appear from these successive steps. Rather, it involves going back and forth between the three steps while focusing on the key concepts and intended learning outcomes.

Table 2.1: Communicative approach (based on Mortimer and Scott, 2003)

	Interactive (Talk involves the teacher and students)	**Non-Interactive** (Talk involves only the teacher)
Authoritative (Considers only the science view)	The teacher leads the students' participating in the talk towards the scientific view	The teacher alone presents the scientific view
Dialogic (Considers both science and students' views)	The teacher elicits, explores and discusses the students' everyday ideas	The teacher alone reviews students everyday views

Communicative Approach: according to the communicative approach of Mortimer and Scott (2003), the talk between the teacher and students can be characterised along two dimensions (see Table 2.1). In one dimension, the talk can be interactive when it involves both the teacher and students; whereas it is non-interactive when the teacher does the talk alone. In the other dimension, the talk can be dialogic if different points of views are considered, whereas the talk will be authoritative if it focuses only on the one view of the scientific account. Considering who talks and the ideas being discussed, four classes of communicative approach emerge as shown in Table 2.1.

Figure 2.4: Components of the Design Brief (based on Ametller et al., 2007)



The authors' approach (as shown in Figure 2.4) to drawing upon these theoretical perspectives on learning is now described using the presented design tools to inform decisions about teaching specific content; the design decisions are then embodied into two products. The first product is the Design Brief that specifies the rationale of the design accompanied by justified design decisions, which is directed to the designer and other designers who might be interested. The other product is the Worked Example that represents one way of addressing the intentions specified in the Design Brief, which is directed to the teachers who will implement the design. Each product is described below, based on the authors' published work (Leach et al., 2006; Ametller et al., 2007; Leach et al., 2009).

- ***Design Brief***

The purpose of the Design Brief is to make the design intentions and decisions explicit and justify the rationale that underpins them. This explication serves as a reference for the designers in the evaluation phase and allows them to check their hypotheses against the actual implementation, and permits others to draw upon the work or judge its validity. The Design Brief consists of three main parts (see Figure 2.4) that specify: (1) the targeted context, (2) the content aims of the teaching and (3) pedagogic strategies and the sequence of the teaching. Each part is described below.

- **Part 1: Description of the targeted context**

This part constitutes a pragmatic description of the targeted context. It aims, on one hand, to identify in advance any contextual issues and constraints that the designer should consider when making the design decisions and enable, on the other hand, others to make judgments about the transferability of the design to their local contexts. It describes the curriculum (stating the key ideas considering previous teaching), students (age, expectations and profile), teachers (background and expectations) and institutional constraints (available facilities, class size, allocated time, and assessment regime and practices).

- **Part 2: Content aims of the teaching**

This part is devoted to specifying the content aims of the teaching using the Learning Demand tool. It encompasses specifications about the key ideas to be taught, as introduced in the official documents, with a commentary to tackle any inconsistencies or omissions from a subject matter perspective. It then summarises the students' likely starting points, derived from previously published research, when they come to learn this specific content. As mentioned before, the designer then identifies the learning demands for students to learn the targeted ideas. Once these demands are made explicit, the designer maps out the goals that address these demands and guide the teaching plan. In order to address the teaching goals, the designer needs to specify and justify sequencing the content and selecting pedagogic strategies.

- **Part 3: Specifications of pedagogic strategies and sequencing of content**

This third part of the Design Brief specifies and justifies the teaching at two levels. The first level is a *large grain size* of detail that considers the overall structure of the teaching for the purpose of addressing three fundamental issues, as follows:

- Staging the scientific story (i.e. introducing the targeted scientific model).
- Supporting internalisation (i.e. providing students with opportunities to develop and use new ideas).
- Handing-over responsibility to students (i.e. using the new ideas in different contexts).

This second level of specification is at *a fine grain size* of detail regarding sequencing the content and selecting the pedagogic strategies to be used to address the teaching goals. The term “pedagogic strategies” refers to ways of working on knowledge towards developing the desired learning (Ametller et al., 2007). The authors suggest that most content-specific teaching goals can be addressed by using the followings strategies:

- Formative assessment
- Drawing an analogy or building a model
- Using empirical evidence
- Setting up a conflict
- Introducing a science view linked to students’ existing ideas

In addition, this part provides specifications to communicate the pedagogic strategies in the classroom by means of using the Communicative Approach tool which links the talk to specific teaching purposes (see Table 2.1).

After developing the specifications of the intended teaching, the Design Brief takes account of how to communicate the designed teaching (i.e. Worked Example) to teachers. This is presented and justified, taking into consideration the context of implementation, teachers’ expectations and available resources, as described in the first part of the Design Brief.

- ***Worked Example***

This process is intended to mould the specifications advanced in the Design Brief into a teachable form (it could be in different forms). It contains a set of teaching/learning activities that follow the specified sequencing and address the pedagogic strategies at a *fine grain size* level of detail, taking into consideration classroom settings. Hence, the language used in the

Worked Example is simpler than that used in the Design Brief, as it is more prescribed and itemised.

The authors (Leach et al., 2009) also make a distinction between the success and failure of the Worked Example and the validity of the design decisions made in the Design Brief, taking into consideration possible causes of the mismatch between the intentions of the designer and implementation by the teacher. It is possible that some aspects of the Worked Example might not effectively address the design intentions, and/or the implementation may not precisely follow the Worked Example. Yet, it is also possible that some aspects of the Design Brief may not work, even if they were successfully addressed in the Worked Example and implemented as intended by the teachers. Results from analysing the mismatches inform different actions as to whether to reconsider the way the Worked Example is being implemented, how to make the Worked Example better address the design intentions or perhaps a revision of the Design Brief itself may be needed, for example, the search for another pedagogic strategy or different sequencing etc.

2.4.1.4 Comparison of the three models

The purpose of this section is to make comparisons between the three models for the purpose of adopting one of them to guide me in developing the intended design. However, it is first necessary to mention that the published work, in English, with regard to the three models varies in the level of theorising and explaining the rationale behind the models. As can be noted from the descriptions above and published articles, it appears that the authors of the Leeds Model are more concerned with explaining the rationale and components of their model in several publications, while the authors of the other two models are more interested in publishing articles about applying their models rather than explaining their rationale.

Considering their similarities, all the three models draw on findings about students' ideas, from different perspectives and approaches. However, they differ in utilising these findings. The Developmental Research model, for example, considers students' ideas to be correct, so common ground with science can be found and then built upon. The Educational Reconstruction model also makes use of empirical findings about students' ideas, with a broad view, however, that includes interests as well as ethical and social implications. While the Leeds Model agrees with the other two models in not treating students' ideas as being incorrect, it adopts a social-cultural perspective in which two social languages can exist and be used in different contexts with different purposes. Considering these theoretical perspectives, the designer's interest is in the procedure of informing the design by empirical findings.

Although the Developmental Research and Educational Reconstruction models offer general guidance for that purpose, only the Leeds Model provides a design tool (i.e. Learning Demand) that links the content to be taught, to students' ideas, and in turn, to mapping the teaching goals.

Another issue lies in making the teaching/learning activities motivating for students. It seems that the Educational Reconstruction model pays specific attention to motivating students to learn science by taking into account their interests and motivations alongside their conceptions. In the same direction, although more practically, the Developmental Research model fosters an approach that develops a global motivation, as well as local motivations, for learning science; in contrast, the Leeds Model does not explicitly account for students' interests and how to motivate them like the other two. Yet, the authors of the Leeds Model can claim that motivating students to learn might be embedded in the learning situations (Boekaerts, 2002) if they are designed in a way that makes sense to learners, encourages them to actively engage with ideas, and allows them to share their thoughts and reflect on those of others. In this sense, the different classes of the Communicative Approach support engaging students and taking account of their thoughts and opinions. As pointed out by Aikenhead (2006), "…engage[ing] students in an interactive way will make school science more relevant to them" (p.74).

Another practical issue that should be highlighted is related to supporting the teacher to implement the intended design. While the Educational Reconstruction model is not explicit with regard to the materials produced for the teacher, the Developmental Research model offers a scenario that prescribes the teaching/learning activities, and the Leeds Model ends with a Worked Example that supports enacting the intended design. However, the Leeds Model goes further by guiding and planning teacher-student verbal interaction according to different teaching purposes. In my view, the Communicative Approach provides a theoretical and practical framework for the teachers' actions particularly when a Worked Example is provided with specified annotations of the desired interaction. In the Leeds Model, the teacher will know when and why to elicit students' ideas using interactive/dialogic talk, how to introduce the scientific view using non-interactive/authoritative talk and will be able to review both sides of views using non-interactive/dialogic talk.

It would also be beneficial to compare the three models in terms of articulating the rationale of design, which is an essential characteristic of design studies. The Developmental Research model provides a scenario alongside the problem posing approach that both specifies and justifies in detail the desired teaching/learning process. The Educational Reconstruction model also offers documents linked to its three components which are related to content, teaching/learning activities and evaluation results, although the nature of these documents has not been specified. The Leeds Model provides justified specifications of the design in terms of the content to be introduced, how the teacher works on certain issues of content and how the content should be communicated to students.

Given that one of the purposes for articulating the rationale of the design and its intentions is to ease communication with other researchers with the intention of enabling them to judge its quality and draw upon it, it can be noted that all three models attempt to fulfil this purpose. However, I sometimes find it difficult to follow the Developmental Research and Educational Reconstructions models due to their complex use of terminology, which might have affected my interest in adopting their models. Perhaps there are more publications which illustrate these two models, but as mentioned by Lijnse (2004), they are published in local languages, not English.

Linked to the need to articulate the design, I found that the Leeds Model is more specific with regard to describing the context of teaching since it provides profiles of students, teachers and the educational regime. Such descriptions are important when others want to make judgements about the suitability of the design for their local needs, particularly when the context of the original design appears to be quite different from their own.

In terms of meeting the iterative process of design studies, the Developmental Research and Educational Reconstruction models are superior to the Leeds Model as they explicitly mention developing the design through several cycles; having said that, although the authors of the Leeds Model do not explicitly mention more than one cycle, the model does not lend itself to one cycle. Rather, the authors offer some insights into refining the Design Brief and Worked Example in the light of findings derived from evaluating the actual implementation and assessing learning. On the other hand, the authors of the Developmental Research and Educational Reconstruction models do not mention how findings from evaluations can inform refinement of the original design.

Finally, I want to conclude with a point of interest that I observed in publications of the three models. They have all mostly been employed by researchers or doctoral students who closely work with, or are supervised by, the authors. This can be deduced from the countries in which the research has been conducted or from acknowledgments dedicated to the authors of the models. In fact, employing a design model requires following procedural details, which might require support and guidance from the authors in order to use the model as intended. To this end, the support and guidance received from the authors of a particular model may encourage its use.

Given the characteristics of the Leeds Model in terms of the clarity of its procedural steps and the level of articulation of the design intentions which will help to guide development of the teaching and enable others to judge and draw upon the design and the support I received from the authors, I have decided to use it in my study.

The next sub-section highlights issues concerning the implementation of the designed sequence in classrooms.

2.4.2 Implementing teaching sequences

Although this phase is essential in the iterative process in design studies, it appears that it has been paid insufficient attention (Rowan et al., 2009) compared to the design. Indeed, it is the implementation phase that establishes whether the design intentions stand up to the test of workability. It is also in this phase that the role of the teacher becomes critical in implementing the teaching as intended. Despite this importance, the problem of overlooking the implementation phase has been raised as a criticism of design studies. Bauersfeld (1979) touches upon this problem, saying:

> *…both research and development had focussed on only one of two main determinants of the learning process: the pupil or the curriculum. They did not consider the influence of the teacher nor of the general context of instruction* (p. 200).

In an attempt to detect the relationship between the design and implementation, Rowan et al. (2009) highlight the consequences of the mis/match between planning and implementation with regard to achieving the intended outcomes (see Table 2.2). They suggest that only if an effective design is accompanied by an effective implementation are desired changes expected to occur in teaching and learning, and therefore the expected outcomes can be observed. In other cases, however, changes might be limited to improvements in the teaching without affecting learning or no improvements may be seen in teaching or learning. Although the actual relationships might be more complex than this table might suggest, the focus is on recognising the effect of the implementation phase and the importance of finding ways to ensure effective implementation, that is, implementing the design as intended.

Table 2.2: Linking design to implementation (Rowan et al., 2009)

Effective Implementation	**Effective Design**	
	Yes	**No**
Yes	Changes in teaching and learning	Changes in teaching without effects on learning
No	No changes in teaching or learning	No changes in teaching or learning

It seems that one of the factors that might limit achieving the desired implementation is the shortage of guidance directed to the teachers. Leach (2007), for example, in his account of the failure of a teaching sequence of Modelling Change, indicates that providing teachers with more explicit guidance might help them to identify precisely the aim(s) of the teaching and how to achieve them. Guidance is particularly needed when the design adopts a novel approach that puts new demands on the teachers (Smith and Lott, 1983). In such cases, Asoko (2002) affirms that, with regard to teaching sequences that adopt unconventional perspectives, teachers are unlikely to implement them as intended, if they do not recognise the theoretical underpinnings.

Furthermore, a handicap to effective implementation is the modifications that teachers make when implementing a given design (Tiberghien, 1996, Pintó et al., 2005). The variation between what is intended and what is actually implemented is seen as a challenge that teaching designers need to consider when engaged in developing a teaching sequence (Collins et al., 2004). In order to limit the effect of these modifications, Leach (2005) asserts the importance of '…enabling teachers to recognise which features of a design are central to its rationale, and therefore should be modified with extreme caution, and which features are less critical'(p.3). Limiting the modifications that teachers might make to the design should be started before the implementation phase. A strategy used in the Leeds Model is annotating the Worked Example with symbols referring to the nature of activities that the teacher should maintain (Leach et al., 2006).

Another issue related to implementation in general is consideration of the execution of the design by teachers who have different backgrounds or expertise (Nurkka, 2005) rather than limiting the implementation to only one teacher. On one hand, different backgrounds might result in different reflections, whether in revising the design *per se*, or the ways in which it is implemented. On the other hand, the implementation of the design by teachers with different expertise may increase the transferability of the developed design and recommended domain-specific guidelines.

The next sub-section considers the evaluation of the designed sequence using evaluation models and methods to gather evidence about implementation and achievement of the desired outcomes.

2.4.3 Evaluating teaching sequences

The evaluation phase is of crucial importance in design studies because the evaluation results suggest possible improvements and offer evidence for the domain-specific guidelines (Confrey, 2006). Literature suggests, however, that evaluation of interventions is not easy and, unfortunately, at times it has been executed incorrectly. As Schwartz et al. (2008) claim, design researchers have devoted efforts to developing the design of the teaching sequence, which represents only half of the equation, and still have not yet paid sufficient attention to the other half concerning evaluation. In line with this criticism, Altschuld and Kumar (1995) conduct a review of the evaluation of programmes in science education over a twenty-five-year period from 1966-1991 and conclude that the field lacks comprehensive approaches to evaluation. In particular, they found the use of evaluation models for appraising science education programmes to be limited.

This sub-section presents an existing model which can be used to evaluate teaching sequences, highlight its strengths and limitations, and then suggest a way to improve it to meet characteristics of design studies. It then present methods found in the literature by which researchers gather evidence about implementation and learning outcomes.

2.4.3.1 Models of evaluation

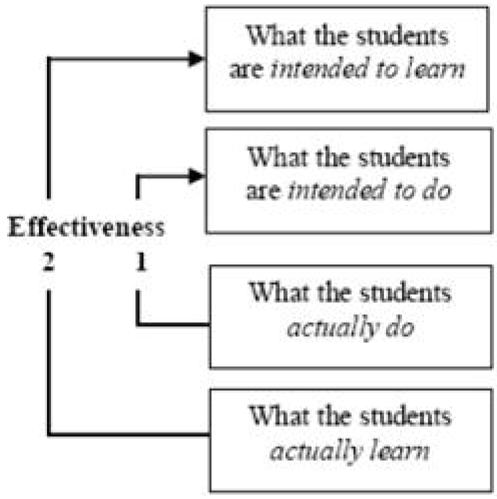
I concur with Altschuld and Kumar (1995) regarding the advantage of conducting an evaluation using a model to guide thoughts and actions. To clarify what I mean by "model", I find it useful to adopt the definition advanced by Madaus and Kellaghan (2002) because it fits with the purpose of evaluation in design studies. They define the model of evaluation as a construct of:

> *…the main concepts and structure of evaluation work serving the function of providing guidelines for using these concepts to arrive at defensible descriptions, judgments, and recommendations*(p.20-21).

Bearing in mind that design studies seek to develop and test domain-specific guidelines while improving practice and producing effective materials (Brown, 1992; Collins, 1994; Cobb et al., 2003), the researcher should attempt to gather information with regard to effectiveness, as well as to describe the process that led to this effectiveness (Buty et al., 2004; Méheut and Psillos, 2004). However, firstly it is necessary to describe what is meant by effectiveness and whether the chosen model meets that definition.

To clarify and measure effectiveness, Millar et al. (2002) propose a model that distinguishes between two types of effectiveness in the context of labwork (see Figure 2.5).

Figure 2.5: Modes of Effectiveness (Millar et al., 2002)



The model accounts for evaluation of the learning, as well as the process that led to it, by detecting two modes of effectiveness. The first mode, which they call effectiveness 1, measures the match between the actual actions of *students* during the labwork and the desired actions as specified by the activity's designer. Depending on the match between the two, decisions can be made to improve the activity to increase its effect on helping students to learn. The second mode of effectiveness, effectiveness 2, measures the match between what the students actually learnt and what the designer of the activity wanted them to learn. Depending on the match between that which is intended and that which is attained, decisions can also be made to improve the activity. In a recent study, Millar (2009) suggests that this model could be used to measure any teaching/learning activity. In my view, this model may also be useful for measuring the effectiveness of teaching sequences.

In the first instance, the model extends the traditional way of evaluating the instructional interventions as input-output to account for the process that led to the desired output. This is particularly useful in design studies wherein the designer needs to know about the validity of decisions made regarding staging the teaching flow based on assumptions about students' responses while learning a certain scientific idea. In order to validate the effectiveness of the designer's hypotheses, teachers and students' actions must be traced so the designer can identify the parts of the design that went well or the parts that need to be improved.

Although measurement of the learning outcomes is central in accounting for effectiveness, it might be limited to explaining, for example, why the outcomes were not accomplished as intended, or if unexpected outcomes were noticed. It is necessary to know whether students were as engaged in the teaching as expected. Therefore, the model suggests following students' actions to see if they behave as planned in order to achieve the desired outcomes. To illustrate, if students were, for instance, disengaged with an 'x' learning task that was intended to develop a 'y' idea, this can, to some extent, explain why students did not learn this idea.

However, despite the model's usefulness in evaluating teaching sequences, it has, in my view, one shortcoming. While it takes account of the student's actions, it fails to consider the effect of the teacher. Even in practical work, the teacher's actions precede (in the form of giving instructions and pre-discussion), accompany (in the forms of mentoring and scaffolding) or follow (in the forms of post-discussion to make sense of the laboratory task) students' work and therefore cannot be disconnected from students' actions with regard to learning a given practical task. Indeed, as argued in the previous section, the role of the teacher is critical in leading effective, or ineffective, implementation. Leach and Scott (2002) also criticise such approaches in design studies that do not sufficiently consider the role of the teacher. Therefore, the model should be extended to consider measuring the match between the teachers' actions that were intended in the design and what is actually enacted by the teacher. I shall present in the methodology chapter an extended model of evaluation based on that of Millar et al. and illustrate how I use it in evaluating the designed sequence.

Measuring effectiveness in the two modes specified above requires data to be gathered in different approaches, sources and forms. Most have already been widely used in evaluation research and design studies.

2.4.3.2 Methods of evaluation

Design studies focus on documenting a given intervention with regard to intended actions as well as attained outcomes. In order to capture these two sides of effectiveness, Altschuld and Kumar (2002) call for:

> *…the use of multiple sources of data and multiple methods to provide documentation regarding how innovative programs are being implemented and in determining their outcomes* (p.2).

Collins et al. (2004) also suggest using an evaluation profile that combines quantitative as well as qualitative analysis in order to optimise understanding of the effectiveness of the design.

In consideration of the evaluation model presented above, the attained outcomes can be measured by assessing students' achievement of the pre-determined outcomes through written tests or interviews, while evaluating the match between the design intentions and students/teachers' actions requires gathering qualitative descriptions of the implementation through observation, video analysis and seeking participants' views through interviews.

- ***Written probes***

Regarding the issue of effectiveness, the researcher might ask questions like "Did students who followed the sequence attain what was intended?" In investigating effectiveness in terms of the outcomes, the researcher's task is to proffer evidence showing that this specific sequence has enhanced students' learning with respect either to the aims of the sequences "internal evaluation" or with respect to another approach "external evaluation" (Méheut and Psillos, 2004). The purpose of the external evaluation is to show that a given approach is more effective than another approach, while the purpose of the internal evaluation is to show the extent to which a given approach has achieved its aims. Proving the effectiveness demands the use of an experimental design which is a "quasi-experiment" for the external evaluation and "one group design" for the internal evaluation (Cohen et al., 2007). Both designs use pre-post test techniques that assess students' learning. Researchers usually use tests in three successive stages to establish the baseline of students' learning, to evaluate students' learning after completing the intervention and to evaluate the intervention's lasting effect (Bechhofer & Paterson, 2000). In designing and analysing these tests, researchers use different approaches, as described below.

- **Approaches used to frame and analyse written probes**

Two main approaches, using a wide range of techniques, have often been used to probe understanding (see Table 2.3 below) (Driver and Erickson, 1983). The first is a phenomenologically-framed approach in which the probes are designed to assess students' understanding in terms of phenomena, changes or events, allowing students to use their own language and concepts that they think relevant. The second is a conceptually-framed approach in which understanding is elicited within an explicit scientific context using scientific terminology, and students are expected to use knowledge and meanings developed in science lessons.

Table 2.3: Framing and analysing probes (based on Driver and Erickson, 1983)

	Framing the probes	
Analysing students' responses	***Conceptual*** Probes framed to assess understanding about taught scientific content	***Phenomenological*** Probes framed to explore which knowledge students use to explain a phenomenon or event
Nomothetic Responses analysed against accepted scientific ideas	School exams	Measuring the effectiveness of teaching
Ideographic Responses analysed to explore how students conceptualise a phenomenon in their own terms	Measuring the effectiveness of teaching	Researching students' ideas of a scientific phenomenon

With regard to analysing students' responses, the analysis can be conducted nomothetically and/or ideographically, irrespective of how the probes are framed (see Table 2.3). While in the nomothetic approach students' responses are analysed to establish consistency with the scientific view, in the ideographic approach the purpose is to identify patterns in students' understanding and thinking about the natural world without necessarily matching the scientific view. Table 2.3 shows examples of combining approaches of framing and analysis to serve specific purposes. However, it should be emphasised that neither framing the probes nor analysing students' responses can purely adhere to one single approach. Rather, although the main orientation of the probe leans toward one approach, it shares features with other approaches as well (hence, detached lines are used in Table 2.3).

- **Limitations of the written probes**

All assessment techniques contain advantages and disadvantages. This section highlights some of the issues related to designing and using written probes. Firstly, the approach used in framing the probe might limit the opportunity to reveal what the students know or understand about a given concept. If, for example, the students do not explain a phenomenon or an event after they have been exposed to an intervention in which specific content was presented, the researcher should exercise care in concluding that students did not develop knowledge related to this phenomenon. Rather, students may not be able to apply or relate the knowledge developed in this particular context. In order to overcome this limitation, the researcher might use a combination of probes that are conceptually and phenomenologically framed to assess students' understanding in different contexts.

Another issue is related to students' interpretations of what is intended in the probe, which might differ sometimes from what is intended by the assessor. In this respect, Clerk and Rutherford (2000) point out that language is a crucial factor in probing students' understanding. If students, for example, could not answer the question due to linguistic confusion, it is different from a situation whereby they could not answer due to limited understanding. Overcoming this limitation requires piloting the probes and checking readability before actual use.

Also, the familiarity of the test in the post-test phase might threaten the validity of the assessment (Cohen et al., 2007). With regard to pre-post test techniques, the researcher follows changes in students' learning, and often uses the items, or similar ones, in both the pre- and post-tests. It is expected that students, when trying to respond to an item, may remember their previous responses and decide to follow them. Alternatively, students might ask each other, as usually happens, how they answered in the pre-test and they might respond in the post-test as their classmates did in the pre-test. Such cases might limit the inferences made from the written probes.

The final limitation of the written probes is their insufficiency on their own to reveal the effectiveness of the design. It is acknowledged that an important aim for developing a teaching sequence is to find out “what works” in the purpose of informing practice (Millar et al., 2006). However, the provision of “what works” is more than evaluating effectiveness in terms of learning gains; it also requires understanding of what happens inside the classroom as well as how teachers and students perceive the designed teaching. Such data can be obtained from detailed qualitative descriptions of the implementation and participants’ responses in interviews. In addition, the qualitative data might complement, interpret, support or even challenge the quantitative data. The next sub-sections present issues related to gathering qualitative descriptions to evaluate teaching sequences.

- ***Qualitative descriptions***

Qualitative descriptions can provide data that cannot be gathered by using written probes. Such descriptions can offer answers to questions like "What is happening when students experience the sequence?", "Is the sequence implemented by teachers as intended by the designer?", "Are the improvements in students’ understanding caused by the sequence?" and "Which components of the sequence are most important and can explain the improvements?" In the evaluation of teaching sequences, the researcher might be interested in investigating what happens in the classroom in terms of teachers' enactments of, and students' engagement with, the teaching sequence. On the other hand, it is important to consider the context in which the design operates. Alongside the possibility of explaining the effectiveness of the design, it also assists in determining the needs of participants and/or constraints imposed by the system (Altschuld and Kumar, 1995).

With regard to teachers’ enactment of the sequence, researchers indicate, as mentioned above, that teachers' enactments are often not very consistent with the design specifications (Tiberghien, 1996, Pintó et al., 2005). Then, it can be asked, "If teachers make modifications during the implementation, to what extent a claim can be made towards the effectiveness of the designed teaching sequence without making reference to these modifications?" Therefore, in order to make judgments about teaching effectiveness, the actual implementation should be documented and matched against the design intentions. Another reason for the importance of tracing teachers’ enactments is to validate the assumptions advanced by the designer in terms of the teachability of the general pedagogy (e.g. using a dialogic teaching) or the workability of domain-specific practices (e.g. conducting a demonstration to address that carbon dioxide has mass). On the other hand, if it is acknowledged that the teacher has an influential role on the ways that students construct scientific knowledge (Driver et al., 1994b), then we should investigate what the teacher did to enhance or limit students' efforts. For all these reasons, investigation of teachers' enactments is central to a better understanding of the effectiveness of the design and workability of domain-specific guidelines. Evidence of teachers' enactments can be traced by analyzing teaching videos of the actual teaching (Gais, 2005).

With regard to students' engagement, tracing students' actions can help us to validate our assumptions about the trajectories that students are expected to follow when stimulated by teaching. In addition, students' engagement can partly explain or challenge the findings related to the learning outcomes, in the view that the learning outcomes are closely related to engagement (Capie and Tobin, 1981). However, it is first necessary to define what is meant by "engagement".

Fredricks et al. (2004), in their extensive review of school engagement, distinguish between three interrelated types of engagements, that is: behavioural, cognitive and emotional engagement. While behavioural engagement means basic participation which is indicated by concentration, making effort, and on-task time, cognitive engagement goes beyond the task to the ideas intended in engaging with the task. Such engagement can be seen when students ask for clarification, express beliefs and views, participate in a series of questions, try to understand other peers' views to build on new ideas (Scott et al., 2006a) and maybe challenge others', or even scientific, views. Yet, emotional engagement can be revealed by students' motivation, interest and enjoyment.

Evidence of engagement can be obtained from different data. Analysing students' actions (Gais, 2005) and written classroom work can offer indicators of their behavioural engagement. Cognitive engagement, on the other hand, can be traced via classroom verbal interactions (Scott et al., 2006a) and written classroom work as well (Matsumura et al., 2002; Borok et al., 2005). Yet, evidence of emotional engagement might be difficult to obtain from classrooms, at least in this study. Seeking direct responses from students and teachers in interviews might reveal how students were emotionally engaged.

2.4.4 Summary of literature related to developing science teaching sequences

In the third main section of this chapter, I reviewed the literature related to designing science teaching, implementing the designed teaching and measuring its effectiveness. With regard to designing science teaching, following substantial research on students' ideas and the convincing evidence of the effect that these ideas have on future learning, calls are advanced to plan teaching in a way that takes students' ideas into account (Ausubel, 1968; Driver and Erickson, 1983). However, these empirical findings do not say much about how to plan teaching (Lijnse, 1995). To meet this particular need, researchers in science education propose particular design models and tools with the aim of developing short teaching sequences about specific science topics in order to make the rationale of the design explicit to others. Then, researchers take these sequences to classrooms employing design studies approaches, taking advantage of the distinctive features that meet the need of developing teaching sequences (Millar et al., 2006).

In my view, the Leeds Model fits well with the intended yield of design studies, as it can assist in articulating and justifying design decisions about a given content and guide development of the teaching sequence (i.e. Worked Example), as well as evaluate implementation. By means of using the Leeds Model, findings from the evaluation can highlight possible revisions to improve the original design and come up with a set of domain-specific guidelines for teaching plant nutrition.

The following section is intended to set out the aims of research and emerging questions.

2.5 Research aims and questions

My purpose for reviewing the literature on students' ideas of plant nutrition, models for designing science teaching and design studies is to guide me in developing a teaching sequence about plant nutrition to be used in Saudi schools. As previously mentioned, plant nutrition is an important topic in biology and constitutes the basis for understanding other related concepts. Furthermore, the characteristics of design studies fulfil the purposes of developing domain-specific teaching sequences. On the other hand, considering the needs of the Saudi context, such a design study can improve learning of science concepts as there is convincing evidence that designing teaching sequences informed by research findings on students' ideas can improve students' learning (Leach et al., 2006). Moreover, exploring how both Saudi teachers and students receive new innovations might help in developing an understanding of how to better approach Saudi schools with change, particularly as the Ministry of Education is currently reforming science and mathematics education (Ministry of Education, 2007).

To this end, the key aim of this research is: *to develop a teaching sequence about plant nutrition for the Saudi context*. Three secondary aims and three questions emerge from this aim:

- **Research aim 1**: To use the Leeds Model to design a teaching sequence about plant nutrition for male Saudi school students aged 15-16

While no research questions emerge from this aim, developing the teaching sequence constitutes an essential step to be able to follow the other research aims

- **Research aim 2:** To determine the effectiveness of the teaching sequence in terms of meeting its design intentions and achieving the expected learning outcomes.

  Issues related to data collection and analysis will be addressed through the following questions:

  1. *To what extent was the planned design implemented as intended?*
  2. *To what extent did the students develop the desired learning outcomes?*

- **Research aim 3:** To determine how the teaching sequence and associated teaching practices were perceived by Saudi teachers and students.

  Issues related to data collection and analysis will be addressed through the following question:

  3. *How did the teachers and students respond to the key conceptual and pedagogical aspects of the teaching sequence?*

The next chapter (Chapter 3) addresses the first aim of the research, which is using the Leeds Model to develop a teaching sequence about plant nutrition.

CHAPTER 3: DEVELOPING THE TEACHING SEQUENCE

This chapter presents the development of a teaching sequence, which fulfils the first aim of my study. The sequence is presented through two products, that is, Design Brief and Worked Example. The three parts of the Design Brief are described (context, refining the content, content aims for the teaching) while links are made to the Design Brief in Appendix A. The Worked Example is then outlined including details of the teaching/learning activities and five lessons. The last section of this chapter brings together the Design Brief and Worked Example, structured around seven Key Design Features (KDFs).

3 CHAPTER 3: Designing the teaching sequence

3.1 Introduction

The first aim of this study is to use the Leeds Model to develop a teaching sequence about plant nutrition for male Saudi school students aged 15-16 (see section 2.5). To fulfil the design component of this aim, a Design Brief has been developed and then addressed through the Worked Example, which draws on the sequence produced in the EPSE project (Hind et al., n.d.) with several adaptations to meet the Saudi context. The purpose of this chapter is to present the specifications (i.e. rationale, intentions and justification of content) of the Design Brief and Worked Example, using the Leeds Model. The actual procedure for designing these two products is described in the methodology chapter (see section 4.3.3).

The following sections first provide an overview of the Design Brief, including specifications of its content based on parts of the Leeds Model. An overview of the Worked Example is then presented to capture its main characteristics, teaching/learning activities and outlines of the five lessons. The final section brings the Design Brief and Worked Example together through seven Key Design Features (KDFs) that summarise essential design decisions made in both products. Later, these KDFs will be used to report the evaluation of the teaching (see section 4.3.5).

A full version of the Design Brief is presented in Appendix A, and some translated samples of the Worked Example are provided in Appendix C.

3.2 General overview of the Design Brief

As mentioned in Chapter 2 (see section 2.4.1.3), the Design Brief explicitly specifies the design intentions and how these intentions are addressed through a set of justified design decisions. Three aspects of the design specifications are addressed by the Design Brief through three separate parts (including internal sections), that is, the context of the design, the content presented in official documents, aims of teaching and pedagogic strategies used to address the teaching aims. I added a fourth part devoted to refining the content presented in the textbook. The following sub-sections describe the four parts of the Design Brief.

3.2.1 Part 1: The context of the designed teaching

The first part is devoted to providing descriptions of the contextual characteristics (curriculum, students and teachers) and institutional constraints that were met in the design phase. The purpose of this part is twofold. On one hand, it enables me as a designer to identify the key ideas to be targeted in the design and to pre-consider any constraints or expectations that should be met in the teaching. On the other hand, it enables others to capture the whole picture, as linking the implementation and evaluation results to the context would enable them to judge the transferability of the design, or parts thereof, to their own contexts.

The first section of this part is mainly informed by a conceptual analysis of the Grade 10 textbook, while the remaining sections are informed by my personal knowledge based on my own experience of 15 years working for the Ministry of Education as a high school biology teacher, headteacher, biology supervisor and textbook author.

The next section presents specifications related to curriculum, students, teachers and institutional constraints.

3.2.1.1 Curriculum

In Grade 10, students start learning science in the form of separate subjects, namely physics, chemistry and biology, over two classes per week (45 minutes each). The textbook is the main source for content, teaching and assessment. The biology textbook used by year 10 consists of ten units divided between two semesters. Each unit focuses on a broad topic which can be taught over 4-6 lessons. At the end of the unit, a set of questions are presented and are usually used as homework assignments. Teachers also might use some of these questions in exams. The textbook presents the content as definitions and facts, only taking account of the disciplinary view, while the conceptual or pedagogical aspects are missing. Like other textbooks, some pictures are usually provided to enhance learning of the facts or maybe to make the presentation of the facts more attractive.

The topic of photosynthesis has not previously been taught as a separate topic. Only the terms ‘photosynthesis’, ‘chlorophyll’ and ‘plant nutrition’ were briefly mentioned (in Grade 7 and in the 1st semester of Grade 10), and photosynthesis will be revisited in Grade 11 with more technical details mainly related to light/dark reactions. In both grades, photosynthesis is introduced within the topic of plant nutrition. At the time of introducing the topic in Grade 10, students had already been introduced to plant morphology, the structure of a plant cell, different food groups (carbohydrates, proteins and fats), biochemical processes in plants and chemical reactions. These topics constitute prerequisites to comprehend photosynthesis.

The Grade 10 textbook presents plant nutrition through the following (summarised and translated by the researcher, and reviewed by two supervisors and two teachers of biology):

- Plants make their own food without being dependent upon any organic resources. Food-making means synthesizing organic components from inorganic components.
- In the presence of light energy and other requirements, water is brought up from the soil and carbon dioxide is absorbed from the air and is used by plants to make food inside chloroplast, which is located in leaf cells.
- Plants need other elements in the form of minerals.
- The chemical equation for photosynthesis is: $6\ H_2O + 6\ CO_2 \longrightarrow 6\ O_2 + C_6H_{12}O_6$
- Photosynthesis is completed through two phases, light and dark reactions (this aspect constitutes about 50% of the content).
- Food is exported out of the leaves to other parts of plant (e.g. roots, stems and flowers).

3.2.1.2 Students

Schools in Saudi are single-sex. Students (the words "students" means “boys” when used in this thesis in terms of the Saudi context) are aged 15-16 in year 10, which is the first year of secondary education (middle school and secondary education are separated into two stages and two different schools). Students are usually equally assigned to classes with regard to age, nationality and ability; they rarely work in groups or do practical work. Their role in the class is limited to listening and writing down the teacher’s notes. Therefore, it is not common for students to promote their ideas or comment on those of others or teachers. They might talk at the end of the lesson if they want to ask for clarification on what has been said or to ask further questions related to the presented topic. To this end, it is expected that students will find it difficult to shift to the new teaching style and associated activities adopted in this sequence. They might need guidance and monitoring from the teachers when taking part in the activities.

3.2.1.3 Teachers

All high school biology teachers specialise in biology and at least hold BAs in Botany, Zoology or Microbiology. Some might pursue an additional year of educational training before working in schools which covers courses on educational psychology, educational assessment and biology instruction. In addition, student teachers conduct a pilot while teaching in schools during the second semester under the supervision of their university tutors.

Biology is usually taught in a classroom which has no more equipment or facilities than a normal white board. Although teachers are trained to do practical work, they rarely practice it because school labs are mostly reserved for physics and chemistry teachers.

At the beginning of the biology lessons, the teacher usually stands in front of the class initiating questions to recall what was taught in the previous lesson. They then introduce the new topic either directly or by raising a general question as an entry point. Then a transmission style of teaching is used to present facts and definitions and verbal demonstrations. In addition, the teacher might draw on the board or use a poster of pictures presented in the textbook. Very often students copy down the teacher's writing from the board. Some teachers might dictate the key ideas or simply refer to them in the textbook and ask students to highlight or underline them. Notes taken in the lessons and/or textbooks are the main source that students rely on for exam preparation. If the teacher finishes before the end of the class, he might ask questions in order to recall or repeat information from the lesson.

Most of the teachers are neither familiar with contemporary pedagogies nor with some aspects of the content presented in this sequence (I made this assumption when I first met the teachers to introduce my study). Therefore, it is expected that teachers might find the teaching sequence demanding and considerably different from their usual practice.

3.2.1.4 Institutional constraints

Classrooms are very basic with individual tables and chairs arranged in rows facing the board. Class sizes vary from 25 to 40 students. As discussed, biology classes are mostly taken in classrooms rather than science labs, which are very often prioritised for physics and chemistry classes. Internet access is very limited in schools and rarely integrated with teaching.

Teachers are officially required to follow the content presented in the textbook. The topic of plant nutrition, including photosynthesis, is expected to be introduced to pupils over the course of two lessons in the third week of the 2nd semester. Students are assessed twice with regard to the content presented in the textbook. The intention for both assessments is to determine their pass rate.

3.2.2 Part 2: Refining the content presented in the textbook

The second part of the Design Brief concerns refining the key ideas resulting from the conceptual analysis. Although this part is not found in the Leeds Model (see section 2.4.1.3), it was important to refine the key ideas found in the Saudi textbook as they fall short, in my view, of the basic accurate introduction of plant nutrition at this age. The following characteristics capture the content presented in the textbook:

- An emphasis on a disciplinary knowledge perspective that advances introducing recall of facts and definitions at the expense of developing explanations. None of the conceptual difficulties involved in learning plant nutrition were addressed;
- While the importance of glucose was briefly mentioned as food for plants, assimilation of biomass was ignored. Furthermore, despite mentioning glucose as food for plants, this was not emphasised as the theme of the unit focused on the photosynthetic process more than its consequences for plants;
- Misleading sentences that might present the roles of soil and minerals as equal to carbon dioxide and water. For example, the textbook includes the following:
    - *"Notice: photosynthesis is really an amazing process because with a little soil, water, and light a small seed can result in a big plant which can grow up to be as long as tens of meters".*
    - *"Plants take in carbon dioxide from the air and absorb water and minerals from the soil to synthesis organic substances which constitute its food.*
- Details concerning the structure of plastid and light/dark reactions are presented which are, on one hand, not fundamental to an understanding of photosynthesis at this age, and might, on the other hand, disturb grasping the essence of the topic. It was reasonable to omit the light/dark reaction, particularly as they will be thoroughly revisited in Grade 11.

With this in mind, I decided to refine the textbook content with a view to only focusing on the key ideas necessary to understanding photosynthesis and sought to exclude interfering content that might distract students from learning the key ideas. This refinement was enhanced by the reviewed literature concerning students' ideas about plant nutrition (see section 2.2.6) and previously developed sequences about plant nutrition (Oldham et al., 1985; Roth and Anderson, 1987; Hind et al., n.d.). To this end, the following ideas were identified and targeted in the design:

- ***Photosynthesis***: carbon dioxide combines with water using light energy, which is trapped by chloroplast, to produce glucose, as a main product, and oxygen, as a by-product. Photosynthesis takes place in chloroplasts that are located in leaves. It is described at a molecular level by the equation: $6\ H_2O + 6\ CO_2 \rightarrow 6\ O_2 + C_6H_{12}O_6$
- ***Plants exploit glucose in two ways*:**
    - **As a source for energy:** glucose is used as a substrate in respiration from which energy is liberated to carry out biochemical functions.

- **To assimilate plant biomass:** some of the glucose is converted into other complex chemicals such as cellulose, proteins and fats, which make up the plant biomass, with some minerals absorbed from the soil.

In order to ensure that these ideas cover the fundamentals of the topic of plant nutrition and related sub-concepts, I broke them down into small components using Gagne's notion of task analysis (1974) that aims to clarify what a given lesson is "all about" and to determine precisely the content to be targeted in the design. As Appendix B shows, every key idea is itemised to represent the sub-concepts. This breakdown helped me to distinguish between the components of content that are new and those ideas that had been introduced in previous lessons. In the case of the latter, I needed to be sure that this knowledge had already been presented in the textbooks; otherwise, I would have had to include sub-concepts which had not been addressed. In checking the availability of the sub-concepts, I reviewed the three Saudi middle school science textbooks that precede Grade 10. The breakdown showed that all the pre-requisites have been introduced directly or implicitly, with the exception of the concept that "…chemical reactions take place in plants", which is already covered in my design.

3.2.3 Part 3: Specification of the content aims for teaching

The third part of the Design Brief aims to specify and justify the content to be targeted in the design and then presented in the lesson. This specification was informed by an identification of the learning demands that students face when they try to use photosynthesis to explain plant food and extra biomass. Identifying the learning demands requires a comparative analysis between students' every ideas (derived from empirical studies on students' ideas) and views of the school science that will be targeted in the teaching (based on the content presented in the curriculum or textbooks). The resulting learning demands might arise from the conceptual, epistemological and/or ontological aspects of the scientific ideas. Once the learning demands are identified, they will be addressed by a set of teaching goals.

This part of the Design Brief (see Appendix A, part 3) consists of five sections that start from (1) the key ideas to be targeted in the teaching as identified in the previous section (3.2.2), (2) students' likely starting point on the subject of plant nutrition as summarised from the literature (section 2.2.6), (3) the resulting learning demands as a result of comparing 1 and 2, which leads onto (4) mapping out the teaching goals. In addition, a specific section is devoted to present the desired learning outcomes from the point of view of the four sections.

The key ideas are identified in the first section based on a conceptual analysis of the Grade 10 biology textbook and the process of refining the conceptual analysis results, as described in section 3.2.2. Two key ideas are essentials concerning plant nutrition, that is, the nature of plant food and what it is for, and where biomass comes from. To develop these two ideas through photosynthesis, students must understand the basics of the photosynthetic process including requirements for, and products of, photosynthesis. The literature review shows that photosynthesis is a complicated topic, so concentrating on the basics may help students to grasp the topic of plant nutrition (Eisen and Stavy, 1988). In addition, an understanding of the nature of food and what it is for constitutes a first step towards making sense of plant nutrition (see section 2.2.3). Thus, two fundamental key ideas are identified to be taught.

The second section of this part is a summary of students' likely starting points concerning knowledge of plant nutrition. This summary is based on the literature review presented in Chapter 2 (section 2.2). Students' ideas might be similar to the following:

- **Source of plant food**: students believe that plants receive their food from the environment. Examples of this food are: soil, fertilisers, water, minerals and light. Although they might refer to making food internally, they continue to think that inorganic substances are also food. Furthermore, students retain a model of plant food similar to that of the animal feeding model in which food is obtained from the outside and roots function as a mouth. In addition, they consider the function of food is to keep plants alive and healthy rather than a substrate from which energy is liberated in respiration.
- **Plant biomass**: even though students might explain the source of plant food by photosynthesis, it is rather difficult for them to accept that plant biomass could be explained using the photosynthesis model. They often refer to soil and water as sources of biomass.
- **The nature of photosynthesis and what it is for**: students usually struggle to appreciate that gas combined with liquid (carbon dioxide and water) can form a solid (glucose, cellulose and woods). In addition, students might confuse photosynthesis with respiration in terms of mechanism, function and time of occurrence. They might believe the analogy that plants work as filters to clean up the environment, so they focus on oxygen more than glucose as the main product of photosynthesis.

The third section of this part of the Design Brief also concerns specifying the learning demands (see section 2.4.1.3). Considering on one hand the key ideas to be taught, and, on the other hand, the existing ideas that students have; the teaching should address the following learning demands:

- Students regard food as anything that is taken in and its function is to keep plants alive and healthy. However, school science conceptualises the function of food in terms of assimilation of plant materials (including small proportions of minerals) and provision of energy. Therefore, there is a learning demand to *differentiate* food based on these two functions and also to discard soil, water, minerals and fertilisers.
- Students' views regarding gas in general and the cycling of matter may prevent them from *recognising* that carbon dioxide and water can be (1) a source of solid biomass and (2) can form other substances (i.e. glucose). They should *understand* that matter is preserved and can be converted into other forms, irrespective of the particulate nature of reactants and products. In the case of photosynthesis, glucose can be formed by rearranging the atoms which comprise carbon dioxide and water. Furthermore, students have to *recognise* that chemical reactions take place in plants.
- There is still a demand related to using photosynthesis as an explanation for plant food and biomass. Knowing how photosynthesis takes place does not necessarily mean that students will use it in their explanations of plant food. In order to help them link photosynthesis to plant nutrition, students need to *know* the chemicals that comprise plant cells, and then to *recognise* how much glucose is used in assimilating plant cells and, therefore, plant mass. In addition, there is a demand to *recognise* that glucose is the only substrate in respiration from which energy is liberated.

Drawing upon the nature of the learning demand, Leach and Scott (2002) point out that the teaching goals can then be mapped out. However, it should be mentioned, as Leach et al. (2009) assert, that mapping out the teaching goals from learning demands is not a linear process that means, for example, a component of a given key idea linked to an aspect of students' conception will represent a learning demand, and then be addressed by a teaching goal. Rather, it involves a broad consideration of the content to be taught, evidence of students' ideas and how to teach this piece of the content in a way that means students can overcome the learning demand. Therefore, to determine what is involved in learning about plant nutrition, I again used the task analysis to unpick the conceptual components that should be addressed when students come to learn each one of the key ideas. Then, I linked these components to how students think about plant nutrition, as reported in the empirical findings summarised in section 2.2.6. To this end, seven teaching goals were specified to address the learning demands so as to help students retain the key ideas. The seven teaching goals are specified and justified as follows:

1) Considering that students need to conceptualise food in terms of supplying energy, the teaching starts by establishing the view that only organic substances can be regarded as food from which energy is liberated in respiration[1]. Addressing this pre-requisite concept is essential so that students can realize why soil, water, minerals and sunlight cannot be food for plants.
2) This second goal deals with the introduction of a *simple* model of photosynthesis in which carbon dioxide combines with water to form sugar. This will be preceded by eliciting and challenging students' ideas regarding the nature of plant food, and then introducing the photosynthesis model as a possible alternative to explain plant food.
3) In this goal, the idea is to make students aware of their thinking in order to create a need to learn. This can be achieved by problematising photosynthesis, in other words, drawing their attention to the causes that make photosynthesis *implausible*. As it is not expected that students will notice these causes by themselves, the intent is to highlight them and guide students to question the scientific explanation on the grounds:
    - How can a weightless gas contribute to forming other substances?
    - How can combining a gas (carbon dioxide) with a liquid (water) form a solid (sugar)?
    - How can combining simple molecules like carbon dioxide and water form a complex molecule like glucose?
4) The fourth goal deals with addressing the conceptual barriers that hinder students from appreciating photosynthesis. Due to the class size and lack of laboratory sources, these barriers will be addressed through teacher-led demonstrations:
    - carbon dioxide particles do have mass;
    - gas and liquid can be converted into a solid;
    - simple molecules (carbon dioxide and water) can combine to produce complex molecules (sugar) by re-arranging atoms of carbon dioxide and water.
5) After establishing the key aspects of photosynthesis, the teaching moves on to further develop the simple explanation by adding other aspects of the photosynthetic process:
    - plants use energy from sunlight to power the reaction between carbon dioxide and water;
    - oxygen is released as a by-product;
    - photosynthesis takes place mainly in leaves;
    - ways by which plants obtain their requirements for photosynthesis to take place;
    - why glucose is stored as starch.

[1] It is acknowledged that energy can be produced from inorganic substances in chemosynthetic bacteria. However, to avoid complexity, it was decided to generalise for students at this level that energy is liberated from organic substances.

6) At this point, a full version of photosynthesis is presented so it is appropriate to use this explanation to account for plant food and biomass. With regard to biomass, after externalizing students' ideas, the goal is to introduce the contribution that the glucose makes to the materials from which the cell is constructed. The other aspect of this goal is to establish the fact that all creatures[2] need energy to carry out biochemical processes, and glucose is the only source that plants can use to free energy in respiration.
7) The final teaching goal deals with supporting students in practicing the scientific explanation by falsifying everyday ideas of plant food.

In addition, this part of the Design Brief encompasses an additional section, which is not found in the original adopted design model (Leach et al., 2009), which presents the expected learning outcomes as a result of exposure to the teaching. The reason for adding this section is to provide a whole picture of the key ideas, teaching goals and, of course, the desired learning outcomes. The desired learning outcomes take into account ideas presented in the textbook, which are required for assessing students in school exams. To this end, the learning outcomes are as follows:

At the end of the teaching sequence, students should be able to:

- Identify that:
    - Plants make their own food via photosynthesis from inorganic components, carbon dioxide and water.
    - Plants use energy from sunlight to power the reaction between carbon dioxide and water.
    - The products of photosynthesis are glucose and oxygen.
- Explain the nature of plant food and how it is obtained:
    - Plants make (or produce) their own food (or glucose, starch, carbohydrate) from the raw materials available in the environment (carbon dioxide and water) through a process called photosynthesis.
- Explain how photosynthesis explains plant biomass:
    - The extra biomass comes from the food (or glucose, starch, carbohydrate) that plants make (or produce, form, obtain) through photosynthesis, with small proportions of minerals absorbed from the soil.

3.2.4 Part 4: Specification of pedagogic strategies and sequencing of content

The fourth part of the Design Brief concerns addressing the teaching goals through a series of justified decisions (see Appendix A, part 4). It consists of two sections; one which considers the overall teaching and the other which goes into relatively detailed decisions with regard to

[2] The term "creatures" was used to meet the religious expectations of Saudis, and this term is consistently used in the textbook as well.

pedagogic strategies and classes of interaction (see section 2.4.1.3). In addition, a choice of communicating the design to teachers is specified and justified.

As presented in the last chapter (see section 2.4.1.3), the overall structure of the teaching is informed at a large grain size of detail from a social constructivist perspective on learning, considering formal teaching (Leach and Scott, 2002, 2003). Central to this perspective is the differentiation between two social languages; that is, everyday social language and the social language of science. In science classrooms, a problem arises when the two languages meet and students tend to apply everyday language and views to account for natural phenomena. To this end, students need to recognise that scientific phenomena are explained in particular ways. As students cannot discover these explanations by themselves, it is the role of the teacher to introduce students to the language of school science and support them in appreciating its plausibility.

As mentioned in section 2.4.1.3, the teacher's support is structured to serve three functions, though not necessarily sequentially. The first is making the scientific view available on the social plane. It starts by exploring students' knowledge, making the concepts explicit for them, and then challenging their everyday ideas in order to make a need to learn the scientific view, which will be a details-reduced simple model of photosynthesis. Secondly, supporting students in making sense of the scientific view and addressing the problematic aspects of photosynthesis through a series of demonstrations and modelling, namely, carbon dioxide does have mass, it is possible to form a complex substance from simple substances and matter is converted by breaking down and re-arranging atoms of carbon dioxide and water. This will be followed by introducing the role of glucose produced in photosynthesis, whether to build up biomass or as a source for energy. It was decided to go with introducing information in some stages of the teaching where it is believed that students are not familiar with these ideas and will be difficult for them to surmise such facts. The third function is the teacher handing over the developed explanation to the students through asking them to revisit and validate their ideas that were generated in the first stage.

Another aspect that is tackled in this part is the details of the content to be covered and the sequence of presenting the ideas. This is informed by insights from literature on students' ideas (see section 2.2.6), previously-developed teaching schemes (Oldham et al., 1985; Roth and Anderson, 1987; Hind et al., n.d.) and general principles of sequencing that draw upon the disciplinary nature of the topic (Posner and Strike, 1976). The sequencing decisions include the following:

- Addressing the pre-requisites: the literature suggests (e.g. Simpson & Arnold, 1982a) that acknowledging photosynthesis as an explanation for plant food and biomass requires prior understanding of the nature of food and what it is for, that carbon dioxide has mass and that matter can be converted by re-arranging atoms of carbon dioxide and water. To this end, as mentioned in the learning demands, the sequence starts by establishing a definition of food before introducing a simple model of photosynthesis. In addition, the causes of implausibility are addressed before introducing the role of glucose.
- Gradual introduction of details: considering the complexity of photosynthesis, research suggests minimising the details to focus on the basic ideas (Eisen and Stavy, 1988). This is met in the first and second lessons when the scientific explanation is simply introduced and then fully completed later on. Corresponding to this, the light energy aspect is postponed to avoid treating light as a reagent that is equivalent to carbon dioxide and water. Introducing oxygen is also postponed after establishing that glucose is the main product of photosynthesis in order to prevent developing the common idea that photosynthesis is considered to be an oxygen-supply process. Finally, in the course of introducing the role of glucose, an explanation of glucose as a source of biomass precedes the suggestion that it is a source for energy, considering that the latter is more challenging (Driver et al., 1994a).
- Other logical sequencing decisions are advanced like eliciting ideas before introducing the scientific view, and building the explanation before practising it.

The second detailed section specifies at a large grain size decisions about staging the teaching. It also goes into fine-grain size to specify and justify the pedagogic strategies and classes of communication (see section 2.4.1.3) to address the teaching goals. As presented in the last chapter (see section 2.4.1.3), the term "pedagogic strategy" refers to ways of working on knowledge that are used to address content-specific learning aims at a fine grain size. It should not be confused with teaching techniques that will later be specified in the Worked Example to address the pedagogic strategies and guide the teaching at classroom level.

Once a design decision is specified and justified, a choice of communicative approach is also specified, taking into consideration the teaching goal and the pedagogic strategy (see section 2.4.1.3). To avoid repetition and to help the reader to understand how the design decisions are addressed in the Worked Example, I present specifications and justifications of pedagogic strategies in a separate section (see section 3.4).

The final section of this part of the Design Brief describes and justifies decisions concerning the form of communicating the design to teachers. These decisions are informed by availability of resources and how much better teachers would receive and implement the design. Considering the available resources for my scholarship, as well as the fact that Saudi teachers and students are more accustomed to textbooks, I decided to go with paper-based materials.

The next section presents a general overview of the Worked Example.

3.3 General overview of the Worked Example

The Worked Example aims to address the Design Brief by producing teaching/learning materials in order to plan and guide classroom events. It should be mentioned here, that although the development of the Design Brief preceded the development of the Worked Example, some detailed aspects of the Design Brief were modified as a result of thinking how to put the pedagogic strategies into action (e.g. making a decisions to discuss the function of food within the human context).

The Worked Example draws heavily on the sequence that was developed by Hind et al. (n.d.) in the EPSE project. However, several adaptations and improvements have been made to meet the Deign Brief and needs of the Saudi context. In terms of meeting the Design Brief, analysis of the learning demands showed the importance of establishing a scientific definition of food. This issue was not explicitly targeted in Hind et al.'s sequence. To address this issue, I included in the Worked Example a formative assessment regarding the concept and function of food, as well as linking food to energy using the "fuel analogy".

With regard to the Saudi context, as I know that neither Saudi teachers nor textbooks specifically address the concept that "gas has mass", I have added one more activity to stress this aspect. Furthermore, to make the teaching less demanding, I have made the Worked Example more structured for both teachers and students. This is apparent in the scenarios that I added at the beginning of each activity to guide teachers' actions, as well as providing structured worksheets to guide students' discussions. To meet students' expectations, I also developed notes of the key ideas of each lesson to assist them when preparing for school exams. In addition, I provided an activity at the end of the teaching to help students' consolidate the factual knowledge emphasised by the textbook. One further addition is using end-of-lesson quizzes that aim to practice the learnt concepts and check students' immediate understanding.

Yet, there are large parts common to both the English and Saudi sequences. For example, using formative assessment to probe students' knowledge of plant food, setting a conflict based on the sweetness found in fruits, making the causes of implausibility explicit, addressing causes of implausibility and using the photosynthesis model to explain plant food and biomass.

The Worked Example was produced as a pack, in Arabic, and contains an introduction which summarises the teaching approach and its broad aims, states how the pack can be used, offers a summary of students' conceptions about plant nutrition (translated from the literature review), alongside a summary of the communicative approach (based on Scott and Asoko, 2006), and then gives details of the five lessons and associated activities.

For each lesson, the main idea of the lesson is first introduced, followed by the teaching goal and a list of the teaching/learning activities to be performed, including specifications of time, the role of the teacher and necessary materials. Within each activity, the purpose of the activity is specified, simple theoretical underpinnings of the activity are illustrated and a procedural scenario is suggested with annotated symbols referring to the nature of the activity and required class of communication (see section 3.3.3). In addition, each lesson is supported by Power Point slides to guide the teacher in the sequence and enactment of the teaching.

To help the reader appreciates an outline of the Worked Example, the next section presents the nature and types of the teaching/learning activities incorporated in the sequence, and outlines of the five lessons. Further details concerning how the Worked Example specifically addresses precise aspects of the Design Brief are presented in section 3.4 and are linked to the key design features. In addition, some translated samples are appended (see Appendix C).

3.3.1 Teaching/learning activities

The theoretical perspectives adopted in the Design Brief and Worked Example require a different style of engagement on the part of the teacher and students that goes beyond mere presentation and reception of information. The desired engagements can be achieved through activities that are jointly (for both the teacher and students) and/or individually (either the teacher or students) performed. The purpose of this sub-section is to describe the activities used in the Worked Example.

3.3.1.1 Eliciting students' ideas

The purpose of eliciting students' ideas is twofold; firstly, to inform the teacher about students' starting points concerning a given aspect and secondly, to make students aware of their ideas before challenging them or discussing their consequences. In the elicitation, the teacher employs interactive/dialogic talk to follow individual responses, whether through whole class or group discussion. Then, the teacher compares and summarises the key ideas on the board.

Students' ideas are elicited in the first lesson twice with regard to "the nature of food and what food is for" and "the nature of food for animals and plants", and also in the fifth lesson concerning the source of biomass.

3.3.1.2 Discussion

Two styles of discussion (whole class and group) are used to open up a conceptual problem and encourage students to share their thoughts. In addition, the discussions help to check students' understanding of what have been taught or agreed upon, and to reflect on the teacher-led demonstrations. The whole discussion employs interactive/dialogic talk starting with a question raised by the teacher, and then students' responses are followed to make their thoughts explicit or to reach a particular point of view, whether related to students' ideas or school science.

On the other hand, group discussions aim to give students opportunities to think about their ideas, share them, and comment on others' ideas. In addition, the ideas generated from group discussion make the teacher aware of students' ideas so that he knows where to start and how to bridge to the next step. Moreover, considering the Saudi class size, group discussions give the majority of students extended opportunities to air their views.

All group discussions are enhanced by structured worksheets that keep students focused on the purpose of the task and allow them to record and then present their ideas to the rest of class. As group discussion is not very common in Saudi schools, a set of rules is drawn up to be introduced in the first lesson and then to be tacked on the walls around the classroom to remind students of these rules.

Group discussions are used in the first lesson twice to externalise students' ideas of the nature of food for animals and plants, and to determine the source of sweetness. They are also used in the second lesson to help students detect the causes of implausibility of photosynthesis. In the fourth lesson students are also involved in group discussions to determine where photosynthesis takes place and how the requirements for photosynthesis are obtained.

3.3.1.3 Presenting information

Presentation is enacted by the teacher to impart information concerning a given aspect of teaching and is used in situations when it is suited to the teaching purpose, particularly when the scientific ideas are novel to students in the sense that they cannot be predicted or surmised. It should be noted that presentations are usually preceded by questions to engage students. In the design, presentations are used when establishing that food is needed for energy, specifying the requirements needed for photosynthesis, discussing products of photosynthesis, converting glucose into starch, and addressing the structure of plant cells and the chemicals that comprise plant cells.

3.3.1.4 Teacher-led demonstrations

Demonstrations are used to address a certain issue in order to help students make sense of an idea or a concept. While mere presentation only tells what happens, demonstrations make the phenomenon visible and encourage students, through the teacher's guidance, to predict and wonder why this happens. In addition, demonstrations break the class routine and provide some fun to the class' atmosphere (O'Brien, 1991). The teacher's style of communication in demonstrations ranges from non-interactive/authoritative when he introduces the demonstration, to interactive/dialogic when he explores students' predictions prior to the demonstration or follows up their reflections on the demonstration.

Demonstrations are used in the third lesson to address the fact that that gas has mass, a solid can be produced and the role of light energy in powering the chemical reaction. A further demonstration is also used in the fourth lesson to reveal converting glucose into starch.

3.3.1.5 Group work

Students work in groups to achieve a task set by the teacher. It differs from group discussion as students are more physically engaged while at the same time trying to recognise the concept behinds the physical work. Groupwork is used only once to build up a two-dimensional model of glucose by re-arranging atoms of carbon dioxide and water molecules. The purpose of the activity is to help students recognise that glucose is made from the same atoms of carbon dioxide and water with a different arrangement.

3.3.1.6 End-of-lesson quizzes

The purpose of the quizzes is to offer students opportunities to think about and apply the ideas presented in the classroom. They also give the researcher an indication of whether students understand some of the aspects introduced in the lesson. Quizzes are designed to be answered individually on worksheets and students are asked to complete them before leaving the class.

The quizzes are used at the end of the first lesson to check students' understanding of the concept of food, in the fourth lesson to check whether students are aware of the reason that plants convert glucose into starch, and in the fifth lesson to check whether students are able to consolidate the factual knowledge related to photosynthesis.

3.3.2 Notes of the key ideas

The initial intention was to introduce the teaching through a manner that involves more discussions and interactive talk and less presenting and note taking. Therefore, students were asked in the first lesson to write down at the end of the class the ideas discussed during the lesson, whether they resulted from discussions or were introduced by the teacher. However, students did not like this approach and insisted on the need for systemic notes that will help them in exam preparation. This request was also supported by the teachers. Therefore, I prepared five sheets of notes that include the main ideas presented in each lesson. Both conceptual understanding and factual knowledge were considered. The reason for preparing these notes is to meet students' expectations and the assessment regime to which they are accustomed.

3.3.3 Symbols used to guide the teacher

Several symbols are used in the Worked Example to guide the teacher in administering the pre-planned class of communication or to determine the nature of the activity, whether it is to be a discussion, group-work or an individual quiz.

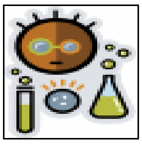
Some symbols indicate the teacher's activity:

Elicitation

Elicitation involves exploring, externalising and recording students' views about a certain concept or issue. You may use open-ended questions that do not necessarily require correct responses inasmuch as to make students think, bring out and talk about their ideas. You should use interactive/dialogic talk, summarise shared ideas and avoid giving evaluative feedback.

Presentation

Presentation is used when you want to introduce the scientific view after students' ideas have been made explicit. Here, you use non-interactive/ authoritative talk.



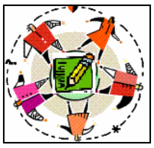
Demonstration

You can use demonstrations to illustrate a certain scientific concept. It's important to encourage students to develop conclusions instead of presenting them yourself. You may use interactive/dialogic and interactive/authoritative talks as indicated.

Support

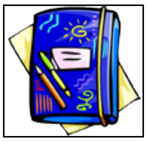
Support involves guiding students through focused questions or commenting on their responses through interactive/authoritative and non-interactive communicative approaches, and you may also employ interactive/dialogic interventions.

Another set of symbols are directed to the teacher in order to monitor students' activities as planned in the teaching sequence. These symbols include the following:



Group-work

Group-work involves discussions or physical work to achieve a given task. Students should use activities worksheets to guide the discussion and record their ideas in order to present them later to the whole class. You should introduce the rules of group-work in the first lesson.



Taking notes

Students record what is presented in the class, or you may distribute the pre-prepared notes of the lesson's key ideas.

Quiz

An individual task that each pupil should complete alone at the end of the lesson.

3.3.4 Outlines of the five lessons

The design decisions were addressed in a Worked Example consisting of five lessons. The purpose of this section is to present outlines of each lesson. The lessons share a general structure that starts with a brief introduction which includes the aim of the lesson and a list of the activities planned to address that aim. Then, the main idea behind the lesson is elaborated to help the teacher grasp what the lesson is about. Within each activity, the purpose, idea behind the activity, allocated time, teacher's role and required materials are all specified. In addition, the desired outcomes from the activity are presented followed by a detailed scenario of the teaching flow.

3.3.4.1 Lesson 1: Introduction and eliciting students' ideas

The aim of this lesson is to externalise students' ideas about the nature of food and what it is for with specific reference to plant food in order to make these ideas explicit before introducing the scientific view. This fulfils the point made in the learning demand that students need to differentiate food in terms of assimilating biomass and energy-supply (see section 3.2.3). This includes tackling why inorganic substances obtained from the environment are not food. To this end, this lesson is organised into three phases.

In the first phase a brainstorming activity is conducted to determine the nature of food and why we, as humans, need it. The human context is favoured over that of plants as it is more familiar to students.

It is made clear to the teacher during this activity that they should expect students to regard food as something to be taken in or something edible. They may also think that food is necessary to keep us healthy and alive, irrespective of the energy supply. The teacher is encouraged to make it clear that, although many materials are taken in, only substances that provide energy can be regarded as food. This is enhanced by an analogy of the elements needed for cars, using fuel “as a source” to explain energy “the target”. That is, although water, oil and fuel are all needed, only fuel makes the car moves. Similarly, all creatures, including humans, animals and plants, need many substances like water, vitamins and minerals. However, energy can only be liberated from organic substances which are, therefore, the only substance which can be regarded as food.

Then the teacher is asked to move on to the next phase to elicit students’ ideas of the nature of plant food. The idea behind the activity is to make students’ ideas explicit for both teachers and students as a preliminary step before challenging them. Through group discussion, students write down their knowledge of food for plants and animals, and the ways they obtain it. Then, the teacher asks groups’ representatives to present their ideas. The teacher’s role is to write the ideas on the board, ask for clarification if needed and then summarise the class’ ideas by listing the key ideas shared by the groups.

The third phase aims to challenge students’ ideas and then direct them to think that a hidden mysterious process happens inside the plant, which is responsible for producing food. It starts with a group discussion after students taste grapes and suggest sources for the sweetness found in the grapes. It is made clear to the teacher that students’ ideas might revolve around soil, minerals and water as sources of the sweetness. After their ideas are written on the board, the teacher suggests an alternative source for the sweetness by presenting a simple model of photosynthesis. The model is introduced through words stating that combining carbon dioxide with water can produce sugar, which we taste in fruit. Rather than favouring this model over other sources, the teacher invites students to question this model as a possible source. Then the teacher concludes the lesson with a promise to discuss this model in the next lesson. At the end of the lesson, students respond to a quiz to check whether they are able to define food according to the energy supply criterion rather than edibility or ingestion.

3.3.4.2 Lesson 2: Re-introducing the simple model and addressing sources of implausibility

The aim of this lesson is to help students to detect sources of implausibility mentioned in the learning demands in terms of recognising that carbon dioxide and water can be a source of a solid (biomass) and can form a substrate for respiration (see section 3.2.3). Once this is set, the teaching then moves to establish the plausibility of the simple model of photosynthesis by addressing causes of implausibility. Referring back to the model introduced in the previous lesson, the teacher re-emphasises the reactants involved in photosynthesis and their molecular status (gas and liquid) and the production, which is glucose. He invites students to consider glucose produced in this chemical reaction as an alternative to soil, water and minerals as sources of plant food. This lesson is introduced through two main phases.

The first phase attempts to help students to recognise why photosynthesis does not make sense to them. The teacher asks students to discuss in groups a virtual dialogue between three students who raise reasons for not believing in photosynthesis. The purpose for conducting this activity is to help students detect the conceptual problems associated with photosynthesis. The outcome of this activity is that students recognise the causes of implausibility, namely, how can a weightless gas (i.e. carbon dioxide) contribute to producing sugar, how can a gas and liquid be converted into a solid and how can simple substances combine to produce a complex molecule (i.e. glucose).

In the second phase, two causes of implausibility are addressed. To show students that carbon dioxide has mass, the teacher performs three demonstrations. First, he shows students that gases occupy space by demonstrating how paper stuffed into the bottom of a glass remains dry when the glass is turned upside down into a bowl filled with water. Then he takes a step further to show that carbon dioxide can be visible in some states by showing the students carbon dioxide emerging from an extinguisher. Finally, to prove that carbon dioxide does have mass, the teacher weighs a balloon when empty and then when inflated with carbon dioxide. The teacher concludes with what would happen if plants incorporate tonnes of carbon dioxide and convert it into glucose, which they really do.

Then the teacher demonstrates how a liquid combined with a gas can form a solid by breathing out in limewater. Keeping the students' attention on the suspended small solid substances formed in the limewater, this can prove that it is possible that plants too form glucose from combining carbon dioxide (gas) with water (liquid). Then the teacher concludes the lesson wondering "What really happens in the reaction between carbon dioxide and water when glucose is formed?" which will be investigated in the next lesson.

3.3.4.3 Lesson 3: Continuing addressing causes of implausibility, and completing the simple model of photosynthesis

The twofold aim of this lesson is to continue addressing the causes of implausibility by helping students to recognise that carbon dioxide and water can combine to form glucose, and then to extend the simple model. This aim is achieved in two phases. In the first phase, the teacher helps students to make sense of photosynthesis by showing them that glucose is formed from atoms derived from carbon dioxide and water. Students are asked to work in groups to build a model of glucose by cutting atoms from carbon dioxide and water. Students were guided by a structural formula of glucose to build this model. The teacher also informs them that there will be leftovers which they should keep for later use. After the activity is completed, the teacher stresses that plants produce glucose in a similar way. Then he wonders "Is this everything that the plants need to produce glucose?"

In the second phase, the teacher introduces the role of light energy in powering the reaction by using a bottle of fizzy water and shaking it many times, thus pretending to mix carbon dioxide with water in order to make sugar, as suggested by the simple model. Then he invites students to taste the mix to see if it tastes sweet. When students do not find it to be sweet, he concludes that something is missing in our model of photosynthesis. The teacher gives students opportunities to guess or recall ideas from previous teaching regarding what is missing. If students suggest light energy, the teacher agrees with this answer. Otherwise, he introduces the fact that energy trapped from sunlight is essential to power the reaction between carbon dioxide and water. Then he adds that plants are able to trap light energy by chlorophyll, which is located in plastids in leaves, and functions as an energy converter.

3.3.4.4 Lesson 4: Completing the photosynthesis model

The aim of this lesson is to develop a complete version of photosynthesis by introducing information that oxygen is released as a by-product, locating the photosynthetic process in the leaf, how the requirements of photosynthesis are obtained, and why plants convert glucose into starch. These aspects are introduced in four phases.

In the first phase the teacher asks students to examine the leftovers kept from building the model of glucose activity, which obviously will be atoms of oxygen. Here, the teacher stresses that oxygen is no more than a secondary product that plants release, most of it through stomata. In addition, he emphasises that the main product is glucose which is plant food. Then the teacher introduces a full version of photosynthesis that contains all the requirements (carbon dioxide, water and light energy) and products (glucose and oxygen).

In the second phase, the purpose is to determine where photosynthesis takes place. The teacher asks students to discuss in groups the most appropriate part of the plant to accommodate photosynthesis. Using the requirements as criteria to determine this part, students are provided with worksheets and asked to compare roots, stems, leaves and flowers based on the availability of requirements, and also to give a reason for their choice. The teacher then follows up students' choices, concludes that photosynthesis takes place in the leaves and justifies this by the availability of requirements.

In the third phase, students discuss in groups how the leaves obtain the requirements. Students are asked to use arrows and words to trace how each requirement arrives at the leaf, and where products go after they are produced. The teacher also follows up students' responses and summarises the right responses.

In the fourth phase, the teacher introduces the fact that if we examine a leaf wherein photosynthesis takes place, we will not find a trace of glucose. The reason for that is that plants immediately convert glucose into starch. The teacher then wonders "Why do plants need to do this?" To answer this, the teacher demonstrates how glucose and starch differ in solubility in water. He uses two glasses to show that, while glucose dissolves into water, starch remains suspended. To explain the reason behind this, he draws a simple analogy saying that if we push an individual out of the class this will be easy, but if we want to push out a group this will be hard or impossible. After giving students opportunities to relate this to plants, the teacher concludes that, in order to keep starch inside the leaves, plants store glucose in the form of starch to prevent it from exuding out of the cell.

3.3.4.5 Lesson 5: The fate of glucose: using glucose as a source for biomass and energy

The aim of this lesson is to use only photosynthesis as an explanation for the extra biomass and energy supply (in order to address the third learning demand presented in section 3.2.3), and then to support students in using this explanation. This lesson consists of three phases, namely, where plants' biomass comes from, the fact that glucose serves as a substance for energy, and reconsideration of the old ideas of plant food.

In the first phase students are asked to discuss Helmont's experiment in groups and to agree/disagree with his conclusion that plant biomass comes from water. After following the resulting ideas, the teacher introduces the structure of the plant cell, emphasising the components of each part. The purpose of introducing these facts is to show students that most chemicals which comprise the cell come from photosynthesised glucose, with minor proportions of nutrients absorbed from the soil (here, the teacher also stresses the role of minerals). Then the teacher refutes Helmont's conclusion, as extra biomass in fact comes from photosynthesised glucose.

In the second phase, the teacher establishes that glucose is the only source of food for plants. The teacher starts with the fact that all creatures, including plants, needs energy to carry out biochemical processes. This energy can only be liberated, in the case of plants and animals, in respiration from organic substances. In the case of plants, glucose is the only organic substance they access and therefore can be regarded as food, while soil, water, and minerals are not food because they do not supply energy.

The purpose of the third phase is to help students try out the scientific explanation by re-considering the old ideas generated in the first lesson concerning the nature of plant food. The teacher asks students if it is true that plants get food from the soil, water or sunlight. The teacher raises the question "What would happen to a plant if it was left in the dark for a long period?" Through a whole class discussion the teacher follows up students' ideas and concludes that plant would die due to shortage of glucose. Finally, the teacher presents students with a quiz to check if they can consolidate the factual knowledge related to photosynthetic process. The quiz is based on drawing an analogy between bread making in bakery and food making in plants (Modified from Armbruster, 1986). By using a worksheet, students should identify the raw requirements and how they are obtained, the source of energy and the main products.

3.4 Specification of the pedagogic strategies

As described in the last chapter (see section 2.4.3.1), the purpose of this part of the Design Brief is to show how the teaching goals are addressed through pedagogic strategies including specifications of the favoured class of communication. In addition, this section describes how the pedagogic strategies are also addressed in the Worked Example. Although descriptions of the Worked Example are not originally included in the Design Brief, bringing them here together with the pedagogic strategies might help the reader to follow how the design decisions were addressed in the Worked Example, particularly as the Worked Example is not in English.

I chose to trace how the teaching goals identified in the Design Brief are addressed by the pedagogic strategies by focusing on seven Key Design Features (KDFs). The KDFs summarize the pedagogic strategies and other essential design features which are used to address the teaching goals within the Worked Example, and therefore form the basis for evaluation of whether design intentions were actually implemented, and if so, whether intended design outcomes were achieved. While the KDFs share elements with the teaching goals, they are different in two respects. First, the KDFs are broader than the teaching goals as they account for the pedagogic strategies. In this sense, the teaching sequence is more represented by the KDFs than the teaching goals. The second difference lays in the function of each as a result of their components. The teaching goals inform the development of the Design Brief while the KDFs 'summarise key decisions about how the Design Brief will be operationalised in the Worked Example and so form the basis of the evaluation.

In this section, each KDF is presented and the associated design decisions made to address the learning demands and teaching goals are specified and justified, followed by a description of how the KDF is embodied in the Worked Example. Later, in the evaluation of implementation (Chapter 5), the reader is briefly reminded of these design decisions and how they are demonstrated in the actual teaching.

3.4.1 KDF 1: Eliciting students' ideas and establishing a definition of food

The first teaching goal concerns (see section 3.2.3 and Appendix A, part 3) the establishment of a scientific definition of food. The rationale underpinning this goal is that the first learning demand suggests it is necessary to *differentiate* that food is needed as a source for biomass and energy, rather than for keeping plants alive or healthy. Unless the way that students conceptualise food is considered at the beginning of the teaching sequence, students will continue to view a variety of substances as food, regardless of whether they supply energy or build up biomass. This, in turn, will affect their views of the nature of plant food. The key design feature is therefore to:

KDF 1: Open up, through formative assessments, students' ideas of the nature of food and what it is for, in order to make explicit to students and teachers how students consider food in general. Once these ideas are externalised, the teacher guides students in developing a scientific definition of food based on an energy-supply criterion. Then, the teaching moves on to consider students' ideas regarding the nature of plant food, and challenges their ideas to make a need for learning, so students can consider an alternative view, namely, photosynthesis.

Conducting a formative assessment will make students aware of their ideas as well as inform the teacher of students' starting points (see part 4 of the appended Design Brief, 1st point). It is assumed that students misunderstand "the nature of food" and "what food is for". Once these misunderstandings are brought to light through an interactive/dialogic interaction, the teacher guides students to address the first learning demand by establishing a definition of food based on an energy supply criterion, and then examine their ideas of food against the scientific definition.

The teaching then moves on to reveal through a formative assessment what students' views concerning the nature of plant food. Students hold various views on plant food based on the animal feeding model that lead them to believe that plants take in substances from the outside (see section 2.2.3). Examples of these substances are: soil, water, minerals, fertilisers and sunlight. The Design Brief anticipates that students might also regard photosynthesis as a way of obtaining food, although fragmentally. The purpose of this second formative assessment is to make students aware of their ideas and then show them their limitations before introducing a simple model of photosynthesis (see part 4, point 2 of the appended Design Brief). The teacher is encouraged to employ an interactive/dialogic interaction without providing at this point any evaluative feedback. It is also not expected that students immediately examine their knowledge of plant food against the agreed definition. Rather, they need time to reconsider their views in a different context. The view adopted in this teaching approach is to gradually guide students through "small steps" towards reaching the desired outcome (Driver et al., 1994a, p. 11).

Then the teaching turns to set a conflict with the purpose of challenging students' views of plant food to prepare them to consider photosynthesis as a possible alternative to soil and water etc. The conflict is set with an ordinary observation of the sweet taste found in fruits (see part 4, point 3 of the appended Design Brief). The conflict is stimulated by the question "How can soil, water and minerals provide sweetness in fruits?"

With regard to addressing this KDF in the Worked Example, although the sequence is related to plants, the Worked Example suggests dealing with the concept of food in a human-related context, which is more sensible for students as they can discuss something familiar to them. The sequence also suggests developing the concept of food over two steps by asking students "Why do we need food?", and "What substances can serve these needs?" The teacher is asked to raise two questions: "What is food?" and "Why do we need food?" and then perform a collective brainstorm to answer these two questions. The Worked Example explicitly specifies that interactive/dialogic talk should be used when probing students' responses. The teacher then writes these replies on the board before establishing the scientific view.

Figure 3.1: The Fuel Analogy

Food Is to Me as Fuel Is to Cars

It is rather hard for pupils to move from the everyday idea that food is anything taken in to the scientific view that food is a substance serves for liberating energy in respiration. We can exemplify the scientific view by drawing an analogy to things needed for cars. First, ask pupils to tell you about things that cars need, and why cars need them. Their responses will contain water (to cool down the engine), oil (function as lubrication), and fuel (to keep the car moving). Now focus on the fuel as an analogy to food. Both of them provide the needed energy. Neither cars nor people can manage with out them. Although cars and people need other things, the most important is what supplies energy, which is fuel for cars and food for people. Then tell them that we as human really need minerals, vitamins and water. However, they do not supply energy. After building the analogy make it clear to the pupils that only substances can supply energy can be called food.

It is expected that some students refer to getting energy from food, which is the scientific view. In this case, this comment can be used as an entry point to emphasise the fact that food as a substance serves in respiration to liberate energy. An analogy (modified from Whaley, 1994) is suggested to approach the concept of food (see Figure 3.1). In addition, a quiz is conducted at the end of the lesson to practice this definition and check students' understanding. In the quiz, students were asked whether the glucose solution given to patients in their veins can be regarded as food, and to justify their responses.

To elicit students' ideas about plant food, another activity is designed which instructs students to discuss in groups "What is food for animals and plants?" This discussion is enhanced by a worksheet to record and then present ideas to the whole class. The concept behind the activity is specified for the teacher in the following extract:

Extract 3.1: Conducting a formative assessment to elicit students' ideas of plant food (p.9)

This activity aims to encourage students to air their ideas about plant nutrition to prepare them for the later introduction of the scientific view. This is important because teaching the topic of plant nutrition cannot be detached from the ideas that students hold. It will not be a surprise when you find out that students believe that soil, water, minerals, light and fertilisers are plant food. It is also expected that students will have fragmented ideas about photosynthesis, but they will not be able to put them together coherently to explain plant nutrition and growth. Research suggests that it is insufficient to superficially talk about these ideas without letting students discuss and document them. So, let students talk in groups about their ideas, then comment on each of them and summarise them on the board. The key outcome expected from this activity is a list of ideas about plant food.

Another activity is also planned to challenge students' ideas by setting a conflict based on the sweetness found in fruit. The students will first taste grapes and discuss in groups where the sweetness comes from. Students are also aided by a worksheet (see Appendix C). The Worked Example guides the teacher through the following introduction:

Extract 3.2: The concept behind setting a conflict with students' ideas of plant food (p.10)

The purpose of this activity is twofold: to discuss and challenge students' ideas of plant food and to prepare them for the scientific view. This activity focuses on helping students to recognise the limitations of the ideas generated in the previous activity, by setting a conflict based around the sweetness found in fruit. It is important that students (not the teacher) realise the limitations of their ideas, as they cannot explain the sweetness. At that time, students will be ready to look for an alternative explanation because they will not accept the confusion. The teacher then introduces the simple form of photosynthesis through a data show projector.

3.4.2 KDF 2: Introducing a simple model of photosynthesis

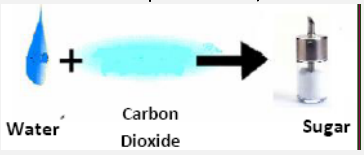
As previously mentioned in section 3.2.3 with regard to sequencing the content, reducing the details introduced in the topic of photosynthesis may help students grasp its essence. This view is adopted in both the Design Brief and the Worked Example. In addition, incorporated details will be gradually introduced to allow time for students to accept them. To this end, a key feature of the design is to:

KDF 2: introduce a simple form of photosynthesis as a possible explanation for plant food, which deserves consideration and questioning.

Photosynthesis at this point is reduced to the features that constitute its essence. The teacher introduces this model through non-interactive/authoritative interaction, showing that plants have the ability to combine carbon dioxide with water in order to produce sugar. The Worked Example addresses this feature through a presentation by the teacher. It starts by setting out the purpose of this activity, as follows:

Extract 3.3: Introducing a simple model of photosynthesis (p.16)

This activity aims to introduce an alternative possible explanation for the sweetness found in fruit, and to delve into the photosynthetic process. Re-state students' ideas recorded in the previous lesson concerning the source of sweetness and why they are limited when explaining its presence. Then, with a sceptical tone, suggest that some people (you may avoid saying scientists at this point) indicate that plants are able to produce sugar by themselves. In addition, state that this explanation (avoid describing it as scientific explanation) needs to be considered and questioned.



Try to keep it as simple as it appears in the slide by referring only to carbon dioxide and water as reactants, and to glucose as a product. Omit light energy, chlorophyll and oxygen and avoid presenting a chemical formula using only pictures and words. After presenting this model, ask if we can accept this explanation and if there are any problems which make it unconvincing.

3.4.3 KDF 3: Addressing the causes of the implausibility of photosynthesis

As previously mentioned (see section 2.2.5), even though students were taught photosynthesis as an explanation for plant food, they continue to hold the view that plants obtain food from the environment. As discussed in the second learning demand, this is because appreciating photosynthesis requires developing pre-requisite concepts in terms of understanding the nature of food and the concept of matter, which prove to be difficult for students to understand. Unless the conceptual barriers were made explicit to students and then addressed, it is unlikely that students will conceptually accept photosynthesis as an explanation for plant food and biomass (see part 4 of the Design Brief, points 5 & 6). To this end, the feature of the design concerns:

KDF 3: Highlighting the causes of the implausibility of photosynthesis to students, and then addressing these causes through demonstrations performed within interactive/authoritative and interactive/dialogic interactions. The causes of implausibility are:

- Carbon dioxide is only a weightless gas.
- How can chemical reactions take place in plants?
- How can simple molecules (carbon dioxide and water) combine to produce a complex molecule (sugar)?

To overcome these causes, two pedagogic strategies are suggested: teacher-led demonstrations (to show students that carbon dioxide exists and does have mass, combining liquid with gas can form a solid) and building two-dimensional models (to show that plants built complex substances from atoms found in simple substances).

The Worked Example addresses this KDF through two steps; firstly, by making the causes of implausibility explicit to students through group discussion enhanced by an activity worksheet. The Worked Example provides guidance to the teacher to perform this step, as follows:

Extract 3.4: Highlighting the causes of implausability to students (p.17)

This activity aims to help students to realise the conceptual problems that hinder their appreciation of photosynthesis. These problems are:
How can a gas (carbon dioxide) contribute to making glucose, while gas is nothing?
How can simple substances (carbon dioxide and water) combine to form glucose?
One of the problems encountered when teaching science is that we introduce it as unquestionable facts. However, even if students do not show their doubt of a concept, it does not necessarily mean that they understand it or that they even know why they do not understand it. Therefore, there is a need to highlight the aspects that do not make sense to them. In the case of plant nutrition, students experience problems with the concepts of mass and cycling of matter. They see gases as weightless substances and therefore carbon dioxide cannot contribute to making sugar. On the other hand, they find it difficult to accept that simple substances like carbon dioxide and water combine to form a complex substance like glucose. This activity aims only to detect these problems without providing a resolution for them at this point, which will be the task of the next lesson.

The second step involves addressing the causes of implausibility. For carbon dioxide, the teacher performs a demonstration of how paper stuffed into the bottom of a glass remains dry when the glass is turned upside down into a bowl filled with water. This means that air prevented the water from wetting the piece of paper. Then the teacher reveals that carbon dioxide can be visible when it is released from a fire extinguisher. Also the teacher demonstrates that carbon dioxide has mass and weight by weighing a balloon when it is empty and then inflating it with carbon dioxide (see Figure 3.2).

In order to show students that simple substances can form a complex solid substance, the Worked Example suggests a demonstration in which carbon dioxide is bubbled into limewater to make solid suspensions. Like the previous demonstration, the teacher is guided to perform and discuss with students the conclusion drawn from this activity in relation to photosynthesis (see Figure 3.3).

Figure 3.2: Carbon dioxide has mass

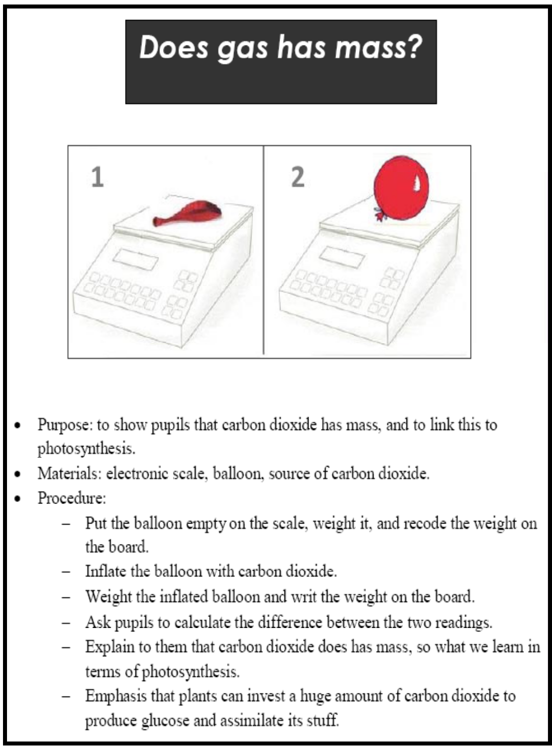
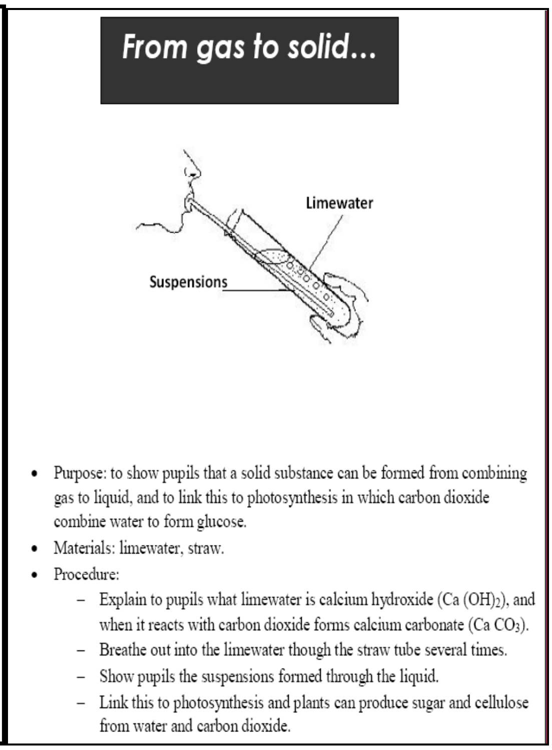


Figure 3.3: Solid can be formed from a gas and liquid



Then the Worked Example goes on to address the cycling of matter by showing students that it is possible to produce glucose from atoms found in carbon dioxide and water. This is done through student-dependent activity in which they work in groups to build a two-dimensional model of glucose by cutting out photocopied molecular formulas of carbon dioxide and water molecules, separating atoms, and then re-arranging them to build up a glucose molecule. The teacher asks students to keep the leftovers (oxygen) for later use. Then the teacher emphasises that glucose is no more than atoms found in carbon dioxide and water arranged in a different structure.

3.4.4 KDF 4: Completing the simple model

After the causes are, hopefully, addressed, it is time to present the photosynthetic process in its complete form. Reasons for postponing introducing the role of light energy, oxygen release and the conversion of glucose into starch are presented below (part 4 of the appended Design Brief, points 7, 8 and 9). The KDF related to introducing these aspects is:

KDF 4: Completing the simple form of photosynthesis by adding, through non-interactive/authoritative talk enhanced by demonstrations, the role of light energy, the release of oxygen as a by-product, locating photosynthesis in the leaves and storing glucose as starch.

With regard to the role of light energy, it is common for students to regard light as food for plants (as sunlight keeps plants healthy) and/or treat light as a reagent equivalent to carbon dioxide and water rather than a source of energy to power the reaction (see section 2.2.5). In addition, students confuse energy, heat and light. To avoid these confusions and therefore ease the acceptance of photosynthesis, introducing the role of light energy is postponed, despite its fundamental role. Moreover, although I disagree with the details of light/dark reactions presented in the textbook, I was uncertain about how much information in terms of the role of light energy is required to appropriately understand photosynthesis. Moreover, research does not offer guidance on this particular issue. Therefore, bearing in mind the key ideas targeted in the teaching, I decided to state that "Light energy is an essential requirement and the reaction cannot be completed without it, and chlorophyll is responsible for trapping and converting light energy". The importance of light energy in powering the reaction is introduced through a simple demonstration enhanced by non-interactive/authoritative talk.

The concept of releasing oxygen as a by-product was intentionally postponed to avoid developing the common misunderstanding that photosynthesis is an oxygen-supply process, and plants therefore are oxygen supplier organisms (see section 2.2.5). Limiting the simple form of photosynthesis only to producing glucose might help students to recognise that glucose is the main product while oxygen is only a by-product, which is leftover from the reaction. This is introduced through non-interactive/authoritative talk, as students will not be able to recognise this aspect themselves.

Finally, the Design Brief attempts to locate photosynthesis in the leaf, as that is the only part of the plant that can access requirements for photosynthesis as it contains chlorophyll. In addition, storing glucose by turning it into starch is demonstrated by showing the different solubility of glucose and starch, and the definitive loss of food if the cells store food in the form of glucose.

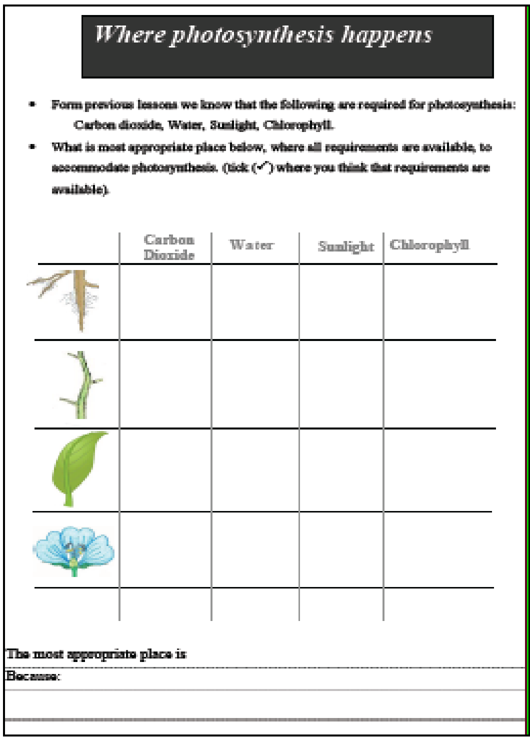
Turning now to the Worked Example, the role of light energy is addressed through a demonstration of mixing water with carbon dioxide using a bottle of fizzy water. The teacher invites students to test the mixture to see if they can taste any sweetness, which should be present according to the simple model of photosynthesis. As students will confirm its absence, the teacher questions whether something is missing from our model. The Worked Example also indicates that some students may be aware of the involvement of light energy in photosynthesis. If so, the teacher confirms their view and emphasises that light energy is not a reactant that is equivalent to water and carbon dioxide. Rather, it is only a source of energy to power the reaction between carbon dioxide and water.

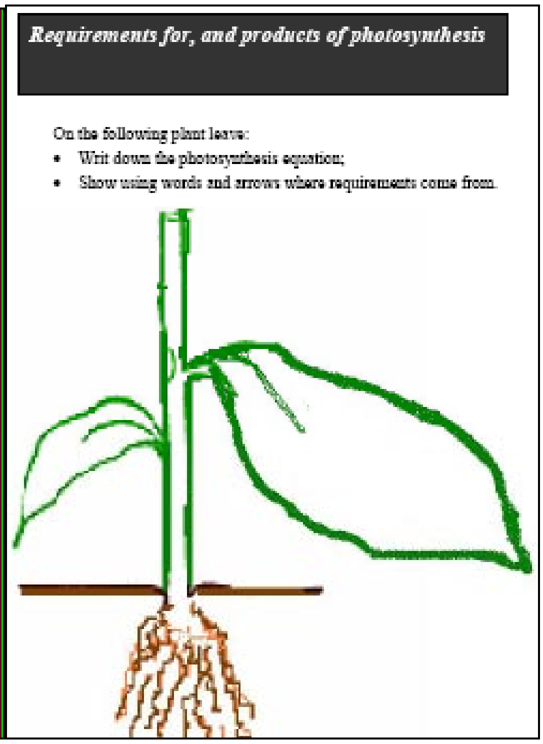
Next, the teacher is asked to consider the release of oxygen as a by-product and to emphasise at the same time that glucose is the key product produced by photosynthesis. Following the jigsaw activity of making up the glucose molecule, the teacher asks students to identify the leftovers, which were obviously atoms of oxygen. Here, the teacher emphasises through a non-interactive/authoritative talk that oxygen is only produced as a by-product, and the main product is glucose.

With regard to locating photosynthesis in the leaves, the Worked Example advises engaging students in deciding the most suitable place to accommodate photosynthesis based on the availability of carbon dioxide, water, light energy and chlorophyll. Students are provided with a worksheet (Figure 3.4) and are asked to compare roots, stems, leaves and flowers to finally determine and justify the most appropriate place. This is also followed by another activity intended to consolidate information presented so far by asking students to follow the requirements and products of photosynthesis using words and arrows (Figure 3.5). In both activities, students are given time to discuss their ideas in groups and present them to the whole class, followed by feedback and a summary from the teacher.

Figure 3.4: Locating photosynthesis in leaves

Figure 3.5: Consolidating requirements and products





Finally, the Worked Example focuses on introducing the fact that glucose is stored in the form of starch. To help students understand the reason behind this, the teacher is asked to demonstrate how glucose and starch differ in terms of solubility in water, which explains why food is stored as starch. The demonstration will show students that, while glucose dissolves in water, starch remains suspended. The teacher is asked to perform this demonstration through the following scenario:

Extract 3.5: Converting glucose into starch (p.36)

- Raise the question "If we test a leaf, would we find a trace of glucose?" Give students chances to respond and explain that we wouldn't because glucose is immediately converted into starch.
- Raise another question "Why do plants do that?" Give students time to respond.
- Demonstrate to students the solubility of glucose and starch in different glasses of water.
- Raise the question "If glucose remains as it is, would it stay or dissolve in cytoplasm?" Give students time to respond.
- Conclude that glucose is converted into starch and stored inside the cell. Explain that starch is polysaccharide combines many glucose molecules.

To check students' understanding of the conservation of glucose and help them to practice the concept, a quiz is conducted at the end of the lesson (Appendix C).

3.4.5 KDF 5: Explaining plant biomass through photosynthesis

As a full form of photosynthesis has been revealed, the Design Brief turns to explain plant growth and biomass through photosynthesis, which constitutes one of the key ideas targeted in the teaching sequence. In this regard, research indicates that students tend to attribute biomass increase to soil and water (see section 2.2.4). Therefore, there is a need to elicit students' ideas before delving into explaining the increase of biomass. To this end, the KDF involves (point 10 of part 4 in the appended Design Brief):

KDF 5: Conducting a formative assessment of students' ideas regarding the source of extra biomass to make explicit for both students and teachers the students' starting points. Then, moving to revise the basic structures of plant cells and the substances which make up these structures, to show students how much glucose contributes to them, and to emphasise the limited role of minerals absorbed from the soil.

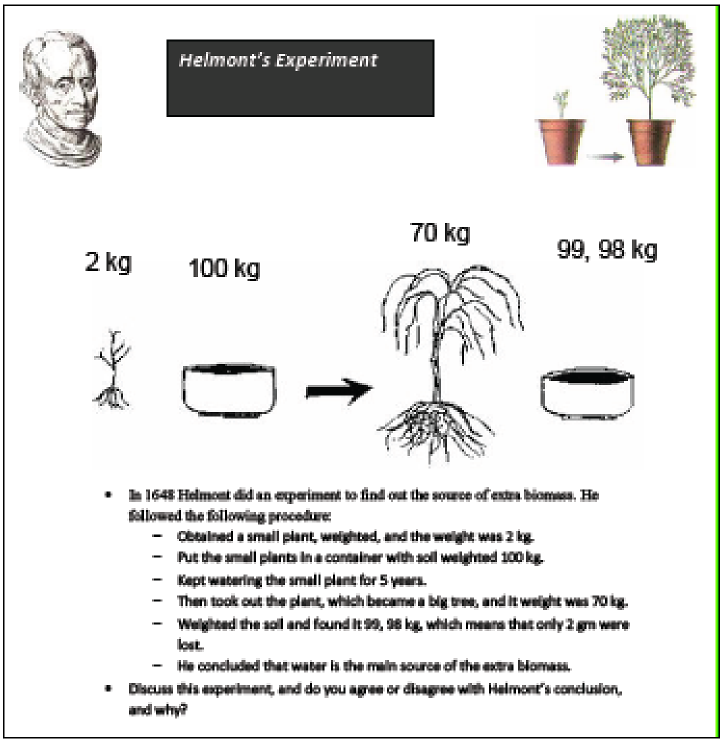
The purpose of the formative assessment is to make explicit for the teacher and students how students explain the extra biomass. This is followed by an introduction of facts concerning the structure of plant cells, emphasising the amount of glucose invested in the chemicals comprising the cells. This introduction includes the following:

- The cell wall is made of cellulose which is a type of carbohydrate (chains of glucose molecules).
- The cell membrane is made of protein (composed of glucose and a small amount of nitrogen) and fat (made of glucose molecules).
- Cytoplasm consists of carbohydrates, proteins, fats and water.
- Plastids contain chlorophyll, which is formed from glucose with a small amount of magnesium.

In addition to introducing these facts, the Design Brief suggests explicitly tackling the role of minerals absorbed from the soil, which constitute a very common misunderstanding amongst students. It will be emphasised that only very small proportions of minerals are used in the chemicals of which the cells are made. This might, therefore, help students to recognise that minerals play a limited role in explaining the extra biomass. Moreover, other ideas generated in the formative assessment should be refuted as an explanation for sources for biomass.

The Worked Example addresses this KDF through a formative assessment based on Helmont's experiment. Students are asked to follow Helmont's experiment and question his conclusion that "Water is the source of extra biomass" (see Figure 3.6). After group discussions, the teacher follows up students' ideas and summarises them.

Figure 3.6: Helmont's expirment



The Worked Example then suggests introducing facts about the structure of plant cells and the components of cell parts (see Appendix C). The purpose is to show students that most of the chemicals used to build up the cell come mainly from glucose produced in photosynthesis. Next, the teacher returns to students' ideas and examines them through non-interactive/dialogic talk, stressing that plants' mass is made of glucose and other substances that are formed by glucose rather than soil, water or minerals.

3.4.6 KDF 6: Explaining plants' use of produced glucose as a source of energy

The third key idea targeted in the teaching sequence concerns how plants use produced glucose as a source for energy to carry out biochemical functions. This aspect proves to be challenging for students, as they consider inorganic substances to be food for plants, as well as the fact that they do not usually link food to energy. At this point of the teaching sequence, students can appreciate that glucose is plant food because, one on hand, they are able to define food based on energy-supply, and they can make sense of photosynthesis as a process. As students cannot independently discover or investigate at this age that glucose serves as a substrate for respiration from which energy is liberated, the teacher introduces this fact through interactive/authoritative talk in three steps: (1) all creatures need energy to carry out biochemical processes, (2) energy is only liberated in respiration from organic substances such as glucose, (3) the only source for glucose is photosynthesis. Therefore, soil, water, minerals and light cannot serve in respiration. To this end, the KDF is:

KDF 6: To close up the photosynthesis model by introducing through an interactive/authoritative talk the fact that produced glucose is the only substance from which energy is liberated in respiration.

The Worked Example addresses this aspect by introducing the fact that all creatures need energy to carry out biochemical processes and, whether in plants or animals, glucose is the only substance which serves to release energy in respiration. Moreover, the Worked Example advances using questions to develop this concept following this scenario:

Extract 3.6: Addressing the need for energy in plants (p. 45)

- Introduce the fact that all creatures must carry out biochemical processes (ask students for examples of these processes).
- Introduce the fact that glucose is an essential substance from which energy is liberated in respiration.
- Ask students "How both plants and animals obtain the necessary energy?"
- Conduct a whole-class discussion to conclude that food is needed to supply energy, although food is obtained differently.
- Ask students "What would happen to the plant's starch if the plant is left in the dark for a long period of time?" Emphasise that the stored starch is the only source of food, so the plant would eventually die.

3.4.7 KDF 7: Practicing the scientific explanation

The Design Brief ends by providing students with opportunities to practice their knowledge by revisiting their previous ideas of plant food that emerged from the earlier formative assessments. This part of the teaching sequence corresponds with the third stage of the sequence of handing-over responsibility to students (see section 3.2.4). In addition, it has been documented in the literature that students continue to consider inorganic substances to be sources of food and biomass, even after formal teaching, and some of them refer to photosynthesis simultaneously with other inorganic substances (see section 2.2.3). The purpose of this final phase, therefore, is to re-stress information using the scientific explanation to account for sources for food and biomass by revisiting the old ideas of plant food and justifying why they are wrong in the scientific sense. To this end, the KDF is:

KDF 7: To practice using the taught knowledge to validate everyday ideas concerning plant food and biomass.

The Worked Example addresses this by first ensuring that students are able to consolidate the taught information with regard to the photosynthetic process. Students are asked to discuss in groups an analogy drawn between bread baking and food making (modified from Whaley, 1994) in terms of requirements and how they are obtained, and the products resulting from each process. The purpose is to ensure that students can bring together requirements and products of photosynthesis.

Next, the teacher is asked to revisit the ideas recorded in the first lesson with regard to plant food. The purpose is to validate these ideas justifying why they cannot be considered to be plant food. Here, the teacher leads discussions through an interactive/dialogic interaction to link the scientific definition of food to the food produced in photosynthesis, and to deny that inorganic substances are food for plants.

The next chapter concerns the methodology of the study. It starts by addressing the research question and then presents the research strategy, data collection and analysis, and touches upon the quality of the research and ethical issues.

CHAPTER 4: METHODOLOGY

This chapter will consider the methodology of the study. It starts by describing and justifying how the research questions were addressed and then justifies the choice of employing case study research to conduct this study through three phases of design, implementation and evaluation. A section devoted to data collection and analysis describes and justifies choices of the techniques used to collect data and approaches used in the analyses. Finally, in two separate sections the quality of research and ethical issues is considered.

4 CHAPTER 4: Methodology

4.1 Introduction

This chapter presents the methodology, which seeks to account for the preparation for and conducting of the research. The purpose of this chapter is to 1) describe how the research questions were addressed, 2) provide an overview of research strategy, including the development, implementation and evaluation of the teaching sequence, 3) report how data were collected and analysed, and finally 4) consider the quality of the study and ethical issues.

4.2 Addressing the research questions

The first aim of this research is to *use the Leeds Model to design a teaching sequence about plant nutrition for male Saudi school students aged 15-16* (see section 2.5). To fulfil the design component of this aim, the Design Brief was developed and addressed by a Worked Example, as presented in the previous chapter. The purpose of the Design Brief was to make explicit the design decisions in order to guide the development of the Worked Example and function as a checking reference for measuring the effectiveness of the implementation. Details of the Design Brief and Worked Example are presented in Chapter 3 and Appendices A and C.

An essential characteristic of design studies is the iterative process through which the design is evaluated to measure its effectiveness and to inform re-designing the product to improve its quality. In the case of this study, the rationale for the designed teaching was made explicit in the Design Brief, which made it possible to check its assumed effectiveness against the actual implementation and attainment. Refinement of the original design can then be informed by results obtained from evaluating the actual implementation, as well as results obtained from assessing attainment. To this end, two modes of evaluation have emerged which will be investigated through two separate research questions.

RQ 1: To what extent was the planned design implemented as intended?

This question emerges from the second aim that concerns *determining the effectiveness of the teaching sequence in terms of meeting its design intentions and achieving the expected learning outcomes*. As presented in Chapter two (see section 2.4.3.1), I will adopt a tripartite model for the evaluation that takes account of the intended design, what is implemented in the classroom and what the students had attained. To this end, in this question I focus on the match between the intended design and the actual implementation. I will try to answer whether the actual implantation followed the hypotheses and intentions advanced in the Design Brief and Worked Example. Answering this question serves on one hand to determine the match between what was intended and has been implemented, and, on the other, establishes a basis to explain the effect of the teaching sequence in promoting students' learning. Section 2.4.3.1 describes how I extended the evaluation model that I presented in Chapter 2 to account for both the teachers' enactments and students' engagement, since the original evaluation model does not pay explicit attention to the teacher.

Since it is not possible to trace the implementation of every single aspect of the Design Brief or Worked Example, I developed seven Key Design Features (KDFs) (see section 4.3.5) that summarize *essential* design decisions in the teaching sequence, and therefore form the basis for an evaluation of whether design intentions were actually implemented, and if so, whether intended design outcomes were achieved. I then followed teachers' and students' actions with regard to those KDFs. In order to solidly link the Design Brief to the implementation, I have already presented in the last chapter the specifications of the Design Brief and activities developed in the Worked Example, clustered around the KDFs (see sections 3.4.1 to 3.4.7).

Data used to address this question were obtained from the videotaped lessons and classroom work. From the videos, I developed the first raw descriptions of teachers' enactments of the five lessons, as well as how students were engaged (see Appendix, D). I then focused on each KDF, following how the teachers and students responded during the implementation. I also supported this analysis with excerpts from teacher-student interaction and collected classroom work and end-of-lesson quizzes. Findings related to this question are presented in Chapter 5.

RQ 2: To what extent did the students develop the desired learning outcomes?

This question emerges from the second research aim, that is, *determining the effectiveness of the teaching sequence in terms of meeting its design intentions and achieving the expected learning outcomes*. Based on the tripartite model of the evaluation, by posing this question I will attempt to investigate whether students succeeded in attaining the expected learning outcomes. Three learning outcomes were explicitly specified in the third part of the Design Brief (see section 3.2.3). While the first learning outcome concerns factual knowledge related to plant nutrition (according to which students will be assessed in school exams), the second and third outcomes concern the conceptual understanding of the source of plant food and extra biomass. To this end, three probes were conceptually and phenomenologically framed to assess students' performance three times with pre-, post- and post-delayed tests (see section 4.4.3.1), and then nomothetically analysed (see section 4.4.3.3) to establish the consistency of students' responses with the model answers that represent the desired outcomes, as specified in part 3 of the Design Brief (see section 3.2.3). In addition, the words that students used in these responses were analysed to document the change in their use of scientific words across the three tests (see Chapter 6).

Since the success or failure of any intervention is affected by factors that go beyond the intervention *per se*, I attempt to investigate both teachers' and students' perceptions about the conceptual and pedagogical aspects of the teaching sequence through the 3rd research question:

RQ 3: How did the teachers and students respond to the key conceptual and pedagogical aspects of the teaching sequence?

This question emerges form the third aim of the research, that is, *to determine how the teaching sequence and associated teaching practices were perceived by Saudi teachers and students*. Investigating how teachers and students responded to the teaching sequence is of twofold importance. On one hand, if there are limitations to the teaching sequence that cannot be identified through video analysis or probing understanding, teachers and students can directly point them out. Furthermore, since the Worked Example was not piloted before the actual implementation, it was essential to investigate teachers' and students' views about the content and pedagogies that were used in the Worked Example. Their views will inform design decisions, which, in turn, will inform refinements of the Design Brief and the Worked Example to meet the needs of the Saudi context.

On the other hand, understanding the ways in which Saudi teachers and students perceive novel approaches to teaching can optimize how to approach them with new innovations, particularly when the educational authority is reviewing projects directed to developing science and mathematics education (see section 2.5).

Data relevant to teachers' and students' perceptions were gathered in semi-structured interviews. Teachers were interviewed individually using pre-prepared guided questions. In addition, teachers were given diaries that were specifically designed to report their thoughts lesson by lesson. Students were also interviewed in groups of three, based on performance in the post-test (high, average and low), using pre-prepared guided questions. All interviews were videotaped and transcribed for later analysis. In the case of the teachers, individual stories were compiled from the transcribed interviews, while three collective stories were compiled from students' interviews to represent the three performance groups.

Drawing upon findings collected to address these three questions, discussions are provided in Chapter 8 with regard to refining the designed teaching sequence, developing a set of domain-specific guidelines to teach plant nutrition in the Saudi context, the efficacy of the Leeds Model in enhancing the design and communication of the teaching, and providing reflections about the strengthens and limitations of evaluation model.

Now, I turn to present the research strategy that includes the three phases of developing the teaching sequence, namely design, implementation and evaluation.

4.3 Research strategy

This section seeks to justify the choice of employing a case study as a research strategy. It starts (section 4.3.1) by defining case study research and how it fits my purpose in this study, then section 4.3.2 presents the different forms of case study that suit this particular study. Section 4.3.3 then describes the procedural phases (design, implementation and evaluation) of conducting this study.

As previously mentioned in Chapter 2, design studies employ a variety of research methods and techniques that are commonly used in social science (Brown, 1992; Gorard and Tyler, 2004). The determinant for using a specific research strategy is governed by the aims and issues involved in a certain study (Gerring, 2007). Given its aims, this study involves developing a teaching sequence that goes through designing a domain-specific sequence, implementing the designed sequence in classrooms, and finding out whether the sequence was implemented as intended and whether students attained the desired outcomes. In addition, personal views of participants are seen to be important to understanding the context and its effect on adopting such an approach. After considering these issues, it was concluded that they can be addressed by employing case study research.

4.3.1 Case study research

According to Schwandt (2001), case study research is appropriate when seeking answers to ‘how’ or ‘why’ questions, when the object of study is novel to the context and when multiple sources of evidence are required to answer the research questions. In addition, Yin (2003) suggests using case study research when investigating both processes and outcomes which are of interest to the researcher.

Accordingly, in this particular study, it is necessary to investigate “*how*” the designed teaching is implemented in the classroom (RQ1) as well as the effect of the designed teaching on developing the desired learning outcomes (RQ2). Findings from these two facets can explain why there “was” or “was not” an effect on learning. In addition, as the approach used in this study is contemporary to the Saudi context, I am interested in exploring perceptions of teachers and students with regard to the teaching sequence (RQ3).

4.3.2 Forms of case studies

Yin (2003) distinguishes three forms of case studies, which he calls "*exploratory*", "*descriptive*" and "*explanatory*", depending on the purpose of conducting the research. According to Yin, a case can be *exploratory* when it aims to develop a hypothesis or propositions, *descriptive* when the interest is to develop a description of a phenomenon within its context, and *explanatory* when it investigates cause-effect relationships.

Whereas it is common to conduct a case study that captures one of these three forms, it is possible too, in my view, for a case to reflect all three forms to varying degrees. Rather than making a clear cut demarcation between the three forms, the study can maintain multiple foci at different stages and a combination of these three foci constitutes the whole case study. As presented in Chapter 2 (see section 2.3), design studies usually start with a hypothesis about exploring an effective way of teaching specific content (design phase), document its actual implementation in the classroom to find out whether it was implemented as intended (implementation phase), and report what effect it has on learning (evaluation phase). Bringing together these three phases of design studies and the three foci of case study research, Table 4.1 shows how they can fit together according to the general model of design studies presented in Chapter 2 (see section 2.3).

Table 4.1: Linking design study to forms of case study research

Design study	Developing a theoretical model	Actual behaviour	Actual function
Foci of case study	Exploratory focus	Descriptive focus	Explanatory focus

In addition, similar to this approach, Yin (2003) consolidates the three foci when he discusses applying the case study method to evaluation research, which I believe shares some features with design research. He suggests that case studies can be used to *explain* links between programme implementation and programme effects, *describes* the context in which the intervention occurred and/or develops *illustrative* descriptions of certain issues within the evaluation. To this end, I consider my research strategy to be a case study that captures the three foci mentioned above. The case highlighted in this case study is the design, implementation and evaluation of a teaching sequence about plant nutrition in Saudi schools. Although the sequence was implemented by four teachers, it is still a single case, rather than a multiple case, study because they all enacted the same sequence and I was interested in exploring the same issues (Yin, 2003).

The next section turns to examine how this case study was carried out with regard to the three phases of design, implementation and evaluation. It only focuses on methodological and procedural consideration because the theoretical accounts have already been presented in Chapter 3 (sections 3.3.2/3.3.3/3.3.4).

4.3.3 The design phase

As discussed in Chapters 2 and 3 (see sections 2.4.1.3 and 3.2), I selected and adopted the Leeds Model to design the teaching sequence. Details of the development of the teaching sequence (Design Brief and Worked Example), including specifications and rationale, are discussed in Chapter 3. Here, only the methodological aspects are focused upon in order to describe the actual procedural steps that were followed in developing the Design Brief and Worked Example.

4.3.3.1 Development of the Design Brief

The Design Brief consists of four main parts which include a number of sections. The first part consists of four sections. As mentioned in the last chapter (see section 3.2.1), there was variation between the content presented in the textbook and the content covered in the designed teaching sequence. This variation has an implication on conducting the research according to a one-group design rather than as a quasi-experiment.

I should also mention that the development of these four parts was not as linear as it might appear from my descriptions in the last chapter. Rather, it involved going back and forth between the parts in order to make refinements, additions and alterations. In addition, not all the details that appeared in the final version of the Design Brief were included in the early version that was used to develop the Worked Example. As my thinking evolved, my justifications of the design decisions became clearer and sharper. However, the design intentions and decisions, as well as the pedagogic strategies, remained as specified in the early version of the Design Brief.

4.3.3.2 Development of the Worked Example

The second step in the design phase involved translating the Design Brief into a Worked Example. Given that some teaching sequences about plant nutrition already exist, I chose one that was recently designed by Hind et al. (n.d.). As mentioned in Chapter 3 (see section 2.3), I further developed Hind et al.'s sequence to reflect the Design Brief and meet the needs of the Saudi context.

The developed Worked Example was organised to be taught in five lessons (with a duration of 45 minutes each). It would have been more effective if the teaching sequence had been organised to be taught in more than five lessons, from the point of view of giving both teachers and students more time to practice this novel approach. However, given that Saudi teachers usually introduce this topic in two lessons, it would have been more difficult to persuade schools to participate in the study if they were asked to devote more than five lessons to teaching plant nutrition.

Two Saudi biology education supervisors, who have been involved in authoring high school biology textbooks and developing in-service teacher training, were consulted with regard to the resulting Worked Example. The purpose of the discussion was to check the clarity and general readability of the Worked Example, as well as to assess the suitability of the incorporated activities for the Saudi context. As a result of this consultation, some language modifications were made. In addition, the participating teachers were asked to review the sequence, but they did not raise any concerns.

4.3.4 The implementation phase

The purpose of this section is to describe the implementation phase including providing profiles of the participating schools, teachers and students.

In Saudi, the topic of plant nutrition is first taught in Grade 10 and then in Grade 11 with more technical details. It was not possible to implement the sequence in Grade 11, as students in this year start preparing for intensive examinations related to the General High School Certificate. Therefore, the choice was made to implement the teaching sequence in Grade 10. Since all schools are single-sex in Saudi, and there is no access permitted to girls' schools by males, it was compulsory for me to implement my study only in boys' schools where there are only male teachers.

The implementation phase is now described in terms of the participating schools, teachers, students and the actual implementation. Table 4.2 shows a general overview of the sample.

Table 4.2: Participants in the study

Grade	Age	School	Participants	
			Teachers	*Students*
10^{th} Grade	15-16	A	T1	26
		B	T2	37
			T3	32
			T4	36
Total		**2**	**4**	**131**

4.3.4.1 Participating schools

In terms of the participating schools, the criterion used to select the schools was pragmatic and depended on finding an enthusiastic headteacher who was willing for the study to take place in his school. So, I visited five schools in Riyadh, the capital city, and introduced my study to the headteachers. Only two headteachers agreed that their schools could take part in the study. Once the schools were determined, the teachers and students were automatically selected.

Both participating schools have new governmental buildings and are located in middle-class areas in the north and west of Riyadh. The total number of students in each school is about 800. The sequence was taught in the learning centre rooms in both schools to allow group-work which is otherwise impractical in normal classroom sites where the students are relatively crowded. The school learning centre is spacious, equipped with a whiteboard, overhead projector, and circle tables. Such facilities suit the teaching/learning strategies used in the teaching sequence.

I consider my sample to be a convenience sample in which the participants were chosen on the grounds of accessibility (Cohen et al., 2007). This kind of sampling is justified when there is limited access to the fieldwork (Denscombe, 2003). It should be mentioned that the inferences made from the findings of such a sample can be constrained; however, having said that, I believe that the chosen schools and participants (teachers and students) were typical of the population that can be found in the Riyadh district. In addition, since the sample encompassed two schools from different sites in the city, the four teachers varied in their experience and a total of 131 students participated, there is no reason to assume that the sample is particularly skewed or biased.

4.3.4.2 Participating students

Very often students are distributed over classes in equal proportions, according to their achievements in the previous year's examinations, which might imply that all abilities are represented in all classes. Therefore, classes seem relatively equal overall. Classes were chosen in the first school by the deputy-headteacher, as there was no overlapping between them to allow the researcher to attend and videotape the lessons. In the second school, the teacher himself selected the class that was most convenient for him. A total of 131 students from four different classes (in two schools) took part in the study. There were normal absences from the students where one or two did not attend school due to illness.

4.3.4.3 Participating teachers

All the four participating teachers were specialists in biology, whose teaching experience varied from four to 16 years (see Table 4.3). In addition, teachers varied in their enthusiasm during the implementation, which can be indicated by their preparation prior to the lessons. There were no absences from the four teachers.

Table 4.3: Profiles of teachers (T=Teacher; S=School)

Teacher	Background	Actual implementation
T1, S "A"	Experienced teacher with nine years of teaching high school biology. Enthusiastic about the teaching sequence and willing to develop his own practice.	Came prepared to the lesson, tried to follow the scenario, kept asking for feedback on his teaching.
T2, S "B"	Young with four years of experience teaching high school biology. Limited enthusiasm compared to other participants, though committed to implementing the teaching sequence.	Taught based on information provided in the introduction programme, an emphasis on involving students' ideas, but mostly to gain correct answers.
T3, S "B"	Senior teacher with 16 years of experience in teaching high school biology. He was delighted to participate in the implementation, though pessimistic about students' responses.	Came prepared to the lessons, tried to follow the scenario; struggled in the first lesson and was not satisfied with his performance, though confident in the remaining lessons.
T4, S "B"	Young with five years of experience in teaching high school biology, limited experience with classroom management. He is undertaking an MSc. Positive about the teaching sequence.	Came prepared to some lessons, tried to follow the scenario, and struggled to manage the class with groupwork and probing students' ideas.

As a school policy, teachers had to accompany students to the learning centre from their classrooms, which sometimes affected the time allocated for the lesson. If they were late, they made up for it by taking a few minutes from the next class.

Saudi teachers are not familiar with participating in research, nor are they accustomed to the strategies incorporated in the sequence. For example, early informal interviews with the teachers indicated that they were unaware of misconceptions, cognitive conflict, analogies and interactive teaching, all of which were notions employed in the sequence. To prepare them to implement the sequence as intended, I organised and ran three introductory sessions (lasting about two hours each) to introduce the content and associated pedagogic strategies.

The first session concerned students' conceptions of plant nutrition. The second session introduced different ways by which teachers can communicate with students for different purposes, using the notion of Communicative Approach (see section 2.4.1.3). The final session was devoted to reviewing the sequence and associated techniques lesson by lesson, focusing on the teaching purposes and teaching/learning activities. In addition, the teachers were encouraged to try the techniques out in their normal classes before actual implementation. This preparation was done separately in the two schools. The sessions were fully attended except for one absence from one session from T2.

Each teacher was provided with a package containing the whole teaching sequence, materials needed for activities, and PowerPoint slides of the five lessons saved on a CD. In addition, I offered short individual meetings, prior to the lessons, in case the teachers wanted to ask for clarification. In these short meetings, we briefly ran through the content and activities of the lesson to be taught.

4.3.4.4 Actual implementation

The plant nutrition unit is usually taught in the first week of the second semester, which was in mid February 2008. However, I asked the teachers to postpone teaching plant nutrition to allow for more time to prepare to conduct this study. The sequence was thus taught in mid March 2008 in five lessons (lasting 45 minutes each) in both schools. It took three weeks to complete (two lessons per week). Table 4.4 shows a summary of the implementation and other research activities.

Table 4.4: Time of the implementation and other research activities, 2008

Tasks	Feb		Mar				Apr				May			
	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Preparation	■	■	■	■				School holiday						
Pre-test				■										
Implementation					■	■	■							
Observations					■	■	■							
Post-test							■							
Interviews										■	■			
Post delayed-test														■

The sequence was taught simultaneously in different time blocks to allow the researcher to observe the lessons. In order to familiarise both teachers and students with my presence, I attended one lesson in each class prior to the actual implementation. The teachers introduced me to the students as someone who is interested in improving biology education, who will help both teachers and students during the teaching of the next five lessons. So, during the teaching I assisted in preparing the materials required for each lesson and helped to distribute and collect activities sheets and quizzes.

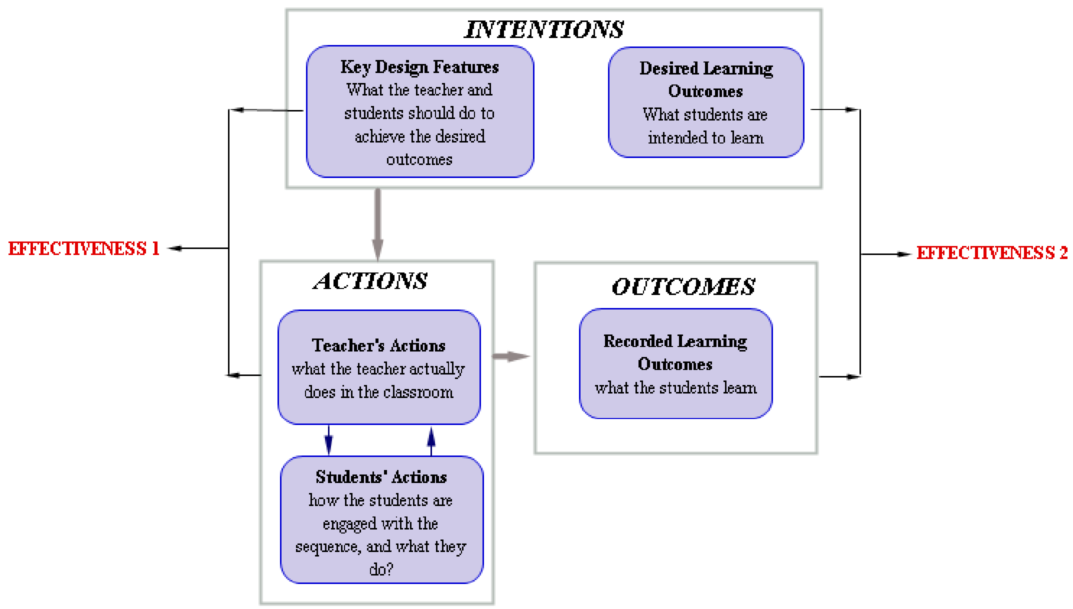
I also reminded the teachers if they skipped any significant activities in the teaching sequence, which I only had cause to do in one occasion with T2. All the lessons were attended by me and the teachers, they were videotaped and notes were kept.

4.3.5 The evaluation phase

As previously mentioned (see section 2.4.3), evaluation of the resulting design is at the heart of design studies because it is only through this phase that designers can test the workability of their hypotheses and products and the evaluation results can inform the required revisions. This section only describes the model of evaluation and how it was used, as the discussion chapter (see section 8.5.2) will reflect upon the strengths and limitations of the evaluation model by drawing upon the notion of meta-evaluation, as described by Stufflebeam (2000).

I used an extended version of the model proposed by Millar et al. (2002) (see section 2.4.3). Millar et al.'s model is intended to evaluate practical work in terms of the match between what is intended and implemented on one hand, and what is intended and attained on the other. I suggested in Chapter 2 (see section 2.4.3) that Millar et al.'s model takes account only of students' actions and does not consider the teachers' enactments. I believe that the teacher has a critical influence on the effectiveness of the implementation and students' learning. In this sense, the effectiveness should be seen through a tripartite profile that takes account of the intended design, implemented teaching (including teachers' action and students' engagement) and the attained outcomes. The next section describes how I used the extended model presented in Figure 4.1.

Figure 4.1: A model for evaluating the Teaching Sequence (extended from Millar et al (2002))



As Figure 4.1 shows, the model consists of three components: intentions, actions and outcomes. One of the links between the intentions box and the actions box represents the match between what is intended to be implemented and what was actually implemented, which is called effectiveness 1. The reason for tracing the actual implementation is that claims made with regard to the recorded outcomes should be based on the ways the sequence was implemented by teachers and students. Furthermore, documenting what really happens in the classroom will validate the assumptions advanced in the Design Brief and, therefore, will help in formulating the domain-specific guidelines to teach plant nutrition.

However, it is rather difficult to measure the match between all the design specifications and all the actual actions of teachers and students. Therefore, as mentioned before (see section 3.4), I narrowed my focus by developing seven Key Design Features (KDFs) (listed in Table 4.5 below) that summarise the pedagogic strategies and other essential design features which are used to address the teaching goals within the Worked Example, and therefore form the basis for evaluation of whether design intentions were actually implemented, and if so, whether intended design outcomes were achieved. To establish the match between what is intended and what is implemented, I traced teachers' and students' actions with regard to the seven KDFs (see Chapter 5).

Table 4.5: Key Design Features (KDFs)

- **KDF 1**: Open up, through formative assessments, students' ideas of the nature of food and what it is for, to make explicit to students and teachers how students consider food in general. Once these ideas are externalised, the teacher guides students in developing a scientific definition of food based on energy-supply criterion. Then, the teaching moves on to consider students' ideas concerning plant food, and challenges their ideas to make a need for learning, so students can consider an alternative view, namely, photosynthesis.
- **KDF 2**: To introduce a simple form of photosynthesis as a possible explanation for plant food, that deserves consideration and questioning.
- **KDF 3**: Highlighting to students the causes of the implausibility of photosynthesis (carbon dioxide particles do have mass, gas and liquid can be converted into a solid, simple molecules (carbon dioxide and water) can combine to produce a complex molecule (sugar), and then addressing these causes through demonstrations performed within interactive/authoritative talk.
- **KDF 4**: Completing the simple form of photosynthesis by adding, through an authoritative talk enhanced by demonstrations, the role of light energy, the release of oxygen as a by-product, locating photosynthesis in the leaves and storing glucose as starch.
- **KDF 5**: Conducting a formative assessment of students' ideas of the source of extra biomass to make explicit for both students and teachers the students' starting points. Then, moving to revise the basic structures of plant cells and the materials from which these structures are made, in order to show students how much glucose contributes to them, and to emphasise the limited role of minerals absorbed from the soil.
- **KDF 6**: To close up the photosynthesis model by introducing, through an interactive/authoritative talk, the fact that the glucose produced is the only substance from which energy is liberated in respiration.
- **KDF 7**: To practice using the taught concepts to validate everyday ideas concerning plant food and biomass.

The second link between the intentions box and outcomes box represents the match between what is intended and what is attained, which is called effectiveness 2. The learning outcomes are specified in the third part of the Design Brief (see section 3.2.3) and are presented below in

Table 4.6. Evaluating students' actual learning against desired learning constitutes a basic judgment of the quality of the teaching sequence. Indeed, what is intended is to enable students to develop a scientific understanding of the targeted key ideas. To this end, the learning outcomes were assessed using three written probes. To establish the baseline of students' knowledge related to plant nutrition, the three probes were administrated a week prior to the implementation. Then, a week after the implementation, the same three probes were administrated to assess students to establish whether they had developed the desired learning outcomes. To determine students' retention of learnt ideas, students were assessed a month after the implementation. It is acknowledged that a month is a short period to check long-term understanding. However, the time restriction for the field trip and school closure imposed the timing of the post-delayed test. The statistical significance of changes in students' responses was determined using McNemar's test[1].

Table 4.6: Learning outcomes

At the end of the teaching sequence, students should be able to:

- *Identify that:*
  - Plants make their own food via photosynthesis from inorganic components, carbon dioxide and water.
  - Plants use energy from sunlight to power the reaction between carbon dioxide and water.
  - The main product of photosynthesis is glucose, while oxygen is released as a by-product.
- *Explain what plant food is and how it is obtained:*

  Plants make (or produce) their own food (or glucose, starch, carbohydrate) from the raw materials available in the environment (carbon dioxide and water) through a process called photosynthesis.
- *Explain how photosynthesis explains plant biomass:*

  The extra biomass comes from the surplus food (or glucose, starch, carbohydrate) that plants make (or produce, form, obtain) through photosynthesis, with a small proportions of some minerals.

4.4 Data collection and analysis

A range of data collection techniques are usually used in design studies. These include: documents, paper-and-pencil probes, videos, questionnaires and interviews. In this particular study, the research was designed to evaluate the effectiveness of the design in terms of the match between the intended and implemented teachings (RQ 1), and the match between the intended and attained learning outcomes (RQ 2). In addition, there was an interest in the perceptions of teachers and students towards the design (RQ 3).

[1] McNemar's test (a type of Chi-Square) is mainly used to assess change before and after an intervention in which subjects are used as their own control (Cramer and Howitt, 2004).

To address these needs, main data were collected through videotaping the actual teaching and through assessing students' responses using three written probes. This data were used to answer RQ1 and RQ2. In addition, it was important to explore teachers' and students' perceptions towards the intervention to answer RQ3. Thus, interviews were conducted with students and teachers.

The secondary data collection techniques were the written classroom work, end-of-lesson quizzes, and teachers' diaries. Data gathered through these techniques were used to augment and triangulate findings from the main data. Detailed accounts of each technique used to collect data follow, together with the rationale for using the techniques, details of administration and the approaches used for analysis.

4.4.1 Videos of the actual teaching

RQ1 seeks to discover whether teachers' and students' actions proceeded as planned. The design intentions were summarised into seven KDFs, and the task was to find out whether they were followed by teachers and students. A straightforward method used to capture actions in the classroom is videotaping of lessons (Confrey and Lachance, 2000). Videotaping records what was presented in the classroom, how it was presented and how it was responded to. It also tapes teacher-student interactions while addressing a certain KDF. Bearing in mind the nature of this study, analysed interactions were used as supportive indicators of teachers' and students' actions, rather than in the interest of analysing the interactions themselves.

4.4.1.1 Videotaping the lessons

Prior to implementing the teaching sequence, I obtained oral consent from the teachers and I asked them, in turn, to obtain oral consent from students. During the implementation, a fixed camera was located at the back of the room, and was operated by the researcher. The focus was mainly on the teacher and the board more than the students. However, students' voices were recorded, and they were videotaped when they were responding to the teacher's questions or presenting their group's work. These technical decisions were applied to recording all five lessons, for each of the four teachers, making 20 lessons in total. Within each lesson, the videotaping excluded the beginning and end of the lessons where there was no actual teaching, as students were either entering or leaving the learning resource centre. Therefore, the length of each recording varied from 35 to 40 minutes, depending on how quickly the teachers started the lesson.

A threat to the validity of data collected from videoing lessons is that a video camera can create a problem of reactivity on the part of students and teachers (Cohen et al., 2007). In my research, it is possible that the presence of the researcher and the camera affected the behaviours of students and teachers. In my view, I can distinguish between two kinds of changes in behaviour that can be caused by the camera and/or its operator. The first is temporary in the form of students' interest and curiosity, which I believe disappeared within a few minutes. The second is that behaviours of teachers and students positively changed as a result of being videotaped, but there was no reason to assume that was the case in this study. Rather, the videotapes show cases where some students, who were right in front of the camera, were disengaged despite the fact they knew they were being videotaped. In addition, the teachers in the interviews confirmed that students were not affected by being videotaped.

The next section turns to describe how the videos were analysed.

4.4.1.2 Analysis of videos

The purpose of videotaping the lessons was to evaluate whether the teaching was implemented as intended by both teachers and students. Evidence from the actual implementation was used to answer RQ1 and to explain some issues related to assessing learning outcomes. Therefore, the focus was on teachers' and students' actions.

Roschelle (2000) suggests reducing the video data to the segments that represent the interesting events. To this end, the interesting events in this study were actions of the teachers and students in terms of the design decisions, as summarised in the KDFs (see Table 4.5). Also, teachers' and students' actions are defined in Chapter 2 (section 2.4.3.1).

The nature of this study and the purpose of analysing videos determined how the analysis was approached. Given that RQ1 seeks to establish the match between the intended and implemented teaching sequence, I needed to follow teachers' actions and students' engagements. As discussed in Chapter 2 (see section 2.4.3.1), descriptions of these actions are needed to compare them to the design specifications. Therefore, I decided to describe the teachers' and students' actions in terms of each KDF. The details of the descriptions varied amongst the KDFs depending on the teaching/learning activities assigned to a given KDF. Therefore, the descriptions may focus on the actions of teachers or students, depending on the nature of the activity and if it was directed at the teacher or students.

The procedure of the analysis started by determining the actions required for implementing each KDF. The actions were prepared in a list after reviewing the Design Brief and Worked Example. I watched each lesson in its entirety first to familiarize myself with its content and the voices of teachers and students. I then watched the videos focusing on the listed actions and made descriptions, in my words, of the actions of teachers and students and the time spent on them (see Appendix D for samples resulting from analysing the first lesson). These descriptions contained qualitative (e.g. how the actions happened; the ideas introduced etc.) as well as quantitative accounts (e.g. how many groups had participated, how many students presented a particular idea etc.). In addition, in the initial analysis I made judgements about the implementation of each activity by the teachers, as to whether the activity was fully implemented, partly implemented, replaced, or ignored. However, my final judgements concerned the KDF as a whole more than the single activities, although these judgements were informed by how the activities were implemented. I also gave specific details of teachers' actions if there was variation in their implementation. Otherwise, I refer to the teachers (as plural) to mean that they the four teachers implemented what is described.

I then compiled a whole description of each KDF from these descriptions. This step involved going back to the videos to check the descriptions and to add more details. In addition, the whole descriptions were supported, when appropriate, by excerpts from teacher-student interaction. As some actions involved using worksheets and responding to end-of-lesson quizzes, I supported the whole descriptions with qualitative and quantitative evidence from students' work. After the whole descriptions were compiled, I highlighted general issues arising from them. Results of the video analysis are presented in Chapter 5.

4.4.2 Students' written work

The teaching sequence included learning activities that the students were asked to perform in groups during the teaching. All the activities were supported by worksheets on which students recorded their discussion results; they were then reported to the whole class by a representative. Examples of these activities include formative assessments of "the nature of plant food", "the source of sweetness in fruit", "the implausibility of photosynthesis", and "the source of biomass based on Helmont's experiment". All the worksheets that were used in the activities were collected from students at the end of each lesson.

In addition, students were asked to individually respond to quizzes at the end of the lessons. Examples of these quizzes include "the nature of food" (to check how students define food), "food found in leaves" (to check whether students are aware of the conversion of glucose to starch) and the "bread making analogy" (to check whether students are able to consolidate factual knowledge related to photosynthesis). Details of the worksheets and activities are presented in Chapter 3.

The collected worksheet activities and quizzes were used as secondary sources to look for indicators of behavioural and intellectual engagement. According to Matsumura et al. (2002), “Analyses of student work can provide useful information about student learning” (p.208). Borok et al.’s (2005) report also that students’ written work can provide an accurate representation of students’ actions in the classroom.

4.4.3 Written probes

RQ 2 concerns the match between the design intentions, in terms of the desired learning outcomes, and the recorded learning outcomes. This match is mirrored in the evaluation model as *effectiveness 2*. Determining this match requires probing students' attainment of the desired learning outcomes, which were specified in the Design Brief (see Table 4.6).

As presented in Chapter 2 (see section 2.4.3.2), probes for assessing students’ understanding can be conceptually or phenomenologically framed (Driver and Erickson, 1983). In this study, both approaches were used. The first probe was conceptually framed to elicit students' knowledge in relation to the science curriculum, according to which students will be ultimately assessed. It was necessary to ensure that students attained the scientific content as presented in the textbook, which is directed to developing names of requirements for, and products of, photosynthesis. This knowledge is also a pre-requisite to be able to explain plant food and biomass through photosynthesis, which was assessed in the 2nd and 3rd probes. It was essential to use phenomenologically-framed probes in order to find out whether students were able to apply the learned knowledge in relation to phenomena and instances related to plant food and biomass.

With regard to the techniques used in the probes, an open-ended paper-and-pencil technique was advanced. Given that this study was not mainly concerned with characterising students' understandings, it was decided that using the paper-and-pencil form will be sufficient in assessing learning outcomes. In addition, a practical reason was related to the time limit of the scholarship, as I did not have sufficient time to conduct, for example, individual interviews to probe students’ understanding.

With regard to the source of the probes, as to whether they were derived from other studies or developed by the researcher, the topic of plant nutrition is one of the most researched biological concepts in terms of probing students' understanding. In many studies, researchers developed or adopted each other’s instruments. Therefore, I decided to adopt previously developed and validated probes rather than developing new probes, as long as they meet my purposes in terms of assessing students’ learning. Since the plant nutrition sequence was developed by EPSE project (Hind et al., n.d.), I turned to the probes that were used in the same project to assess students' understanding. I found that two probes fulfilled my purposes for assessing the first and third outcomes, while I designed another probe to assess the second outcome.

The next sub-sections describe how the probes were developed, translated, piloted, administrated, and the approaches that were used in the analysis

4.4.3.1 Probes used in assessing students' learning

Three learning outcomes were targeted in the teaching sequence (see Table 4.6). This sub-section presents each learning outcome and outlines how it was assessed by the written probes. It also presents how each probe was developed, the purpose it was intended to achieve, and its limitations.

- **The first learning outcome**

For the first outcome, students are expected to develop factual knowledge related to photosynthesis, that is, to know that plants combine carbon dioxide with water to synthesise glucose; that light energy is trapped to power the reaction, and oxygen is released as a by-product. To this end, there was no need to explain that glucose is used as a source for energy or to assimilate plant materials. The knowledge assessed will be factual in nature. Students' responses will reveal whether they: 1) had met the requirements of the school assessment which focuses on gaining the facts as presented in the textbook, and whether 2) the sequence had helped students to develop the factual basics to be able to explain plant food and biomass. Figure 4.2 presents how assessment of this learning outcome was addressed in the first probe, *Plant as a Factory*.

Figure 4.2: Plant as a Factory probe

Question 1

- Some people think a plant is a bit like a factory.
  - a) In the space below explain in what ways you think a plant might be a bit like a factory. (Use a diagram or a cartoon to explain your ideas if this is easier.)
  - b) If you are thinking of the plant as a factory, what is the most important part ? (e.g. root, steam, leaf, flower) Explain why you think this.
    - – The most important part is:
    - – The reason for my answer is:
  - c) Each factory produces a product/s, what is/are the main product/s that plants produce. Explain as much as you can.
  - d) In order that plants make this/these products, what do plants need? Use a diagram or a cartoon to explain your idea if this is easier.

The probe was adopted from EPSE, with slight modifications raised when it was piloted. The purpose of the probe is to find out if students have acquired basic factual knowledge related to photosynthesis, namely, what are the products and requirements. It starts by drawing an analogy between factories and plants, in the sense that they both make products (see Figure 4.2). It is intended to go beyond simple recall, so the reference is to the production features of photosynthesis, without directly naming the process. The reason behind leaving the probe open to students' interpretation, rather than making a direct reference to photosynthesis, was the common view of seeing photosynthesis as a gaseous exchange process by which oxygen retains its balance in the ecosystem. Therefore, students will decide for themselves the main product that plants make.

The probe consists of four items with spaces provided for open-ended responses; students are asked to justify their responses, and are encouraged to use drawings if they wish. The first two items are used as warm up stage intended to introduce the analogy of "*plant as a factory*" and stimulate students to think about the production features of photosynthesis. While the first item introduces the analogy, the second item encourages students to locate the production process in one of the parts of the plant. The pilot revealed that students were confused about the word "part" and were puzzled by there being more than one part of the plant. Therefore, the second item was modified by adding "the most important part" and by specifically naming root, steam, leaf and flower, as examples.

The third item starts with the fact that all factories make products, and students are asked to specify the main product that plants make, which is glucose. The fourth item is linked to the third item in which students are asked to specify what is required in order to make this product, namely carbon dioxide, glucose and light energy.

There was a limitation to this probe, however, with regard to the first two items when it was administrated in the pre-test. It seemed that students were not able to relate the probe to the context of plant nutrition, which affected how the students interpreted the probe. Another limitation related to the inter-dependency between the items, in that responding to an item required an understanding of the preceding item. Therefore, if a student, for example, could not understand the first two items, his chance of responding correctly to the third and fourth items might be minimised. The third limitation related to building the probe around an analogy. In fact, Saudi students are not accustomed to this style of indirect analogy-based question. Questions found in the biology textbooks are mainly directed to ask about factual knowledge. So, it is possible that students were struggling in the pre-test to determine what was really meant by the probe.

- **The second learning outcome**

The second learning outcome concerns an explanation of the source of plant food, which constitutes one of the key goals of the teaching sequence. To address this goal, the sequence offered activities to challenge students' ideas of plant food with regard to soil, water, fertilisers and minerals. In addition, the conceptual barriers that cloud students from seeing the plausibility of photosynthesis were addressed, and the fate of glucose as a source for energy was explained. A large proportion of teaching time was devoted to developing the view that plants photosynthesise food (glucose) from inorganic materials (carbon dioxide and water) taken in from the environment in the presence of light energy. As the sequence stressed the substances that are not food for plants, the students were required to *explain* the source of plant food based on photosynthesis, and also to distinguish this food from other substances which are not food (e.g. soil and water). To this end, the probe should present distracters and ask students to identify plant food and how it comes about. A phenomenologically-framed probe would serve this purpose.

Figure 4.3: The *Food* Probe

Question 2

- Three students were talking about plant food as follows:

  Ahmad says: 'I think that plants get their food from the soil.'

  Saleh says: 'I think that plants make their food'

  While Ali says: 'I don't think plants need food at all: only animals need food.'

– I think .... (choose one of the students above) is right, and the reason is:

....

....

....

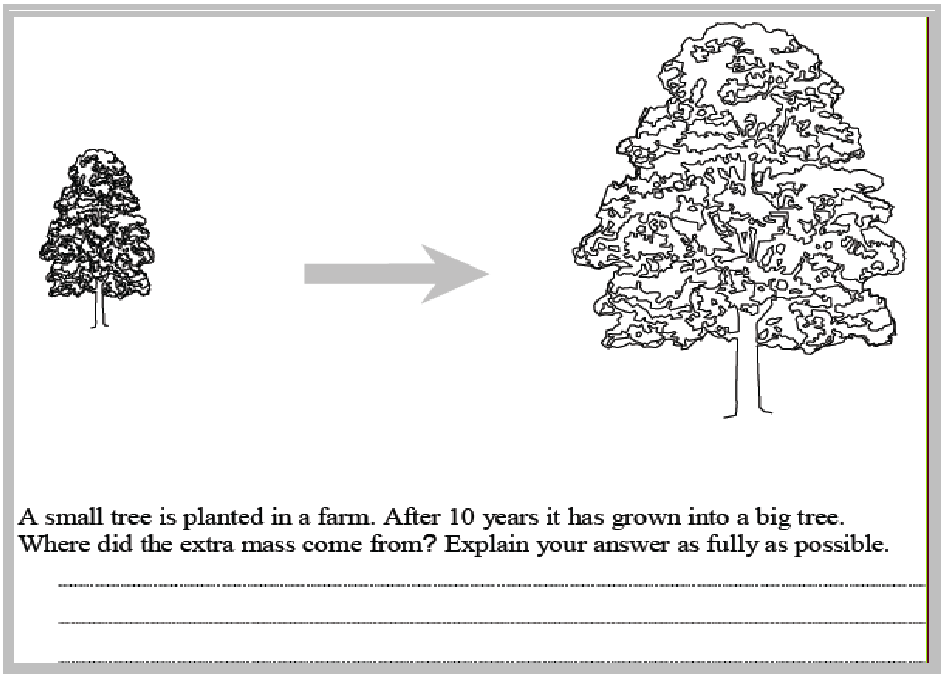
To assess students' learning, students are presented with three statements, two of which are based on students' common ideas that plants obtain food from the soil or that plants do not need food at all (see Figure 4.3). Only one statement refers to the scientific view that plants make their own food. Students are asked to choose the statement that they agree with, and justify their choice through an open-ended response. Due to the way the probe was designed, students need to specify the nature of food, and then explain how it is obtained.

- **The third learning outcome**

The third learning outcome is about explaining that biomass comes mainly from photosynthesised glucose. In the sequence, the photosynthesis model was used to account for the source of biomass. In addition, the sequence revisits the structure of a plant cell to show students how much glucose is invested in the chemicals of which the plant cell is made. At the end of the teaching, it is expected that students will be able to explain that the extra biomass comes mainly from photosynthesised glucose. Therefore, a phenomenologically-framed probe would be suitable to assess students in explaining the biomass that plants put on.

To assess students' learning, students are presented with a picture showing a small tree that has grown over 10 years to become a big tree (Figure 4.4). Specifically, students are asked to explain the source of the extra mass gained over the 10 years. It should be mentioned that a similar activity was used in the context of examining Helmont's conclusion that water is the source of extra biomass.

Figure 4.4: The *Biomass* probe



4.4.3.2 Translation, piloting and administration of the probes

The probes were translated into Arabic by the researcher. Then, the English and Arabic versions were sent to two doctoral students who are native Arabic speakers and fluent in English, who specialise in science education and TESOL. They were asked to review the probes in terms of the match between the two versions, their suitability for Saudi students and the wording of the questions. Based on their comments, the wording was slightly modified. In addition, the final Arabic version and the expected learning outcomes were sent to two Saudi biology educators, the two who reviewed the sequence, to check validity. They independently decided that the probes met the content of the learning outcomes.

Next, the checked and translated version was piloted with a class of 32 students who were in year 11 at the time of the pilot and whom had studied plant nutrition the previous year. The purpose of the pilot was to check clarity and determine the time required to respond to the three probes. Some modifications were made in light of the pilot. The second item of the first probe was modified by giving examples of the most important plant parts that help plants in their production. In addition, the second probe was modified by asking students to specify in writing the statement they have chosen instead of only ticking it. Students were also able to answer the three probes within 45 minutes, which is one lesson's time.

The probes were administered three times as pre-, post-, and delayed tests. Students from the four classes were given all the available time in a lesson (45 minutes) to respond to the probes on the same day and at the same time to prevent them from obtaining information about the tests from each other. The tests were introduced by the researcher, and teachers were blind to the probes before their first administration. Students were told that I was more interested in establishing what they think than in grading their responses. In addition, students were encouraged to ask for clarification if they did not understand the questions. Any clarifications were shared with all classes to provide equal opportunities. Students were supervised by their teachers during the tests, and were also encouraged not to leave questions unanswered. In cases where some students were absent, which were small numbers for each test, the teachers were asked to follow up by asking the students to respond to the tests. Therefore, the entire sample (131 students) responded to the three tests.

4.4.3.3 Analysis of the written probes

This sub-section describes the approaches used to analyse students' responses, how the coding scheme was developed and applied, and the reporting of the inter-coder reliability.

As presented in Chapter 2 (section 2.3.4.2), probes can be nomothetically or ideographically analysed. Given RQ2, the purpose of analysing students' responses in this study was to find out the extent to which they developed the desired learning outcomes. To this end, a nomothetic approach of analysis was appropriate to analyse students' responses. Therefore, conducting a detailed analysis that characterises students' ideas is beyond the scope of this study.

In addition to this qualitative analysis, a quantitative analysis was conducted to analyse the words that students used in their responses. It was assumed that an indication of the development of students' knowledge can be reflected by students abandoning words mostly associated with everyday views (e.g. soil, minerals, fertilisers) or starting to use words mostly associated with scientific views (e.g. carbon dioxide, light, glucose). For example, the word "soil" was commonly referred to amongst students when accounting for plant food or materials that plants need in order to make productions. Therefore, the regression of students' use of the word "soil" can be taken to be an indication of development towards the intended view. In contrast, an increase in the use of the word "glucose" can indicate how the students started to use the correct scientific terms when referring to plant food. As previously mentioned this analysis was used within the qualitative analysis rather than standing in its own.

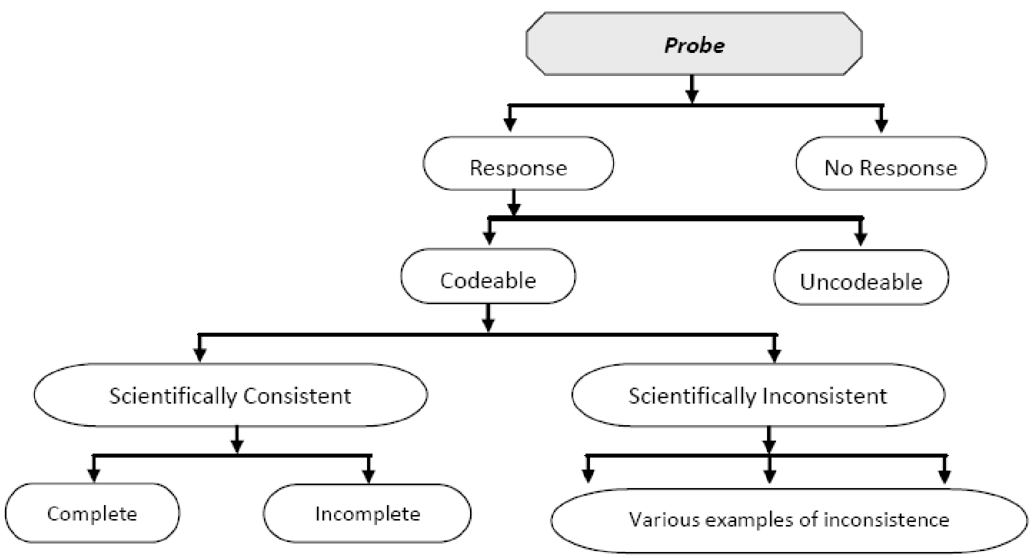
- **Developing the coding scheme**

Sorting students' responses into certain categories is an essential step when analysing data gathered through open-ended questions. With such categorisation, changes in students' responses can be traced over time. Choices behind the categories adhere to the type of evaluative outcomes. In this study, the focus was on finding out how effective the teaching was in meeting the study's aims (as specified in the learning outcomes) by assessing students' performances after exposure to the teaching sequence. This type of evaluation requires a nomothetic analysis (see section 2.4.3.2) of students' responses to be carried out to determine how successful students were in meeting the model answers. Within such a nomothetic analysis, students' responses will be categorised with regard to consistency/inconsistency with the scientific views, as specified in the model answers.

The coding scheme was developed through four steps:

1) I read through students' responses to the pre-, post- and delayed tests. This broad reading helped me to explore the nature of the data and start to think about choices of analysis.

Figure 4.5: categorisation of students' responses to the three probes



2) I was then concerned with developing a pre-defined nomothetic categorisation of students' responses in terms of consistency/inconsistency with the scientific view. Three main categories were defined, as Figure 4.5 shows, based on the rationale presented below.

A review of students' responses showed that some students left some, or all, of the questions unanswered. This constitutes the first level of the coding scheme that comprises two categories: *Response* and *No-Response*. Although this kind of response cannot be coded in any way, it is still useful to take them into consideration in order to discover how comfortable students were when responding to the probes. Then, a review of the *Response* category showed that it was not possible to code all replies, as some merely repeated or misinterpreted the probe, as the respondent had presented unrelated information. This type of response was denoted as *Uncodeable* and presented as *Others* when reporting the findings. Although such responses cannot be used to discover the extent of students' understanding, calculating them might reveal how clear the probes were to the students. Only the remaining responses, represented on the left side of Figure 4.5, were coded and were therefore used to measure students' attainment of the desired learning outcomes.

The codeable responses on the left side were coded either as *Consistent* (whether they were *Complete* or *Incomplete*), or *Inconsistent* with regard to the scientific view. The *Consistent-Complete* sub-category comprises responses that are in line with the model answer as stated for each probe. The second sub-category, *Consistent-Incomplete,* comprises responses that show a semblance of the model answer, although they do not fully cover all of its components. It is also essential that they do not show or imply any contradictions with the model answer. The reason for this sub-category (*Consistent-Incomplete*) is that the responses showed an understanding of the fundamental aspects of plant nutrition and only lack some details of factual knowledge. It should be mentioned that the *Incomplete* responses were very few when compared to the *Complete* responses.

Finally, responses that fall short of the criteria stated in one of the *Consistent* sub- categories were assigned to the *Inconsistent* category. Responses in this category might reflect erroneous views that explicitly or implicitly show contradictions with the model answer.

Although the basic organisation of the coding scheme was pre-defined, as the analysis is nomothetically-framed, assigning students' responses to the appropriate category emerged from students' responses themselves rather than, for example, from a logical predetermination that these types of responses will fall into this specific category. Students' responses were reviewed to precisely define each category with actual examples. This involved going back and forth between reviewing students' responses and refining the criteria for inclusion in a specific category until all criteria were defined and covered all the possibilities found in students' responses, so the boundaries between the categories were delineated as much as possible.

3) Once the draft scheme was developed, it was tested with samples of students' responses and changes and modifications were made as appropriate. Then, the coding scheme was applied for coding responses from the whole sample with regard to the three probes. In addition, I coded responses in terms of each probe across the three tests. It is assumed that working within each probe through the whole sample and across the tests will provide equal coding, as I coded responses at the same time and applied the exact same criteria.

Also I was not restricted to the wording used in the model answers. Synonyms are initially acceptable as long as they do not conflict with the model answer. If there was, however, a possibility that the synonym implied confusion or a potential misunderstanding, I searched for contextual signs to make sure that the student used the term accurately; for example, when the word "food" was used as a synonym for "glucose".

All the coding was conducted in Arabic and only the final calculations were provided in English. Examples of students' responses were translated by the researcher, and checked against the original Arabic responses by a post-graduate Arabic student in the field of science education, who is fluent in English and undertaking his doctoral study in an English university.

- **Inter-coder agreement**

The inter-coder reliability of analysing students' responses was measured by applying the coding scheme to 10% (16 students' responses were chosen randomly, four from each class) of the sample by an independent coder who was undertaking postgraduate study in science education. The coder was informed of the aims of the study, research questions and the purpose of analysing students' responses. Then, the coding scheme was fully explained. The coder was provided with all students' responses for the three tests. The unit of analysis was a student's response to a particular probe. After the chosen sample was coded, a comparison with the original coding was made and an overall agreement of 90% was reached.

The next sub-section aims to define the three categories with regard to the three probes, including the model answer, criteria for inclusion and corresponding examples.

- **Probe 1, *Factory Probe*: Requirements for, and products of photosynthesis**

Data presented here was gathered from students' responses to the *Factory Probe* (see Figure 4.2). The purpose of this probe is to assess students' factual knowledge of requirements for, and products of, photosynthesis. It consists of four items. The first and second items introduce an analogy (Plant as a Factory) as a warm up to stimulate students to think about photosynthesis without explicitly mentioning it, while the third and fourth items ask about the product(s) that plants make and the requirements needed. As the first two items are used only as an entry point to the next two items, the coding mainly focuses on the third and fourth items, which are specifically intended to assess requirements and products. Hence, as the third and fourth items focus on the same process (photosynthesis), responses will be analysed jointly as one item.

The model answer sought for this probe is:

> *Glucose is the main product that plants produce, and oxygen is released as a by-product. Requirements (things) needed for producing this main product(s) are carbon dioxide, water and light energy (sunlight).*

After this clarification, the categories to which students' responses were accordingly coded, criteria for inclusion and some examples will be defined.

1. Consistent with the scientific view

Responses included in this category are divided into two sub-categories: "*Complete*" and "*Incomplete*".

a) Consistent and complete

Responses coded in this sub-category should include components of the model answer. However, it is not conditional that responses follow the stated wording. Responses are acceptable as long as they include the essence of it. Below is an example of a response that was worded differently:

> *Glucose is the main product, which is plant food, and oxygen, which is a by-product, will be released out. Requirements needed are, carbon dioxide, water and sunlight energy* **Post-3-7**

Responses that replaced glucose with starch, sugar or food will be acceptable. Only the word food will be thoroughly checked to make sure that it was meant as a synonym for glucose (as explained above). Also, it is not required that students specify that oxygen is a by-product of photosynthesis. The order of glucose and oxygen is not a concern here, as it is quite difficult to assume that the item first mentioned necessarily reflects that the respondent thinks it is the essential product.

Alongside naming glucose and oxygen, some students added fruit and crops as other products. This did not affect the assignment of the response in this category. It is assumed that some students tend to provide as much information as they can to maximise their chance of providing an acceptable answer. This extra information did not affect the consistent responses as long as the information provided did not conflict with itself, or with the model answer.

The three requirements needed to produce glucose and oxygen must be provided to code the responses in this category. Replacing carbon dioxide with air and/or sunlight with heat will not be acceptable. Examples of acceptable answers were:

Carbon dioxide + Water, in the presence of light **Post-2-1**

Plants need raw materials which are a) carbon dioxide b) water and c) sun light **Post-3-19**

Adding soil, minerals, a clean and healthy environment, and caring as contributory factors still represent an acceptable answer.

Plants need water, carbon dioxide, light and minerals. **Post-4-22**

Plants need sunlight, water, carbon dioxide, and fertilised soils. **Post-4-16**

Provision of the chemical equation of photosynthesis is regarded as a "*Consistent*" response unless other parts of the reply conflict with the equation.

b) Consistent but incomplete

This sub-category involved responses that missed one of the requirements or products as specified in the model answer. It was essential for responses in this category not to show signs of conflict and/or ambiguity with the model answer (these will fall into the third category). Responses coded here appeared to focus only on glucose but missed oxygen:

Glucose results from photosynthesis. **Post 2-7**

However, in the case of responses that referred only to oxygen, the coding will differ. If there was a sign that the student perceived photosynthesis as merely a gaseous exchange process, then this was not coded in this category as it might reflect a misunderstanding of the purpose of photosynthesis. Otherwise, the response was coded in this category:

Oxygen; plants take carbon dioxide from the air, water, and light to meet requirements from the plants which results in oxygen **Post-3-30**

Similar to the first sub-category, adding soil, minerals and a healthy environment did not affect the coding of the response in this category. Also, if the term "photosynthesis" was added as an addition to the other two requirements, it was acceptable as long as the term was added as a clarification rather than a requirement *per se*:

Carbon dioxide + water + light (photosynthesis) **Post-3-30**

Replacements of the requirements were treated differently. If carbon dioxide was replaced with air, it was acceptable as long as other requirements were provided as necessary. The main concern was that students did not confuse oxygen with carbon dioxide as a requirement or name carbon dioxide as a product, which might reflect confusion with respiration. However, if there was a sign that air was regarded as a group of varied gases needed for photosynthesis, then it was coded as an *Inconsistent* response.

> *Water + light + air (photosynthesis)* **Post-2-4**

In addition, replacing sunlight with heat will not be acceptable, as it might reflect another misunderstanding related the concepts of energy, light and heat.

2. Inconsistent with the scientific view

This category involved responses that contain a conceptual contradiction of the model answer, or responses that did not account for the process of photosynthesis whatsoever. This appeared in different ways. For example, although requirements were mentioned, minerals, fertilisers and soil were thought to be as important as essential requirements, or photosynthesis *per se* was regarded as a requirement:

> *Plants need photosynthesis to produce food* **Post- 4-27**

Also in this category are responses that regarded air as a requirement for photosynthesis with confusion over what was meant by air. Here is an example:

> *Sunlight, water and air (oxygen and carbon dioxide) are needed to carry out photosynthesis* **Post- 2-2**

Another example of responses coded in this category is stating that plants produce food, which is not a synonym for glucose, and only to the advantage of humans in the forms of fruit, crops etc.:

> *Plants produce food and oxygen,… [this food is] absorbed from water and minerals found in the soil.* **Pre- 1-32**
>
> *Plants take in materials from soil and convert them into food* **Pre- 1-7**

Also responses naming oxygen as the only product produced by plants were coded in this category. They might appreciate the process of photosynthesis, but only as a gaseous exchange process, or they might perceive plants as living things that produce oxygen for the sake of humans:

> *From photosynthesis plants release oxygen for us which is used by mankind* **Pre- 1-13**
>
> *Oxygen; because plants absorb carbon dioxide and give us oxygen.* **Pre- 1-1**

3. Others

This category involved responses that misinterpreted the probe by focusing on the macroscopic view (environmental) of requirements which plants need such as fertilisers, minerals, water, care etc., or that focused on visible agricultural products such as fruit, flowers, vegetables and crops etc.

> *(Plants produce) vegetables such as lettuce, and fruit such as apples, oranges etc.* **Post-3-32**
>
> *The most important things are 1) water without which human, plants, and animals cannot survive; 2) a good climate combined with lands suitable for agriculture; and 3) the availability of air which plants use to grow.* **Post-4-32**

Also tautological responses or those leaving the probe unanswered will fall in this category.

- **Probe 2, *Food Probe*: the source of plant food**

Data related to this probe was gathered from students' responses to the *Food Probe* (see Figure 4.3). The purpose of this second probe is to assess how the students explain the source of plant food through photosynthesis using the related factual knowledge they have been taught. In this probe, students are presented with three statements regarding the nature of plant food and are asked to select the right statement and give a reason why they think it is correct.

A logical consideration of students' responses is that they fall into one of the following groups: right statement with correct explanation, right statement with incorrect explanation, wrong statement with correct explanation and wrong statement with incorrect explanation. It is simple to code the first and fourth responses as *Consistent* or *Inconsistent*. Only the responses in the middle might be problematic. To overcome this, the main focus was on students' justifications rather than the choice *per se*, as choosing the right statement does not necessarily imply that the respondent was able to correctly justify his choice. Therefore, the analysis focuses only on the justifications.

The model answer sought for this probe is:

> *Plants make (or produce) their own food (or glucose, starch, carbohydrate) from the raw materials available in the environment (carbon dioxide and water in the presence of sunlight), through a process called photosynthesis.*

Similar to the first probe, it seems that students' conceptualisation of food might differ from the scientific view, which requires careful coding. Therefore, use of the word food will not be acceptable unless signs were found to support the fact that it was used correctly. These signs could include relating food to photosynthesis, stating that food comes from carbon dioxide and water and refuting soil and minerals as plant food. However, if students referred to food that comes from raw materials, this was not acceptable because raw materials can include substances rather/more than the requirements needed for photosynthesis.

After this clarification, the categories to which students' responses were accordingly coded, criteria for inclusion and some examples will be outlined.

1. Consistent with the scientific view

Responses included in this category are divided into two sub-categories: "*Complete*" and "*Incomplete*".

a) Consistent and complete

This sub-category involved responses that state full and consistent answers regarding the source of plant food. As previously mentioned, the wording was not a concern as the students might use words that mean or lead to the required model answer. Below are two examples:

> *Plants themselves make food by combining water, absorbed from soil, with carbon dioxide, which comes from the air, and trapping light with chlorophyll to make food inside leaves, photosynthesis results in glucose and oxygen.* **Post-3-2**
>
> *Biology scientists suggest that plants are capable of making their food from raw materials available in the environment (carbon dioxide, water, sunlight), this food is glucose.* **Post-3-4**

Shorter responses were also coded here as they contained the essence of the model answer. These acceptable short answers might refer to glucose/food as product of photosynthesis, since glucose is produced from raw materials, and food is produced from raw materials:

> *Plants produce food by themselves through the photosynthetic process* **Post-2-4**
>
> *Because it [plant] produces glucose* **Post-2-6**
>
> *By combining carbon dioxide with water, with light from the sun, plants make glucose* **Post-2-21**
>
> *Plants make glucose through photosynthesis* **Post-4-3**
>
> *Because a plant makes its food from raw materials, which are water carbon dioxide and light, it's called "autotrophic"* **Post-1-7**

However, if the requirements of photosynthesis were listed as plant food, it was coded as *Incomplete* and assigned to the next category (see the next category). If the reference was only to the term "raw materials", the response will be coded *Inconsistent* as "raw materials" might refer to soil, water minerals etc.

Also, if the idea of obtaining food from the soil was refuted and the fact that a plant makes its food was generally emphasised, it was coded in this category. The reason for this is that it is clear that the student rejected the idea of obtaining food from the soil, which might reflect that he appreciated the process of food making.

> *Plants produce food by themselves, but don't take it from soil, because soil doesn't provide energy.* **Post-3-32/ 1-14**

Thus, using the term "autotrophic" was only acceptable if there was a sign of appreciating that plants make food by themselves through photosynthesis (see the example below). Otherwise, responses will be coded as *Incomplete* if there were no signs of either consistency or inconsistency, and it was coded as *Inconsistent* if I found a sign of conflict with the scientific view.

> *Plants are autotrophic, which means that they are able to produce food by themselves, carbon dioxide + water to give glucose* **Post-3-3**

b) Consistent but incomplete

This sub-category mainly involved responses that did not clarify the nature of plant food and/or where it comes from. However, it was essential for coded responses in this category not to show signs of conflict and/or ambiguity with the model answer (those that showed conflict were coded as *Inconsistent*). Responses coded here included perceiving plants as "autotrophic" with a general reference to the food making process. Although the response reflected an appreciation of this special way of making food, it did not state the nature of that food or how it is produced:

> *Plants are referred to as "autotrophic" because they make food by themselves from raw materials, and do not need help…* **Post-3-7**

Another example was when the requirements needed for making food were provided and plants were appreciated as "autotrophic". Although there was no reference to the food making process, which is essential to distinguish this "food" from substances taken in from the environment, the requirements were stated correctly and plants were appreciated as autotrophic:

> *Plants obtain food from raw materials available in the environment and it's called "autotrophic". The raw materials are carbon dioxide, water and sunlight.* **Post-1-12**

2. Inconsistent

This category involved responses that reflected a conceptual contradiction with the model answer in which photosynthesis and soil are both perceived as sources of food:

> *Plants feed through roots and by photosynthesis* **Post-2-9**

> *Plants obtain food from soil and photosynthesis* **Post-2-19**

> [2 statements were chosen] *plants take some of their food from soil and produce some.* **Post-3-30**

Another case was when there was no reference to making food. Rather, water, minerals, soil, fertilisers, sunlight and/or air were thought to be the only source for plant food:

> *Because soil makes plants grow, and the sun makes plants grow* **Post-3-36**
>
> *Plants obtain food from a number of sources which are: soil, water, minerals, fertilisers and glucose.* **Post-4-1**
>
> *Plants absorb water and minerals by themselves, and because of this they are called "autotrophic"* **Post-4-5**
>
> *Plants cannot make their food by themselves…they need food like people and animals, and soil provides energy and food.* **Post-4-11**
>
> *Plants absorb food from the soil, fertilisers and another things* **Post-1-38**

3. Others

This category contained responses that were only tautological or in which the probe was left unanswered. It was noticed in the second probe that not as many responses were coded as *Others* compared to the first probe. This might be ascribed to the level of clarity of this probe (i.e. direct not analogous), as well as its narrow structure.

- **Probe 3, *Biomass Probe*: Source of Biomass**

Data related to this probe was gathered from students' responses to the *Biomass Probe* (see Figure 4.4). The purpose of this probe is to assess how students will account for the source of extra biomass through photosynthesis using related factual knowledge they have been taught. Students are presented with a picture showing a small tree that has grown into a big tree after having been watered for 10 years, and are asked to explain where the extra biomass comes from. The model answer is:

> *The extra mass comes from the surplus food (or glucose, starch, carbohydrate) that plants make (or produce, form, obtain) through photosynthesis.*

The word "food" proved to be problematic, similar to the former probe. Meanings that students assign to "food" could be different from the scientifically acceptable definition. They might see soil, water, minerals, fertilisers, light and/or air as food. Therefore, the meaning of "food" was determined based on the contextual signs in students' responses. If the signs to either the correct or incorrect meanings are not found, then responses will be coded in the second sub-category (consistent but incomplete). After this clarification, the categories to which students' responses were accordingly coded, criteria for inclusion and some examples will be outlined.

1. Consistent with the scientific view

Responses included in this category were divided into two sub-categories: "*Complete*" and "*Incomplete*".

a) Consistent and complete

This sub-category involved responses that stated full and consistent answers regarding the source of extra biomass. The response should refer to making food, as well as the source of this food. Using interchangeable words is acceptable as long as they do not contradict the essence of the model answer.

> *The reason for the increase in tree mass is glucose, which is used in two ways; 1) to provide the plant with the energy needed for carrying out biochemical processes, and 2) to use the surplus to build up plant mass.* **Post-2-8**

If the response only referred to the photosynthesis process in general without explicitly mentioning food etc., then the responses were not coded in this sub-category, as the process alone does not account for the extra mass. Rather, it was coded as *Incomplete* and will fall into the next category.

b) Consistent but incomplete

This sub-category contained responses that did not explicitly state that the increase in biomass is due to glucose. Furthermore, it was essential for responses in this category not to show signs of conflict and/or ambiguity with the model answer (those which showed conflict were coded as *Inconsistent*).

Incompleteness can be indicated by responses that ascribe the extra biomass to photosynthesis as a process, with no reference to glucose or food, as long as there were no signs of explicit conflict with the scientific view:

> *The plant has grown up because it has completed the photosynthetic process.* **Post-2-17**
>
> *Photosynthesis is the main source for the tree growth.* **Post-4-25**

Also included in this category are responses which give the requirements needed for photosynthesis as a reason for the extra biomass. It seems that the respondent has some knowledge of photosynthesis and, at the same time, seems to be aware that soil, water, minerals etc. are not sources of extra mass:

> *It's carbon dioxide, water and sunlight that causes this tree to grow and become like this, and very few minerals are absorbed from the soil.* **Post-1-15**

Another case of incompleteness is when "food" is regarded as a source of the extra biomass with no references to either correct or incorrect signs regarding what the word "food" means.

The reason they are coded in this category is that a general statement that ascribes the extra biomass to food is scientifically acceptable. However, in the intervention, students were presented with an extended explanation and they were expected to provide it. An example for such a response is:

> *Food is responsible for the increase in plant mass; when food increases, the plant starts to become bigger.* **Post-2-2**

2. Inconsistent

This category involves responses that reflect a conceptual contradiction of the model answer when photosynthesis and soil are both perceived as sources of extra biomass:

> *Photosynthesis and water.* **Post-2-18**
>
> *Photosynthesis and keeping the plant well fed.* **Post-2-26**
>
> *There are multiple sources, some are: photosynthesis, respiration and absorbing water from soil.* **Post-3-18**

Another case is when there is no reference to photosynthesis at all. Rather, water, minerals, soil, fertilisers, sunlight and/or air are thought to be the only source of the increased biomass. In some cases, food might be referred to, but only as something taken in from the environment through roots. Examples that represent these cases are:

> *The reason is food availability in the plant's surrounding area.* **Post-3-12**
>
> *There are many factors, but water is the most important.* **Post-3-24**
>
> *The availability of raw materials and the farmer's care helped the plant to grow* **Post-1-1**
>
> *Roots absorb water and minerals then convert them into food, and over time the plant grows, exactly the same as people.* **Post-1-16**
>
> *Watering everyday and sunny conditions help plants to grow...but water is the source of life and if there is no water, the plant will only live for a day or hours.* **Pre-1-35**

Also, although some responses did not refer directly to obtaining substances from the soil, they did refer, however, to how the plant gains these substances. This was regarded as indirectly mentioning erroneous sources of extra biomass:

> *It's because of the capillary and transpiration-pull that transfers food to all plant parts, so stems, leaves and flowers grow and the tree increases over time.* **Pre-4-3**

3. Others

This category contains responses that focus on aspects that were not sought in the probe. Some responses concentrated on the plant morphology rather than the source of mass increase:

> *The mass became larger because of a large quantity of leaves, bigger trunks and its huge shape.* **Post-214**
>
> *Because of the trunk which is the tree's backbone, when it becomes bigger the tree will be bigger as well.* **Pre-2-17**
>
> *The source of increase is the large quantity of leaves, big branches, tall huge trunk and the growth of all plant parts, that is, roots, stems, branches, leaves and so on.* **Pre-4-34**

The focus of another case was on features which refer to living things, whether from a macroscopic (e.g. need for food and growth) or a microscopic point of view (e.g. cell division):

> *Plants are like people, when people feed they grow, so when the tree feeds it grows.* **Pre-3-34**
>
> *A plant is a living thing, and all living things grow, so plants grow.* **Pre-4-13**
>
> *It's due to the slow cell divisions over time.* **Pre-2-1**

Also some responses concentrated on the agricultural aspects that trees need rather than the process that happens inside the plant:

> *Things that plants need to grow up are fertilised soil, continuous watering, availability of sunlight and an open area.* **Pre-1-27**

Also tautological responses or replies which leave the probe unanswered will fall into this category.

- **Comparing changes**

In order to determine the effectiveness of the teaching sequence in meeting its aim, comparisons between students' knowledge gains across the three tests were conducted. Changes to students' gains were assessed individually, as each student was traced through their coded responses. Then, percentages were calculated for the whole sample to show students' movement amongst categories (*Consistent*, *Inconsistent*, *Other*) and across pre-test to post-test, then from post-test to delayed test. McNemar's test was used to assess the significance of changes amongst the three tests. Results of this analysis are discussed in Chapter 6.

The other method of comparing changes was conducted based on students' use of words mostly associated with scientific views (e.g. carbon dioxide, light, glucose) and words mostly associated with everyday views (e.g. soil, minerals, fertilisers). McNemar's test was also used to assess the significance of changes in using words across the three tests. Results of this analysis are discussed in Chapter 6.

4.4.4 Interviews

The use of interviews is advocated in cases where historical accounts are sought with regard to a particular event or activity (Robson, 2002). Interviews allow researchers to investigate what teachers and students think through multi-sensory channels and interactive information exchange rather than second-hand resources such as videos or written probes (Cohen et al., 2007).

Findings from interviews were used to address RQ3, which concerns how students and teachers responded to conceptual and pedagogical aspects of the sequence. It was believed that their direct views of the sequence will augment findings from other sources. The advantage of using interviews is that both students and teachers can directly point to issues that are otherwise difficult to disclose through videos or written probes. To this end, findings from interviews were used to depict how this particular sequence was perceived rather than delving deeply into teachers and students' general beliefs about teaching and learning. Both students and teachers were interviewed using semi-structured interviews with pre-prepared guided questions.

4.4.4.1 Interviews with students

The purpose of interviewing students was to explore their perceptions of the teaching sequence and to discover how they grade their performance; in particular, there was a need to establish whether there were concepts that they did not understand. A set of pre-prepared guided questions (see Table 4.7) were used during the interviews with different wording to make the interviewing informal.

Table 4.7: Guided questions used in students' interviews

1. Did you realise that the teacher's practice was different from his usual style of teaching?
    - What was new?
    - What was the same?
2. How do you rate your learning with regard to plant nutrition compared to other topics in biology? Better, the same, worse?
    - Which parts do you think you understood very well? "Look at your notes of the lesson".
    - Which parts do you feel you couldn't understand? "Look at your notes of the lesson".
3. Which of the following did you like or dislike and why?
    - Being aware of your ideas.
    - Group discussion.
    - Talking to the teacher and other students.
4. Which of the techniques above affected your learning, and in which way?
5. How do you see learning biology after experiencing the sequence?
    - Compare biology to other science topics.
    - What kinds of study skills are required?
6. Are there any ideas you would like to talk about?

The first question tried to detect whether students see any differences between the new approach and the usual practice. Here, the focus was on general issues related to the teaching sequence and the way students viewed it. In addition, there was an emphasis on similarities between the sequence and usual practices. After this introductory question, the focus turned to exploring specific issues related to learning and pedagogy. In the second question, the purpose was to bring up issues about students' own learning, including aspects that they feel they fully understood or did not understand. To help them recall these aspects, they were asked to use their classroom notes. Then the third question explored the pedagogical aspects, namely, eliciting ideas, group discussion and interactive teaching, and how they supported learning. These three pedagogical strategies represent the most apparent practices, and hence were targeted. The last question worked as a conclusion to the interview, asking students for an overall judgment inviting them to compare biology classes to classes of other subjects. The purpose was to see whether students realised the kinds of learning and teaching practices associated with the novel approach that was adopted in the teaching sequence.

4.4.4.2 Interviews with teachers

The purpose of interviewing teachers was to explore teachers' perception towards the content and pedagogic strategies that were used in the teaching sequence. A set of pre-prepared guided questions were used in the interviews (see Table 4.8). The guided questions started by asking the teachers about the differences between their usual practice and the new approach, and their feelings about themselves, their students and biology teaching. It was hoped that teachers' outline of these differences will reveal their general perceptions toward the sequence. Then the focus turned to the content of the teaching sequence, asking the teachers to judge, in view of their performance, the aspects of the content that were effectively or poorly taught, and the reasons behind their judgment. The third question concerned the pedagogic strategies used in the teaching sequence, namely, eliciting ideas, setting a conflict, using an analogy, groupwork and interactive teaching. The purpose was to bring up any demands made by these strategies and to find out, from the teachers' perspectives, how effective these strategies were in enhancing students' learning.

Table 4.8: Guided questions used in teachers' interviews

1. How did you feel about the idea of teaching plant nutrition in a way that differs from your usual methods?
2. How did you feel after you had implemented the design?
   - How did you feel about yourself?
   - How did you feel about your students?
   - How did you feel about teaching biology?
3. What aspects of the plant nutrition topic were effectively taught? Why?
4. What aspects of the plant nutrition topic were poorly taught? Why?
5. How do you think the following strategies contributed to promoting students' understanding, and in which way?
   - Exploring students' ideas, Setting a conflict, Using an analogy, Group discussions and work, Interactive talk.
   - Which of the techniques mentioned above were most challenging? In which way? For whom (you, students, the topic, time etc.)? And why?
   - Which of the techniques mentioned above were most effective, and why?
   - Which of the techniques mentioned above would you want to use in your teaching, and why?
6. How do you compare the sequence to your usual teaching?
7. How do you rate students' engagement with the sequence?
8. Are there any ideas that you would like to talk about?

4.4.4.3 Administrating the interviews with students and teachers

Research suggests that interviewing students differs from adults in that students are limited in their "…cognitive and linguistic development, attention and concentration span, ability to recall, life experiences, and what they consider to be important" (Cohen et al., 2007, p.374). In view of these characteristics, students were interviewed in groups in order to enhance their confidence and give them opportunities to comment on each others' views. The groups were classified according to their achievement in the post-test as high, average or low. Assignment into these groups was based on the total mark gained in the three probes. From each class, three students were interviewed from each achievement group, numbering 48 students in total (36% of the sample).

Students' interviews preceded teachers' interviews on the assumption that this would be more beneficial as the students may raise issues regarding teachers' performance, which could be discussed with teachers. Also teachers did not know which students were going to be interviewed in order to neutralize the teachers' authority on students' opinions. In addition, students were informed that their views will be used confidentially and neither teachers nor the school management team will know about them.

All the interviews were conducted after administration of the post-test during the school day by removing students from their classes. The same room was used to interview all students. To make the atmosphere informal, juice and sandwiches were served. Once students sat down, they were asked whether they were happy to be videotaped, and none of them objected. Then the interview started with an informal chat in order to make students feel comfortable. They were asked to respond to the questions one by one, and if there were any additions, they were asked to make comments. Also students were encouraged to disagree with each other, if they agreed with their classmates, they were asked to explicitly say so. However, students expressed agreement more than comments or disagreement. In addition, the high achievers' responses were more elaborate and richer, whereas the low achievers tended to give either short answers or only nod. In general, students' interviews lasted for about 15-20 minutes.

In terms of teachers' interviews, all the four teachers were interviewed individually during the school day when they did not have classes. The interviews started with informal chats to make the teachers feel comfortable. At the beginning of the interviews, they were encouraged to voice their opinions, whether they agreed or disagreed with the researcher's ideas or the ideas used in the sequence. I fully clarified that the aim of the study is not to report that the experiment had succeeded or not. Rather, it is about reporting what happened and how it happened. Therefore, I stated that their opinions are of high importance as they are the ones who taught the sequence and were very close to students. All the interviews were videotaped after obtaining teachers' permissions. The interviews lasted for about 30 minutes. Teachers' diaries were used during the interviews to stimulate discussions.

4.4.4.4 Analysis of interview data

The main aim of conducting interviews with teachers and students was to discover how they responded to the content and pedagogies of the teaching sequence. All interviews were videotaped and transcribed verbatim. The transcriptions were then qualitatively analysed by comparing similarities and differences within each group of students and teachers, supported by quotations from their oral responses.

In order to analyse teachers' interviews, I first worked on the transcriptions of the interviews by individually highlighting key points of interest in terms of the conceptual and pedagogical aspects of the teaching sequence as well as issues related to the Saudi context. I then converted and classified these points into headings and subheadings to compile an individual coherent story of each teacher supported by quotations from their own words. Finally, looking over the individual stories, I concluded by consolidating the key issues shared by the four teachers. Data from diaries were also used to augment teachers' interviews, when appropriate.

On the other hand, analysis of students' interviews was started by successively working on the transcriptions of each group comprising high, average, and low achievers, in order to highlight and label the key points raised by individuals relating to the conceptual and pedagogical aspects of the teaching sequence. The key points within each group were used to develop the group's story about the teaching sequence. Finally, from the groups' stories, I concluded with issues related to the pedagogical or conceptual aspects of the design, as well as issues relating to the context.

Quotations from teachers' words in the interviews were put between quotation marks (" "), within a paragraph if the quotation is less than two lines[2]. The source of the quotation (**T**1, **T**2, **T**3, **T**4) is put in round brackets ( ) at the end of the quotation, where the letter (**T**) refers to the teacher and the number distinguishes teachers as presented in Table 4.3. If I added my own words to make the quotation clearer, the insertions were italicised in square brackets (**[ ]**). When a part of the quotation was omitted, because it was not of interest, I referred to this omission by three dots (**…**) within the quotation.

The same codes were used in students' quotations. However, the only difference was in the letters used for the source of the quotations. The first letters whether (**H**), (**A**) or (**L**) stand for the groups, whether <u>H</u>igh, <u>A</u>verage or <u>L</u>ow achievers, respectively. The second letter (**C**) stands for the class and the digit refers to the class' number. The third letter (**S**) stands for the student and the digit refers to the student's number in the interviewed group.

4.4.5 Teachers' diaries

The purpose of using diaries was twofold. On one hand, to provide teachers with a tool that could aid them in detecting their perceptions and actions with regard to the design (Halbach, 1999), and on the other, to facilitate them in externalizing their views about the sequence at the time it was implemented. Research criticizes teachers' diaries for being largely subjective (Taber, 2007). However, in this study they were only used to stimulate teachers in the interviews and as a secondary source to triangulate with other findings. To this end, they were not used as a primary source in making any claims.

Table 4.9: Guidelines for diaries

Your thoughts will be helpful in establishing several aspects of the design. Please use this pocket notebook before and after each lesson in order to record issues and insights related to: – Reactions to the lesson as a whole. – Descriptions of something interesting or annoying which happened during the lessons. – Arguments for/against some aspects of the lesson (activities, techniques, ideas, content etc.). – Discussions with your students, regarding the new ways of teaching. – Discussions with other colleagues.

To help organise the diaries and keep them focused on particular aspects, teachers were provided with guidance (see Table 4.9) and a small pocket-sized notebook for each lesson. Each page of the notebook was specified for each lesson in order to record students' reactions to the lesson, unusual observations irrespective of whether they were regarded as good or bad, any thoughts that came to mind during the teaching, and thoughts from discussion with students or colleagues.

Administrating the diaries

After the preparation was complete, diaries were handed to the teachers. They were asked to report their thoughts lesson by lesson regarding the implementation. All the teachers accepted this task without hesitation. However, when they were asked to submit their diaries they required more time to finish them up. So, it is open to question whether the teachers actually did report their thoughts lesson by lesson, or if they reported their thoughts just before returning their diaries.

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[2] As specified in the University of Leeds Research Handbook.

4.5 Quality of the research

Guba and Lincoln (1985) suggest employing criteria to ensure quality when conducting a qualitative study. These criteria include: credibility (confidence in the truth of the data), transferability (findings can be applied in other contexts), dependability (findings would be similar if the same study was repeated by another researcher) and conformability (interpretations and conclusions can be traced to their sources). This section presents how these criteria were met in this study.

The credibility of the research findings are enhanced by several kinds of triangulation. Firstly, triangulations of sources (data obtained from teachers and students, from four different classrooms, and two schools) and types of data (videos supported by classroom written work and teachers' diaries, written open-ended probes, interviews augmented by teachers' diaries). Secondly, data were gathered using multiple methods (video, written probes, students’ written work, interviews and teachers’ diaries). Thirdly, combining qualitative (video, interviews) and quantitative analyses (written probes).

Dependability and conformability were established by presenting detailed accounts of the methodology including methods, instruments and procedures for data collection. In addition, explicitly specifying the Design Brief, including justified design decisions that enable others to check the domain-specific guidelines or replicate the design according to its rationale. Thus, excerpts from teachers’ and students’ interactions and opinions were provided when analysing videos and interviews. All these details might help reviewers who want to follow the research findings through their own tracking and interpretation, whether to check the claims made or to reinterpret the data according to their views.

Finally, the transferability of the research is enhanced by providing detailed accounts of the model used for the design, including explicit and justified specifications of the Design Brief, description of the Worked Example and outlines of the lessons and activities. In addition, descriptions of implementation are provided to consider circumstances and constraints.

4.6 Ethical issues

Ethics in the context of research refer to the rules for conducting the research (Robson, 2002). In the first instance, I obtained official permission to conduct this study in the schools, including performing tests and interviews. In addition, I was honest and faithful with the teachers and students who participated in the study, and I informed them that the purpose of my study is to obtain a doctoral degree.

I was aware that such a design study might put some pressure on teachers, as they were asked to implement a novel teaching sequence that might differ from what they usually do, and there was a possibility of falling short of implementing the sequence as intended. I reassured the teachers that the implementation has no negative consequences on their professional status, and the names of the schools, teachers and students will all be symbolic.

Written informed consent from participants is always required in social research (Cohen et al., 2007). I prepared the forms that specify teachers' rights and the work required. However, the teachers did not want to sign the forms. They suggested that their oral agreements to participate in the study were sufficient. It is understandable because in Saudi culture we do not tend to use written forms with regard to such activities. Obtaining permission from the Educational Directorate was sufficient.

In addition, I paid sufficient attention to the ways in which the data was stored. Firstly, the papers that contain written responses were stored separately from the keys that link the students to the responses reported in the research. In addition, teachers' diaries and field notes of the lessons did not link to a specific teacher as they were only marked with symbols of a letter and a digit (T=denotes the teacher, and the digits 1, 2, 3, and 4 correspond to the four individuals). The digital data (videos and documents) are only marked with symbols of the teachers and students and the keys that lead to them were saved in separate files. Given these precautions, it is unlikely that the names of the participants can be revealed.

The next chapter (Chapter 5) begins to present findings related to implementation of the teaching sequence, which answers RQ1. The main source of the findings is the videotaped lessons.

CHAPTER 5: EVALUATING THE ACTUAL IMPLEMENTATION OF THE TEACHING SEQUENCE

This chapter follows the actual implementation of the teaching in order to establish effectiveness 1 as reflected in the evaluation model, which in turn will answer RQ1. The actual implementation is traced with regard to the seven Key Design Features (KDFs). The rationale behind each KDF is presented as described in the Design Brief, followed by the related teaching/learning activities as specified in the Worked Example, and a description of how these activities were implemented by the teachers and students, together with some reflections. Finally, this chapter concludes with an overview in order to determine the extent to which the actual implementation met the intended teaching.

5 Chapter 5: Evaluating the actual implementation of the teaching sequence

5.1 Introduction

As mentioned in Chapter 2 (see section 2.5), the first RQ aims to investigate "*To what extent was the planned design implemented as intended?*" The purpose of this chapter is to answer this question by analysing data from videotaped lessons, augmented by written classroom work. In addition, links are made, when appropriate, to findings from students' responses to written probes, students' and teachers' interviews, as well as teachers' diaries.

As suggested by the evaluation model, the implemented teaching sequence was evaluated against the planned version in the Design Brief and Worked Example. Chapter 4 (see section 4.4.1) described the procedure I followed in tracing the implementation from the videotaped lessons and written classroom work, limiting my focus to the seven Key Design Features (KDFs), which summarise essential design decisions in the teaching sequence, and therefore form the basis for an evaluation of whether design intentions were actually implemented.

Following this introductory section, this chapter is structured into eight main sections. The first seven sections follow the implementation with regard to the seven KDFs. Each section begins with a brief reminder of the rationale of the KDF, as described in Chapter 3 (see sections 3.4.1 to 3.4.7), and the specified teaching/learning activities as presented in the Worked Example. Next is a description of how the teachers enacted the activities related to this feature, which is taken from the videos. In addition, evidence from the videos and collected classroom work of students' actions and engagement is also examined. At the end of each section, a reflective conclusion is provided to determine the match between what was planned and implemented. My reflections will evolve around the content (i.e. scientific ideas that teachers were asked to introduce), pedagogy (i.e. specified pedagogic strategies and modes of interaction), and assumptions advanced in the Design Brief (i.e. students' starting points and anticipated responses).

The final section pulls out the key issues that were discussed within each KDF to make a general judgement on the match between what was planned and what was implemented with regard to the content that was covered, pedagogies that were used and modes of interactions, and the validity of the assumptions advanced in the Design Brief.

5.2 KDF 1: Eliciting students' ideas and establishing a scientific definition of food

One of the identified learning demands concerns the way students conceptualise food (see section 3.2.3). While in school science plant food is defined as organic substances (e.g. glucose) used as sources for biomass and energy, students regard food as anything taken in from the environment to keep plants alive and healthy (see section 2.2.3). To this end, the Design Brief addresses (see section 3.4.1) this learning demand through conducting a formative assessment and use of interactive/dialogic talk to make students' aware of their ideas, as well as to inform the teacher of students' starting points. Once students' views are brought into focus, the teacher guides students to establish a scientific definition of food, and then sets a conflict between their ideas of food and the scientific definition, before introducing a simple model of photosynthesis.

This is addressed in the Worked Example (see section 3.4.1) through the following activities:

1. Conduct a formative assessment to elicit students' ideas of the function of food and substances that can be called food, employing interactive/dialogic talk with the whole class. Students' ideas regarding the function of food will be elicited within a human-related context to make the concept seem more sensible to students as they begin with a topic familiar to them.
2. Once these ideas are externalised, the teacher uses the fuel analogy to help students differentiate food based on energy-supply. To give students opportunities to practice the scientific definition of food, and to check students' understanding, a quiz is planned at the end of the lesson.
3. After establishing the definition of food, the teaching moves on to elicit students' ideas of the nature of plant food, using a formative assessment conducted in small groups.
4. In order to show students the limitations of their ideas, the teacher sets a conflict using the source of sweetness activity.

With regard to teachers' enactments of the first activity of eliciting students' ideas about the function of food, it appears from the videos that the teachers followed the Worked Example, asking students to respond to the questions "Why do we need food?" and "What is food?" The teachers gave students opportunities to air their ideas while recording them on the board. Afterwards, the teachers raised the question asking students to suggest examples of substances that can be food for humans. As Excerpt 5.1 shows, it seemed that the teachers succeeded in externalising students' ideas of substances that can be called food. On the other hand, this excerpt shows that students' responses matched those that have been documented in the literature, as anticipated in the Design

Brief (see section 3.4.1). During the interactions with students, teachers tended to collect students' ideas and share them with the whole class; yet, they did not ask for elaboration or clarification. Excerpt 5.1 highlights an example where one of the students suggested "iron" as a type of food. The teacher did not ask for a justification "Why iron?" Even when the teacher asked for clarification or justification when one of the students suggested "oxygen", he did not elaborate to the extent of making the student's idea sufficiently clear.

Excerpt 5.1: T4: things that can be called food (T=Teacher, S= Student)

After exploring students' ideas about the importance of food, the teacher moved on to explore their ideas of the nature of food.

T: …now we need to know what things we can call "food", or what is food? (*Students raise their hands*), OK, you at the end,

S1: minerals,

T: hah, another thing?

S2: carbohydrate,

T: what is carbohydrate? What does carbohydrate mean?

S3: they are sugar (*the teacher writes on the board sugar*)

T: can anything else be called food?

S5: vitamins

T: a fourth kind of food? Someone hasn't participated yet,

S6: proteins

(The teacher stops to repeat the responses that are written on the board)

T: anyone who can add?

S7: vegetables and fruits,

T: hah , more!!

S8: water

T: excellent, anything rather than water, hah guys,

S9: fat

T: does anyone have an addition?

S10: iron

(The teacher pauses and looks surprised, but didn't ask for elaboration)

T: ok, any other ideas?

S11: maybe the sun, can we call it food cuz it provides energy?

T: ok, you at the end, the last contribution,

S12: oxygen

T: *(pauses with a surprised look)* why oxygen?

S13: cuz oxygen comes with water,

(The teacher ignores the student's justification and starts to sum up what is written on the board)

In terms of students' engagement with the formative assessment, videos showed that they engaged with teachers' questions through a question-short-response mode. As recorded in the videos, most of the students' hands were raised, asking permission to answer the question of why we need food. In addition, students' responses were directed to the question, which might suggest that they were intellectually engaged (see Excerpt 5.1). Video data also showed that most of the students were in a position to link food to energy, which wasn't anticipated in the Design Brief. Some of them went further to specify that food is needed to carry out biochemical functions and growth. Others added that it is necessary to repair damaged tissues. However, some students still offered non-functional explanations of the importance of food as they said "Food is needed to keep us alive and healthy".

When it came to the question "What things that we can call food?", some of the students generalized the concept of food to include anything the body benefits from, or things needed to supply energy and/or for growth. However, most of them could not link food to energy, as they did earlier. Instead, they tended, as reported in the literature (see section 2.2.3), to consider substances taken in to be food, irrespective of the energy-supply. As shown in Excerpt 5.1, vegetables, fruits, minerals, vitamins, water and even sunlight and oxygen were examples of their responses. Moreover, other examples included "carbohydrates", "fats" and "proteins", which are consistent with school science. This mixture of scientific and everyday ideas might suggest that students were not clear on how to differentiate food.

Then the teachers moved to the second activity, to differentiate food. The teachers drew an analogy with car fuel to show students that, while many things are necessary and fundamental to make cars work, only "fuel" can provide the energy that makes the car move (Excerpt 5.2 below shows how T1 drew the analogy). Once the analogy had been drawn, the teachers returned to students' ideas of food and examined them based on the energy-supply criterion.

Excerpt 5.2: T1 : Drawing an analogy to define the nature of food

T: we need now to discuss the things you have said to establish if they are really food for plants or not. We've a simple example… plants are much like a car, it needs many things which are indispensable, and if one is missing the car stops.
S1: essential things
T: beautiful, yes essential things. The car needs the oil to decrease the engine's friction (the teacher went on to elaborate), water in the radiator to cool down the engine's heat, otherwise the engine will burn (the teacher went on to elaborate), ok, then the petrol, focus here, that produces energy to make the car move. It's like this, the plant needs different things. So, what does a plant need? Plants need water to function as a medium for biochemical reactions (the teacher went on to elaborate). Plants need fertilizers and minerals that contribute to making proteins and enzymes and make the plant healthy, but where is the plant food that provides energy? In the car, for example, what provides energy?
S2: petrol
T: ok, where is the plant food? Can water, minerals, soil, and fertilizers be food for plants?
Sg: Yes, (several voices).
S3: partly yes.

T: ok, let's go back to the central criterion, we mean by a "criterion" something that we obey and follow. Are these providing plants with energy? Any substance whatever it is, if it provides energy, it means that it's food *(pause to encourage students to respond)*

To establish whether the students made sense of the fuel analogy and understood the scientific definition of food, they were asked to respond to an individual quiz. Students were asked whether the IV glucose injected in patients is food, and to justify their answers why (see section 3.4.1). About 53% (*n*=69) of the students said it is food and energy supply was mentioned in their justifications, 45.5% (*n*=60) considered it to be food, yet, they did not mention the energy supply in their justifications, and only 1.5% thought that it is not food. Although it is not possible from students' responses to this quiz to claim any improvement in students' understanding of the definition of food due to the lack of baseline data, a number of responses did refer to the teaching. For example, one student wrote, "*Since we said* [in the lesson] *that food is any substance that provides energy, glucose provided in the IV is food*"(Ausamah, T2's class). Another student defined food regardless of how it was taken "*It's not necessarily that something taken through the mouth to be called food as long as it supplies energy*" (Eisa, T3's class). Such examples may indicate students' engagement with the analogy drawn by the teacher in order to develop a definition of the nature of food.

The teachers then moved on to the third activity concerning eliciting students' ideas regarding "The nature of plant food". Students' ideas were collected and recorded on the board, and later summarised by the teachers. With regard to students' engagement with this formative assessment, the collected classroom work showed that students were behaviourally engaged with the task and all the activities worksheets were filled in. Examples of their ideas of plant food included: water, minerals, sunlight, air, fertilizers and photosynthesis, and some also mentioned that plants eat insects. Only a few said that plants are autotrophic so they photosynthesise food. However, some wrote photosynthesis alongside the other substances that are taken in from the soil through roots. For example, one of the group wrote "*Plants feed in several ways; photosynthesis and through roots*" (T1's class). Another group wrote "*Most of plant food comes from the soil*" (T2's class). These examples confirm the prediction in the Design Brief regarding students' likely starting points (see section 3.2.3).

Afterwards, the teacher introduced the fourth activity (the source of sweetness) that aimed to challenge students' ideas regarding plant food and then to prepare students to consider the simple model of photosynthesis to explain the sweetness found in fruit.

With regard to students' engagement with the activity that was set to conflict with their ideas regarding plant food, videos showed that students were active and motivated to answer teachers' questions and to work and participate in groupwork. Furthermore, the collected classroom work showed that students' ideas could fall into one of two categories. Firstly, students who had mixed views that include inorganic materials and photosynthesis as source of sweetness (most of T1 and T2 students). They suggested that the sweetness comes from glucose produced by photosynthesis. For example, a group of T1's class wrote:

> *"Plants carry out photosynthetic process in which a reaction happens between carbon dioxide and water to produce oxygen and starch (glucose). This glucose gives fruits the sweet taste".*

In addition, although they defined photosynthesis as a reaction which happens inside the plants and produces glucose or carbohydrates, they were uncertain about the requirements needed for photosynthesis because they included minerals and fertilizers as reactants. Below is an example taken from students' classroom work:

> *Plants absorb water and minerals from the soil and carbon dioxide from the air to form complex substances like carbohydrates and glucose that gives the sweet taste found in fruits.* ***(T 3' class).***

On the other hand, the second group thought that materials taken in from the environment are sources of the sweetness (most of students of T3 and T4). For example, one of the groups wrote "…*the plant makes sugar from substances found in the soil as well as water*" (T4's class). Moreover, some simply suggested carbohydrates without reference to how plants obtain them.

Videos showed that the teachers varied in how they followed up and made use of students' ideas. Although the four teachers followed the scenario offered by the Worked Example to challenge students' ideas and bridge to photosynthesis as a possible explanation, T1 and T2 simply stopped at collecting students' ideas and did not comment on them. This is because most of their students suggested photosynthesis. As T1 recorded in his diary "*Students arrived by themselves to the desired conclusion* [photosynthesis]". Maybe he did not see the point of following up on students' ideas as they had already reached the desired conclusion. It seemed that the teachers were prepared to receive ideas that conflict with the scientific view rather than ones that agree with it, so they did not expect that number of students to suggest photosynthesis. However, they did not probe students' understanding of what they meant by "photosynthesis".

On the other hand, T3 and T4 made use of the responses which referred to photosynthesis. They smoothly shifted the discussion to serve the next teaching step in which photosynthesis was presented as a possible source. They also kept linking the alternative explanation to the student who proposed it to emphasise that "photosynthesis' was suggested by the students themselves rather than the teacher or scientists. Excerpt 5.3 shows how T3 employed a whole class discussion through interactive/dialogic talk. When he came to introduce photosynthesis, he asked about agreements/disagreements with this view. He then ended with the suggestion of photosynthesis as a possible explanation for the source of the sweetness found in fruit.

Excerpt 5.3: T3: Where does the sweetness come from?

Students tasted the grapes and read the dialogue for the activity of "Where does the sweetness come from?" The teacher asked students if they thought about:
T: Where does the sugar come from?
S1: from water
T: ok, from water
S2: from minerals
T: from minerals, hah, anything else?
S3: reactions happen inside the plant to produce sugar, I mean water, minerals and fertilizers operate together to produce sugar.
T: anyone who agrees with this fellow, there are reactions inside the plant that produce sugar!!
(about eight hands were raised)
T: any additions or extra information?
S4: yes, photosynthesis… water combines with carbon dioxide to form carbohydrates like glucose.
T: do you mean that photosynthesis is the source of sugar found in fruit?
S5: yes,
T: anyone who agrees *(about eight hands were raised)*
T: who disagrees *(about five hands were raised)*
T: because there is agreement and disagreement, we will take this as a possible explanation for the source of sugar found in fruit.

- **Reflections on teachers' and students' actions**

With regard to the content specified in the Worked Example, the teachers covered the required content related to differentiating food in terms of energy-supply. In addition, after eliciting students' ideas of food for plants, the teachers set a conflict with the purpose of challenging students' ideas, and then guided them to apply the energy-supply criterion to the context of plants and asked them to then consider whether water, minerals and fertilisers can be classified as food. It seemed that, after introducing these ideas, students were in the position of acknowledging that inorganic substances cannot be classified as food for plants and cannot be sources of the sweetness found in fruit. Therefore, they were looking for another possible source for the sweetness.

With regard to the pedagogical aspect of the design, the teachers conducted the required formative assessments and introduced the specified analogy. In addition, they made efforts to employ interactive/dialogic talk in eliciting students' ideas concerning the concept of food and its function, and the nature of plant food. Yet, as Excerpt 5.1 shows, they tended to collect students' responses rather than elaborating or asking for clarification or justification. For example, in Excerpt 5.1, the teacher did not comment on students' responses (e.g. *cuz oxygen* *comes with water*) or ask for clarification even if responses were not clear. A possible reason for not asking for elaboration is that the teachers were asked in the Worked Example not to correct or provide evaluative feedback on students' responses, so they mainly focused on collecting and sharing students' ideas. Another possible explanation is that the teachers were mostly looking for expected erroneous views, which were discussed in the introductory sessions and the Worked Example. Therefore, the teachers unintentionally welcomed the expected views, as they simply met their criteria. Despite these limitations, the videos, as well as groups and individual classroom-work, indicate that students were behaviourally engaged with the tasks, as well as intellectually engaged with the ideas. With reference to the latter, some students asked for clarification (see Excerpt 5.2 when P_{11} asked if the sun is food as it provides energy) and tried to justify their ideas (see P_7 and P_8 responses, Excerpt 5.1) and re-assert ideas presented by the teachers (P_1 in Excerpt 5.2).

In terms of the validity of the design assumptions and decisions advanced in the Design Brief, from what is presented above, it seems that most of the students expressed misunderstandings of the concept and function of food, as was anticipated in the Design Brief and Worked Example. Yet, some students were in a position to link food to energy in an attempt to conceptualise food, which was not anticipated in the Design Brief. As such a view cannot be developed without previous teaching, this suggests that the conceptual analysis was not as accurate as it should be in taking account of previous lessons that dealt with the concept of food. Considering the large number of students who could not link food to energy in the context of plants, this corresponds with assumptions made in the Design Brief that there is a learning demand should be addressed with regard to differentiating food based on its function as a source of biomass and energy before the introduction of photosynthesis.

Similar to some students' success in linking food to energy, others were also aware of photosynthesis as a source of sweetness. Apart from the need to conduct an accurate conceptual analysis, there is another issue related to refining the Design Brief to consider more than one scenario. As mentioned above, T1 and T2 did not expect that students would suggest "photosynthesis" so they ended the lesson assuming that students achieved the desired view. It seems that my focus in the Design Brief was devoted to the most likely teaching scenario and I ignored possible alternatives, like the case of some students suggesting photosynthesis as a source of sweetness. Maybe it might be more efficient when refining the Design Brief to plan more than one scenario to be used by the teacher according to students' responses.

5.3 KDF 2: Introducing a simple form of photosynthesis

After establishing the scientific definition of food, and challenging students' ideas of plant food for the purpose of making a need for learning, a simple reduced model of photosynthesis is introduced. As discussed in the Design Brief (see section 3.4.2), the model is reduced to help students grasp the essence of photosynthesis (reactants needed to produce sugar). Furthermore, the Worked Example suggests that the teacher introduces the model by restating students' ideas regarding plant food and how they are limited in explaining the source of the sweetness. Then, with a sceptical tone, the teacher indicates that some people (*not necessarily scientists*) suggest that plants are able to produce sugar by themselves. Next, the teacher states that this explanation (*without describing it as scientific*) needs to be considered and questioned.

With regard to teachers' and students' actions, videos show that this phase of the teaching was smoothly presented. The teachers followed the Worked Example and reduced photosynthesis to the reactants (carbon dioxide and water) and to the main product (glucose). In the case of T3, for example, following the discussion emerging from the previous activity regarding the source of sweetness, he presented the simple model and asked students who agreed to raise their hands, followed by those who disagreed. Students in general were in agreement with the model rather than rejecting it. Furthermore, as Excerpt 5.4 shows, the teacher was keen to address any rejections of the simple model before delving into a discussion of the model itself. One of the students who rejected the concept was confused by the meaning of "sugar" because he thought that sugar is not a carbohydrate, and the other suggested that soil is needed alongside carbon dioxide and water in order to produce sugar. In the case of soil, the teacher did not explain further, perhaps due to the problematic aspect of the role of the soil in plant nutrition.

Excerpt 5.4: T3: introducing a simple model of photosynthesis

Working on one of the student's suggestions of photosynthesis as an explanation for sweetness, the teacher invited the whole class to consider this explanation and elaborated with more details of reactants (carbon dioxide and water) and the product (glucose); he then said:

T: so, do you accept this view? We need to discuss this!! Ok, people who agree raise your hand up (some did), and people who reject it, raise your hand up (some others did), ok, people who disagree, why is that?

S1: when carbon dioxide and water combine they form carbohydrate not glucose

T: ok, but sugar is actually carbohydrate, so, do you agree now? Aren't you in agreement?

T: ok, who disagrees?

S2: I suggest we add soil alongside carbon dioxide and water

T: ok, we can consider that as well.. now it seems that this is a possible explanation worthy of consideration, and that is what we will do in the next lesson

- **Reflections on teachers' and students' actions**

Given what is described above, it seems that all the teachers introduced all the required content related to the simple model of photosynthesis. In addition, the smooth transition towards accepting photosynthesis as a possible explanation can be considered to be an indicator of the success of the preceding activities, as they created a need for learning and helped students to become open to accepting photosynthesis as a possible explanation. Yet, this can be challenged by the earlier responses that referred to photosynthesis, as they might suggest that some students were already aware of photosynthesis due to previous teaching rather than the effect of the preceding activities. However, mentioning the correct words is very different from offering explanations or even understanding explanations. With regard to the specified pedagogies or assumptions advanced in the Design Brief, no specific reflections can be raised here because this phase of the teaching was short and more dependent on the teachers.

5.4 KDF 3: Addressing the causes of the implausibility of photosynthesis.

As previously mentioned (see section 3.2.3), students usually find it difficult to accept that a solid can be formed from combining carbon dioxide and water. This might be due to a lack of understanding of the pre-requisites related to the concept of mass and cycling of matter. In particular, students might find it difficult to apply these concepts in a living context. To this end, there is a learning demand to help students *recognise* that matter can be cycled in different forms, irrespective of the status of the involved substances (whether liquid or gas). In addition, students need to recognise that chemical reactions do take place in plants at the cellular level. However, before addressing these learning demands, the Design Brief suggests (see section 3.4.3) making students aware of the conceptual problems that make photosynthesis implausible. The conceptual barriers that need to be addressed are:

- How can a weightless invisible gas contribute to making other substances?
- How can gas and liquid be converted into a solid?
- How can complex molecules (e.g. sugar) be produced from combining simple molecules (e.g. carbon dioxide and water)?

The Worked Example suggests working through the following steps:

1. In order to help students identify the causes of implausibility, they discuss in groups a dialogue that represents the aforementioned causes.
2. The teacher moves to address, through teacher-led demonstrations, the first two causes of implausibility (i.e. gases have mass and liquid and gas can form a solid).

3. Then students work in groups to re-model the arrangement of atoms of carbon dioxide and water to form glucose, to help them see that that plants use the same atoms of carbon dioxide and water in a new arrangement in order to form glucose.

With regard to teachers' and students' actions, video data related to the first activity shows that the teachers explained the purpose of the activity and asked students to work in groups. They employed interactive/dialogic talk to follow students' choices of the three statements presented in the activity. They then finally summed up the conceptual problems before moving on to addressing them. Yet, T2 did not implement the teaching like the other three. He guided the class through a whole class discussion to identify the three causes of implausibility. Furthermore, he tended to collect students' ideas rather than discussing their choices and justification. Finally, he summed up the conceptual difficulties and started addressing them.

With regard to students' engagement with the first activity, video data shows that students were engaged in the activity, working in groups to examine the three statements. Given that the desired outcome from this activity is that students identify what makes photosynthesis implausible, the collected classroom work shows that 13 groups (out of 22) disagreed with the three statements, which might suggest that students were in a position of already accepting photosynthesis, so they did not need to think about the causes of implausibility. In fact, only two groups explicitly referred to causes of implausibility. For example, one group wrote "*Ali is wrong because gas occupies space and can produce a solid substance when combines to a liquid*" (**G2, T1's class**). Therefore, it can be said that the majority of students mentioned photosynthesis only as a recall of previous teaching without necessarily understanding the nature of photosynthesis; if this is the case, making students aware of the causes of implausibility is the first step towards building their understanding of photosynthesis.

Of the remaining nine groups who agreed with one of the statements, soil was the statement most frequently selected by four groups (this corresponds with the findings from the pre-test, see section 6.3.1). They justified their choice on the grounds that soil is the only convincing and realistic source for plants. For example, one of the groups wrote, "*We support Saleh because it's closer to reality*" (Group 4 of T3). Another justification opined "*Soil provides some of the reactants needed for photosynthesis, and therefore soil can be partly considered as a source of food*" (Group 2 of T4).

In terms of the activities related to addressing causes of implausibility, the teachers started the first activity by holding demonstrations related to establishing the concept of mass in the case of gas. All the four teachers showed students how paper stuffed into the bottom of a glass will still be dry when the glass is turned upside down into a bowl filled with water. They asked students to give reasons for that and concluded that the air prevents water from wetting the piece of paper. Then, they held a demonstration with a carbon dioxide extinguisher to show students that carbon dioxide is an entity and can be visible. They also showed students that carbon dioxide has mass by weighing an empty balloon and then repeating the action when it was inflated with carbon dioxide. With regard to producing a solid from combining gas with liquid, they held an experiment consisting of bubbling carbon dioxide through limewater to show that combining a liquid and a gas can produce a solid substance. Teachers concluded that there are white solid precipitates in the limewater which prove that combining gas with liquid can produce a solid. They then reviewed with the students the conceptual barriers and asked students “What could happen if plants absorb tonnes of carbon dioxide and combine it with water to produce glucose?"

Excerpt 5.5: T3: air and gas have mass

When the teacher finished the demonstration, he showed students that the paper was not wet:
T: why the paper isn't wet?
Sg: air (the teacher pointed to a student)
S1: air inside the glass
T: what does the air do?
S2: prevents water from reaching the paper
T: OK, this proves what?
S3: air has entity.
T: yes, excellent, air has mass and occupies a space; the same applies to carbon dioxide.

With regard to the way that teachers performed these demonstrations and the way they drew conclusions, this section presents each teacher’s actions when demonstrating that "Air has mass by the upside-down glass experiment". T1 started by stating the fact that air has mass and then he did the demonstration to prove this fact. He went on to explain that the air inside the glass prevents water from wetting the paper. Then he asked students "What does this prove?" Likewise, T2 tended to advance the conclusions instead of engaging students to do so. On the other hand, T3 tended to discuss with students what this demonstration proves and how this applies to the phenomenon under consideration (see Excerpt 5.5). In addition, he kept asking students if anyone was unconvinced of the conclusion. T4 took a rather different approach, though. He asked the students first to predict what would happen to the paper if the glass was turned upside down into the water. Then he required students to explain why the paper did not get wet. However, once the students gave the explanations, he led the discussion and drew the conclusion himself.

With regard to students’ engagement with teachers’ demonstrations, videos show that students paid attention and agreed with the conclusions drawn from the demonstrations. In addition, when they were given the opportunity to engage with the ideas behind the demonstrations, they expressed responses which may suggest that they were intellectually engaged. For example, P_3 in Excerpt 5.5 reasoned that the paper did not get wet because "*air has entity*".

Then the teaching moved on to introduce the fact that glucose is composed of the same atoms as carbon dioxide and water. In the jigsaw activity, all teachers, with the exception of T2, explained the activity and its purpose, which is to see how plants rearrange the same atoms of carbon dioxide and water to form glucose. They also asked students to keep any leftovers. At the end of the activity, only T3 and T4 re-emphasized the purpose of the activity, and then linked it to the next step by asking the students "Is this everything involved in photosynthesis?"

Videos show that students were motivated to build the glucose model. There was enjoyment and competition amongst the groups to be the first to finish the activity. The majority of the groups finished the activity in the allocated time except for four groups (out of 22), which might suggest that enough time was given to students. Whether or not the students engaged with the idea behind the activity is unclear, as the available data neither confirm nor refute any such claim. Therefore, maybe there is a need to include a quick quiz or a post-discussion to explore such engagement.

- **Reflections on teachers' and students' actions**

This KDF constitutes a cornerstone in the teaching sequence as it addresses the learning demand related to the concepts of mass and cycling of matter. Given the presented descriptions of teachers' actions, it seems all the teachers presented the required content. In addition, students seemed engaged with the demonstrations and in building the glucose model.

In terms of the pedagogical approaches used in the demonstrations, teachers varied in their choice of whether to directly present the idea and then demonstrate it (e.g. T1 and T2), hold the demonstration and then discuss its implications (e.g. T3), or to ask for predictions and then hold the demonstration (e.g. T4). While it is notable that these approaches differ in terms of the verbal engagement they invite, the data I collected did not allow me to advance claims with regard to developing students' conceptual understanding. Having said that, one might anticipate, though, that the more students are verbally engaged, the more they are intellectually connected with the concepts behind the demonstration. To this end, the videos showed that students were less engaged in the approaches that started with conclusions (T1 and T2's approach) and then used demonstrations to prove them. It should be mentioned here, however, that the Worked Example did not include any suggestions of how to perform the demonstrations. This might explain the variations amongst teachers. Moreover, it would be more effective to equip teachers with specific guidance on how to better engage students with teacher-led demonstrations.

In terms of the validity of the assumptions advanced in the Design Brief concerning students' responses, the above descriptions show that some of the students referred to the idea that plant food comes from a reaction which happens inside plants. If this was the case, then it raises the question, did they need the step addressing the causes of implausibility? This is hard to answer unless their views were challenged to establish the extent and stability of their understanding of photosynthesis. However, an implication for refining the Design Brief is to consider such awareness of photosynthesis. This can be done by a formative assessment directed to challenge students' existing knowledge of photosynthesis in order to discover whether it relied on conceptual or rote bases. In so doing, students might become better aware of the limitations of their knowledge of photosynthesis, and teachers will also know exactly what students mean when they refer to photosynthesis.

5.5 KDF 4: Completing the simple model of photosynthesis

As mentioned in the Design Brief (see section 3.4.4), after addressing the causes of implausibility, the teaching moves to introduce the photosynthetic process in its complete form. The postponed elements of light energy, oxygen release and the storing of glucose in the form of starch are all discussed as well.

The Worked Example guided the teacher in dealing with the role of light energy, oxygen release, the role of chlorophyll, and the conversion of glucose into starch through the following activities:

1. A teacher-led demonstration to introduce the role of light energy, employing interactive/dialogic and interactive/authoritative talks. To demonstrate that energy is needed to power the reaction, the teacher shakes a bottle of fizzy water (after explaining that it consists of water and carbon dioxide) and allows students to taste that the mixture is not sweet "So what was missing?"
2. With regard to oxygen, it is documented that many students consider photosynthesis to be an oxygen supply process (see section 2.2.5). To ensure that students avoid this misunderstanding, emphasis is put on describing oxygen as leftovers, a by-product and even a wasteful product. The teacher asks students to go back to the leftovers from the jigsaw activity to see that the leftovers are oxygen atoms.

3. Next, the teacher asks students to work in groups to determine the most appropriate part of the plant to accommodate photosynthesis. Water, carbon dioxide, chlorophyll and light all are available.
4. After locating photosynthesis in the leaves, the teacher introduces the fact that glucose is converted into starch. This is aided by a demonstration based on the solubility of glucose and starch.
5. In order to consolidate the information presented so far, a group-activity is introduced asking students to use words and arrows on a drawing of a tree to show what the requirements for photosynthesis are and where they come from, and what the products are and where they go.

With regard to teachers' actions, videos related to introducing the role of light energy show that after all four teachers reviewed the information presented thus far, they started asking students "What would happen if we mix water with carbon dioxide?, Is it going to taste sweet as we have learnt?" They then held a demonstration by shaking a bottle of fizzy water (after they had explained what fizzy water is) to see if this can form sugar. When students confirmed that the mixture did not taste sweet, the teachers raised the question "Is there something missing?" The teachers then introduced the role of light energy, with slight variations.

T1, for example, went on to directly introduce the fact that light energy is the missing part of the mystery. He further instructed that plants have the ability to absorb sunlight using chlorophyll, which is located in plastids in the leaves. He added that plants absorb sunlight to obtain energy needed to produce glucose, and light is used to disconnect and connect bonds between atoms. In contrast, T2 guided the students by suggesting that light energy was the missing link and he closed the discussion at this point. In the case of T3, he led the students to arrive at the idea that light energy is the missing link and then he asked students to accept or reject this idea. When light energy was agreed upon, he explained how plants trap light energy by means of a substance called chlorophyll located in green plastids in leaves. (I did not describe T4's actions because the video of his lesson was corrupted).

In terms of students' engagement with the demonstration of the role of light energy, given that teachers approached it differently, students' engagement also varied. Students of T1 did not have the chance to suggest the missing link. Rather, the teacher directly introduced the fact that sunlight is attracted and energy is used to disconnect and connect the bonds between the atoms of both water and carbon dioxide to form sugar. In addition, the teacher did not check if students made sense of the role of light energy or not. Therefore, students' engagement cannot be confirmed by such non-interactive/authoritative talk. One the other hand, while T2 directed students' attention to the missing part of the reaction and emphasised that there was something missing, he did not explain the role of light energy. Instead, he simply stressed a simple response given by one of the high achievers stating that light energy is needed to make sugar. This might suggest that students were engaged only at the beginning of the demonstration. T3 started by exploring students' views of whether it was enough to say that the process is completed when water combines with carbon dioxide (see Excerpt 5.6). Students mentioned oxygen release and the need for heat and light energy. Then he did the demonstration and asked students "Why did we not find the sweet taste we expected?" Students attributed this to the difference between chemical reactions that happen in plants and the reaction in the demonstration, as plants have a salty substance that helps them to make sugar. Another student suggested light energy. He then focused on the idea that trapping light energy is essential to make sugar. Here, the students seemed engaged by the teacher, as light energy was actually suggested by them.

Excerpt 5.6: T3: The role of light energy

T: is the process completed by combining water with carbon dioxide to produce glucose?
S1: oxygen is given off
S2: heat and light energy, also oxygen is released during the day from photosynthesis while carbon dioxide is released during the night
The teacher did the demonstration and asked students why there is no sweetness after mixing water with carbon dioxide
T: so what is missing here?
S2: the type of reaction happens in plants isn't like the reaction here, they're different, reactions in plants can make sugar
T: hah, any other ideas?
S3: there is a salty component that splits oxygen from hydrogen and then makes sugar.
S4: the reaction is exposed to sunlight
T: Ok, listen, your fellow said light energy, anyone agree or disagree, raise your hands..

The teachers then moved on to the activity related to oxygen release. T3 and T4 turned students' attention to the leftovers from the jigsaw activity and asked students to identify them; they were atoms of oxygen. T1 and T2, however, were more direct saying that oxygen atoms were left over from the jigsaw activity, which are considered to be wasteful or a by-product released through stomata. The four teachers then emphasized that glucose is the main product that plants seek to produce. Given the variation amongst teachers, students were engaged to different extents. While students of T1 and T2 were not given the opportunity to suggest what the leftovers were, students of T3 and T4 were asked to go back to the jigsaw activity to find out by themselves.

Regarding the emphasis on the main product of photosynthesis (i.e. glucose), when the teachers asked the students to determine the main product, most of the students of T1 and T3 said it was glucose, while only one student of T2 said glucose. Students of T4 suggested carbon dioxide, oxygen and glucose. Given the fact that the teachers did not spend much time reiterating the idea that glucose is the main product, the videotaped interaction did not allow me to confirm whether students understood this point or not. Nonetheless, students seemed engaged by the talk led by the teachers. In addition, questions were raised by some students of T3 and T4 regarding oxygen release such as "How do leaves emanate oxygen outside?", an issue that was not targeted in the Worked Example. However, the teachers referred to the stomata as ports through which oxygen is released.

Then the teaching moved on to consider the role of chlorophyll. Videos show that the teachers asked the students to work in groups on an activity sheet to decide the most appropriate parts of the plant to accommodate photosynthesis. They explained that this part should provide water and carbon dioxide and has chlorophyll to attract sunlight. Most of the students chose leaves and the teacher confirmed this choice, emphasizing the availability of reactants alongside light energy, which is trapped by chlorophyll. To consolidate all this information and locate photosynthesis in its chosen place, the teachers asked students to complete a worksheet and use words to name requirements and products and arrows to show where they come from and go to.

In terms of students' engagement, in the activity targeting the most appropriate part of the plant to accommodate photosynthesis, students worked in groups using a comparative worksheet that contains the four inputs needed for photosynthesis, i.e. carbon dioxide, water, light energy and chlorophyll, and they were asked to choose from roots, stems, leaves and flowers. Collected classroom work shows that 20 (out of 22) groups decided that leaves are the most suitable part. Most of their justifications stress that leaves are exposed to sunlight, which is needed for photosynthesis. These responses suggest that students were intellectually engaged with this activity, as well as the fact that they were consistent with the scientific view. However, there was a terminology issue with the students of T1; they were confused as to the term "chlorophyll". It seems that they previously learnt the term "chlorophyll" through an equivalent Arabic term[1]. T1 spent time clarifying this confusion, and he suggested in his diary that the Worked Example uses the term that students used so they would not be confused.

[1] Technical biological terms are translated into the Saudi textbooks in two ways. Some terms are only *Arabised* so the English term is written in Arabic letters, while some terms are translated into equivalent Arabic terms. For example, the term "Chlorophyll" is introduced as it is in English (using Arabic letters), and sometimes as "the greener" (equivalent Arabic term), and the textbook used the two terms interchangeably.

The teaching sequence then moved on to ask students to work on a worksheet showing a diagram of a tree and to use words and arrows to show the substances required for, and produced by, photosynthesis. Students' work showed that the answers from 19 groups (out of 22) were consistent with the scientific view. They named water and carbon dioxide as coming from soil and air, respectively, and the products are glucose and oxygen. In addition, they were aware that light energy is not equivalent to water and carbon dioxide, as they did not group it with the two reactants. However, only five groups described sunlight as energy.

With regard to the activity of converting glucose into starch, videos show that all the four teachers introduced this activity and then wondered “Why do plants store glucose as starch?” The teacher then used interactive/dialogic talk to remind students of the difference between glucose and starch. Students’ responses stressed that whereas glucose is a monosaccharide, starch belongs to the polysaccharides group. Then the teachers held a demonstration to show that, although glucose easily dissolves into water, starch is resistant to dissolution and remains suspended. However, the teachers’ usage of this demonstration varied. Although they all asked the students to suggest the implications of this demonstration for plants, students of T2 and T4 could not do so, so T4 introduced the fact that plants convert glucose into starch in order to retain food inside the cell (T2 did not explain and simply moved to the next activity). On the other hand, students of T1 and T3 responded that glucose would be lost and cannot be stored for later use. In addition, the teachers drew an analogy to explain this fact. T1, for example, explained the analogy saying “*If we want to push one of you out of the class this will be easy, but if we want to push out a united group, this will be hard to do*”.

With regard to students’ engagement with the demonstration of the conversion of glucose into starch, as a result of the variation in teachers' approaches, students also varied in their level of engagement with the idea behind the demonstration. T1's teaching, for example, was mainly lecturing in the form of raising a question and then answering it himself. When he finished making the point of why plants convert glucose into starch, one of the students asked "How do plants do that?", and T1 answered saying "By making molecules linked to each other". On the other hand, T2’s style varied from that of T1, as he allowed his students to answer his questions. After he held the demonstration, he asked students what the insolubility of starch means to plants. Excerpt 5.7 below shows that students were not able to give a scientific justification. Likewise, T4's students could not justify why plants convert glucose into starch. However, students of T3 were able to justify that glucose is converted into starch in order to keep it inside the cell and prevent it from moving out to other cells.

Excerpt 5.7: T2: why is glucose converted into starch?

After demonstrating that glucose is soluble, but starch is not, the teacher asked the students:
T: so, what does this mean to plants?
S1: cuz plants contain water, and glucose dissolves while starch does not
T: so we can…(*another student wants to answer*)
S2: cuz glucose dissolves into water, plants convert it into starch so it will not dissolve
T: so…
S2: cuz starch is plant food when it needs it
T: go on, you're close
S3: plants convert glucose into starch to use it when necessary
S4: also if it is kept as glucose and dissolved into water, and when it's needed the plant needs to do another difficult process to split the glucose from water, but starch will be easy to use

To establish whether students grasped the conservation of glucose, they were asked to respond to a quiz (see Appendix C) that presented an investigation carried out by a student who picked some leaves in the middle of the day and then did a test to find out whether they contained glucose, as the photosynthesis equation suggests; surprisingly, the student did not find any glucose. The students were asked to tick one choice from four, namely, a) photosynthesis does not produce glucose, b) he should pick leaves in the night, c) he should look for something other than glucose and d) a space is provided to suggest another answer. Students were also asked to justify their choices. Only 50% of the returned quizzes (*n*=110) ticked the correct choice (b) and justified that glucose is converted into starch.

- **Reflections on teachers' and students' actions**

It seems that the teachers followed the Design Brief and the Worked Example to introduce the required content. In addition, they all completed the planned demonstrations. However, they varied in the ways they interacted with students. T1 tended to use a lecturing style in which he introduced the ideas directly to the students. Although T2 did engage students through questions, he was less effective in making use of students' questions and linking them to the ideas being discussed. On the other hand, T3 and T4 were more interactive and employed students' questions to develop the targeted point. However, the following up of students' responses and the elaboration mode of interactions was absent from all four teachers' practices. It seems that Saudi teachers are used to the lecturing style of teaching where they mainly introduce the content. However, an effective use of demonstrations might involve prior and post discussions to help students to make sense of the demonstration. As previously mentioned, guiding teachers in how to perform a demonstration was not tackled in the teacher's guide, so teachers varied in their demonstration approaches according to their teaching skills.

It is difficult to make a judgement on how the demonstrations helped students to engage with the intended ideas, as the actions of most students and teachers related to this KDF are linked to teacher-led demonstrations where the interactive talk was limited. However, two general points are presented here. When students were given the opportunity to respond to the raised questions, they seemed to follow the teachers' demonstration. In addition, when the teachers were checking students' understanding, it seemed also that students' responses were in line with the scientific ideas or at least close to them (see Excerpts 5.6 and 5.7). These two points might indicate that the introduced activities were engaging when students were given opportunities to respond. However, this can be challenged when we consider that most of the responses actually came from the high achievers rather than from students of different abilities (my identification of the high achievers was based on my personal observations linked to results of the written probes).

Another issue it would be useful to highlight here is a limitation of the Design Brief related to tackling the role of light energy. As suggested in the Design Brief, most of the teachers stopped at stating that light energy is needed in photosynthesis without explaining why it is needed. Only T1 went further to say that plants use light energy to disconnect and connect the bonds between the atoms. The other three remaining teachers stopped at the fact that light energy is needed to power the reaction. In addition, sunlight was rarely referred to in the teaching as "energy". In addition, students' classroom work showed that only five groups (out of 22) described sunlight as energy. This limitation of the design can be confirmed by students' interviews as well (see section 7.3.4) as they mentioned that they did not fully understand the role of light energy. Therefore, there is a need to refine the Design Brief to reconsider the introduction of light energy in more detail.

5.6 KDF 5: Explaining the produced glucose as a source of biomass

As mentioned in the Design Brief (see section 3.4.5), a decision is made to start with a formative assessment to probe students' ideas regarding where the extra biomass comes from. After making these ideas explicit, the teacher presents information to show students that most of the chemicals of which the cell structures are composed come mainly from glucose, with minor proportions of minerals taken in from the soil.

This KDF was addressed in the Worked Example through the following activities:

1. The teaching starts with a formative assessment to probe students' ideas of the source of biomass. The assessment is based on Helmont's experiment (see section 3.4.5 and Figure

3.6). Students are asked to discuss in groups Helmont's conclusion that plant matter comes from water.

2. Once students' ideas are identified and made explicit, the teacher revisits the structure of a plant cell (which was taught previously) to show students the chemicals of which cells are composed. The teacher presents the following:
   - The cell wall is made of cellulose, which is a type of carbohydrate.
   - The cell membrane is made of protein and fat, which are produced from glucose and fat
   - Cytoplasm consists of carbohydrates, proteins, fats and water
   - Plastids contain chlorophyll that is produced originally from glucose and magnesium.
3. Then the teacher emphasises two ideas, namely, (1) glucose produced from photosynthesis is the main source for almost all plant structures, which means that water cannot be a direct source for the extra biomass, (2) minerals are absorbed from the soil in small amounts and used with glucose to form other molecules.

With regard to teachers’ actions, videos show that all the four teachers asked students to work in groups to examine Helmont's conclusion. Only T1 and T3 fully explained the purpose of the activity. T1 was worried that the students would simply agree with Helmont because he was described as a scientist. So, he made it clear for them that Helmont conducted his experiment about 350 years ago, and even if he was a scientist, this does not necessarily mean that his conclusion was sound.

After the students finished their group discussions, videos show that the four teachers followed up students’ opinions. T1 asked groups' representatives to present their answers one by one, and then he concluded that Helmont was wrong. He explained that the biomass comes from the glucose produced in photosynthesis. He then presented the structure of a plant cell to show them how glucose contributes to the chemicals of which the cell is composed. T2 followed up students' answers without making final comments on their opinions. Rather, he moved on to explain the structure of the plant cell. In addition, he did not make links to Helmont's conclusion until one of the students asked him "Was Helmont's conclusion that water is the source of biomass wrong?" Until then, T2 said that while water is a reactant in photosynthesis, it is not a source for biomass, because biomass comes mainly from glucose. T3 followed up students' opinions group by group and kept asking for clarification when he felt that they were uncertain about their opinions. Before moving on to present the cell structure, he examined students' ideas and clarified that water is needed for photosynthesis, but biomass cannot build directly from water. Rather, glucose is the main source of the extra biomass. T4 followed students' ideas and then moved to present the structure of the plant cell. When he showed them that glucose constitutes most of the chemicals of which the structures are made, he asked the students "What does this mean?" One of the students said that "Water is not the main source for the plant cell structures?” The teacher affirmed his answer, although he did not refer to Helmont's conclusion (see Excerpt 5.8).

Excerpt 5.8: T4: Helmont's conclusion

After presenting the structure of the plant cell and the molecules from which they are made, the teacher asked:

T: what does this mean? What can we conclude?

S1: water is not the main source for biomass

T: excellent, any other ideas,

(the same student continued)

S1: also carbon dioxide, minerals and sunlight are not directly responsible for food making. Rather, plants take them and make food through a series of reactions. Animals get ready food while plants produce their food through photosynthesis

In terms of introducing the chemicals of which cell structures are composed, all the four teachers used non-interactive/authoritative talk. However, only T3 and T4 invited the students to use this information to make conclusions about the source of biomass (see Excerpt 5.8). Also, all the four teachers briefly introduced the role of minerals absorbed from the soil, albeit very briefly.

With regard to students’ engagement, collected classroom work shows that 12 groups (out of 22), irrespective of whether they agreed or disagreed with Helmont, thought that biomass comes from water, water and minerals, water and soil, and water and glucose. Only seven groups made links to glucose, photosynthesis and glucose and minerals. Yet, the responses of three groups were unclear (these results correspond with findings from the pre-test with regard to the biomass probe, see section 6.4.1). These responses indicate that students were intellectually engaged with the formative assessment activity. Moreover, it confirms the assumption advanced in the Design Brief that students’ starting point will be inconsistent with the scientific view. In addition, this might indicate that the existing knowledge that students expressed with regard to photosynthesis (see sections 5.3 and 5.4 in this chapter) did not mean that they had developed an explanation for the source of the extra biomass.

When it came to teachers presenting information related to the cell structure, students' actions were rather limited, as most of their time was devoted to presenting the structure of the plant cell. As mentioned above, only T3 and T4 made attempts to involve students in making sense of this information.

- **Reflections on teachers' and students' actions**

It seemed that all four teachers introduced content related to this KDF. Yet, although the four teachers conducted the formative assessment, they varied in the way they explained its purpose or made use of its results. Only T1 and T3, who were the more experienced teachers, made direct links to Helmont's conclusion and clarified that water is not a source of biomass. The other two did not refer to Helmont until one of them was directly asked by one of his students. However, it should be mentioned that the Worked Example did not explicitly refer to how to relate students' responses to Helmont's activity to the issue at hand.

Another issue is related to whether the students understood the limited role of minerals in building biomass. It is unclear if they did or not because the teachers only briefly referred to this aspect. To go further with this critical issue, more emphasis is needed on the incorporation of an activity in the Worked Example to make students aware of the contribution of minerals to biomass. In addition, a quiz might help to reveal what the students think about the role of the minerals.

5.7 KDF 6: Explaining the produced glucose as a source of energy

The Design Brief suggests postponing tackling the issue of using photosynthesis to explain the source of plant food until after the source of biomass has been dealt with (see section 3.4.6). At this point of the teaching sequence, students know that glucose is produced in photosynthesis, but might not be able to explain that this glucose is an essential substance for respiration from which energy is liberated. The Design Brief suggests that the teacher employs non-interactive/authoritative talk to approach this issue because the concept cannot be independently discovered by students through group activity. It is also difficult to investigate in the lab due to limited facilities.

The Worked Example addressed this KDF through the following activities:

1. The teacher involves the students in interactive/authoritative discussion to establish two points: (1) all creatures need energy to carry out biochemical processes, (2) energy is only liberated in respiration from organic substances such as glucose.
2. Then the teacher makes links to plants, which emphasise that photosynthesised glucose is an essential substance that plants use in respiration. Therefore, soil, water, minerals and light are not essential in respiration.

With regard to teachers' actions, videos show that teachers' actions related to this KDF can be divided into two steps. In the first step, they introduced the fact that all creatures need energy, which is released during respiration, to carry out biochemical functions. They went on to say that animals are different in the sense that they obtain energy from food, which is obtained by eating plants and other animals. Then all teachers, with the exception of T4, involved students in answering the question "How do plants obtain food?" As Excerpt 5.9 shows, T1 was open to inviting all possible ideas presented by students in terms of the nature of plant food. When students offered responses that include soil, light and carbon dioxide, he reminded them of the early established definition that only organic substances can supply energy. Excerpt 5.9 shows how students were confused about the nature of plant food, despite the fact they were on their fourth lesson of the topic of plant nutrition.

Excerpt 5.9: T1: How do plants obtain food and energy?

T: what do you think, how do plants obtain food? It's obvious how animals do, but what about plants? Tell me based on what we have learnt.
S1: from photosynthesis
T: ok, any other ideas
S2: soil
T: hah, others
S3: light energy
T: hah..
S4: carbon dioxide
T: what is the criterion we should follow to say that something is food?
S5: energy supply
T: excellent…what is the thing that provides energy for plants?
Sg: glucose

T3 noticed that his students were confused over whether photosynthesis results in food or energy (see Excerpt 5.10). He stopped at this point to clarify that, while photosynthesis produces food, respiration is the process wherein energy is liberated. In fact, this issue was not explicitly targeted in the Design Brief, as it was decided to separate the two processes (photosynthesis and respiration) to prevent students' confusion. However, it can be seen from Excerpts 5.9 and 5.10 that students were confused by linking food to energy.

Excerpt 5.10: T3: Does photosynthesis produce food or energy?

T: how do both animals and plants obtain energy?
S1: animals eat other animals or feed on plants and then through respiration the food is oxidized to release energy, while plants obtain it from photosynthesis.
T: Does photosynthesis produce energy?
S1: briefly, I mean, photosynthesis produces glucose which is food, and food gives energy.
T: good, does this mean that photosynthesis produces energy or doesn't? You all tell me, "photosynthesis produces energy", is this statement right or wrong?
Sg: *(some said right and some said wrong, mixed voices)*
T: wrong, only respiration produces energy, and when we say respiration we only mean "cellular respiration"

In terms of students' engagement, videos show that students engaged with the teachers' questions although it does not necessarily mean that they were providing correct responses. Indeed, as Excerpts 5.9 and 5.10 show, while some of the students were able to suggest glucose, others still referred to soil, water and light. Only when they were reminded of the energy-supply criterion did they realise that glucose is the only substance that supplies energy.

- **Reflections on teachers' and students' actions**

All four teachers introduced the required content related to this KDF. In addition, the teachers followed the Worked Example and raised questions intended to turn students' attention to the energy-food linkage. However, in terms of students' engagement, it seems that the relationships between photosynthesis and respiration on one hand, and food and energy on the other, proved to be problematic for students. In fact, the Design Brief suggests avoiding this problematic aspect. However, it might be better to immediately clarify this relationship rather than leaving students confused with unanswered questions, which might cause them to develop misunderstandings with regard to food, energy and respiration.

5.8 KDF 7: Practicing the scientific explanation

As mentioned in section 3.4.7, handing-over responsibility to students in using scientific explanations requires the provision of opportunities to practice and apply their knowledge. In addition, as mentioned in section 2.2.5, even after formal teaching, students return to their spontaneous ideas in terms of the source of biomass and plant food, so there is a need to re-emphasise the scientific explanation and revisit the spontaneous ideas.

The Worked Example addressed this KDF through the following activities:

1. Students discuss in groups an analogy drawn between bread baking and food making in plants. The purpose is to ensure that students can bring together requirements for, and products of, photosynthesis.
2. The teacher then revisits the ideas that were recorded earlier in the first lesson about plant food. The purpose is to refute these ideas justifying why they cannot explain plant food and biomass, and to re-emphasise the scientific explanation.

With regard to teachers' actions, videos show that all the four teachers introduced the bread making analogy. In terms of students' engagement, the collected classroom work suggests that they were behaviourally as well as intellectually engaged. The returned sheets (n=118 out of 131) showed that about two thirds of the students gained essential factual knowledge related to photosynthesis (i.e. carbon dioxide and water are the substances needed, and sunlight is the energy source and glucose is the main product). These results correspond with the findings from the post-test with regard to the *Factory Probe* (see section 6.2.1). However, there was much confusion in terms of linking glucose to respiration wherein energy is liberated.

Excerpt 5.11: T1: plants and animals differ in how they obtain food

T: what does it mean when we say that animals and plants obtain food differently?
S1: animals feed on plants and other animals while plants feed on glucose
T: excellent, any other ideas
S2: animals obtain ready food while plants produce their food through photosynthesis
T: yes, plants go through a series of reactions to produce food, hah
S3: plants are autotrophic, while animal are heterotrophic

Then all four teachers moved on to revisit the ideas that were recorded in the first lesson. It seemed that students were able to distinguish between animals and plants regarding the ways both obtain food (see Excerpt 5.11). Their responses included the fact that plants obtain food through photosynthesis, so we can call them autotrophic. Thus, students were aware that photosynthesis is carried out in the presence of sunlight, and if it is missing plants will run out of starch and therefore biological functions will stop. However, there was confusion regarding linking food to energy. As Excerpt 5.12 shows, while students can refute the fact that water and minerals are not food for plants, they could not justify why they are not. In addition, others expressed their belief that other inorganic materials in addition to carbon dioxide and water are needed to produce glucose.

Excerpt 5.12: T3: plants and animals differ in how they obtain food

T: Are water, minerals and fertilisers food for plants?
S1: no, they are not, cuz they do not supply energy.
T: ok, any other ideas
S2: no, they are not, but plants use them to make food.
T: ok, be specific, are they food by themselves or not?
S2: no, only glucose can be food for plant.
T: ok, other ideas!!
S3: no, cuz there are things missing like carbon dioxide and light.
T: well, we conclude that they are not food for plants cuz they don’t supply energy.

- **Reflections on teachers’ and students’ actions**

It seems that the four teachers followed the Worked Example in introducing the bread baking analogy and revisiting students’ ideas of the nature of plant food. However, videos show that students were confused about the link between food and energy, although they might know that inorganic substances are not food for plants. Again, students failed to justify why inorganic substances are not food. An implication for refining the Design Brief and Worked Example is to emphasise the link between food and energy and to define food as a source of energy. This, in turn, requires clarification of the relationship between photosynthesis and respiration, which was avoided in the Design Brief. Moreover, these ideas should be practiced in different contexts related to animals and plants with the purpose of challenging and strengthening students' understanding.

5.9 An overview of the match between the intended and implemented teaching sequence

The purpose of this section is to provide an overall judgement of the match between specifications in the Design Brief and the Worked Example, and the actual implementation. My judgement is based on the key issues discussed within each KDF, and will focus on three facets related to the following three questions:

Content covered: Did the teachers cover the intended content as specified in the Worked Example? An answer to this question is presented in sub-section 5.9.1.

Pedagogies used by the teachers: To what extent did the teachers and students follow the pedagogic strategies and modes of interaction as specified in the Design Brief and specified in the Worked Example? This question is answered in sub-section 5.9.2.

Assumptions advanced in the teaching sequence: Were there any matches or mismatches between the assumptions advanced in the Design Brief and the actual teaching/learning practices? This question is answered in sub-section 5.9.3.

Answering these three questions will enable me and the reader to determine the extent to which the teaching sequence was followed by teachers and students with regard to the KDFs. This constitutes effectiveness1, as reflected in the model of evaluation (see section 4.3.5).

5.9.1 Content covered

"Content" refers to the scientific knowledge included in the Worked Example, whether it is facts, concepts or explanations. A central point of establishing the match between the teaching sequence and the actual implementation is to find out whether the intended content was covered. The content is mentioned first because if the content was not covered, then following whether the related pedagogic strategies were used or not will be meaningless. This is because the pedagogic strategies were specified to address a given aspect of the content rather than practicing the strategy *per se*.

The teaching sequence starts by establishing a definition of food based on the energy-supply criterion. The teachers used the fuel analogy to introduce students to the fact that only energy-rich or organic substances can be called food. This issue was debated in the first and second lessons, and was revisited in the last lesson. The descriptions provided showed how the teachers kept reminding students of the energy criterion over and over again (see sections 5.1, 5.2, 5.7 and 5.8). However, while this part of the sequence was introduced by the four teachers, the way it was introduced will affect how it was understood. In other words, introducing the scientific definition does not necessarily imply that the students understood it or would be able to use it effectively. In fact, the IV quiz revealed that only 53% referred to the energy-supply criterion. This might concur with findings documented in the literature (Leach and Lewis, 2002) that developing conceptual knowledge does not necessarily entail making appropriate use of it in novel contexts. Furthermore, there was confusion and difficulty amongst students with regard to the meanings of and relationships between the terms “food”, “energy”, and “respiration” (see sections 5.2, 5.7 and 5.8). Rather than pointing to the shortcomings of the teachers, it is acknowledged that the Design Brief was limited in dealing with these concepts.

After clarifying the nature of food, the purpose was to challenge students' ideas regarding the source of plant food before introducing a simple form of photosynthesis (carbon dioxide + water → sugar) as a possible explanation. All four teachers ended by presenting this simple explanation (see section 5.3). However, a number of students appeared to be already familiar with the term “photosynthesis” and perhaps its relation to plant food.

With regard to addressing the causes of implausibility, namely, the concepts of mass and cycling of matter, the teachers helped students to detect these conceptual problems (see section 5.4). They then turned to addressing the causes of implausibility. These pre-requisites were essential in the Design Brief as they constitute one of the learning demands (see section 3.2.3). The content related to addressing the fact that carbon dioxide has mass was tackled through three teacher-led demonstrations. Then, the teachers dealt with the conversion of matter through the limewater demonstration which showed the students that a solid can be formed from combining gas with liquid, as happens in photosynthesis. The last part was related to the re-arrangement of carbon dioxide and water atoms to form glucose, which was achieved by building a model of glucose (see section 5.4).

With regard to the content related to the completion of the simple model of photosynthesis, the teachers talked through information relating to the role of light energy, the release of oxygen and the storing of glucose in the form of starch (see section 5.5). The content related to light energy was limited to *telling* the students that sunlight is needed and is trapped by chlorophyll. Only T1 explained that light energy is used to disconnect and connect the bonds between atoms. In the interviews the students stated that they could not fully understand the role of light energy in photosynthesis, and they felt that they needed more details on this topic.

The teachers then introduced the fact that oxygen is released as a by-product. They were asked in the Worked Example to place extra emphasis on the idea that oxygen is released only as a by-product, while glucose is the main product of photosynthesis. The teachers then ended by presenting the full chemical equation of photosynthesis. Also, the students were scaffolded to determine that photosynthesis takes place in leaves on the grounds of the availability of the reactants (i.e. carbon dioxide and energy), light energy and chlorophyll. In addition, the teachers explained the reason that glucose is stored as starch, based on the solubility of starch and glucose.

After completing the photosynthetic process, the teachers turned to introduce the role of glucose as a source for biomass and energy (see sections 5.6 and 5.7). With regard to biomass, all four teachers introduced the basic structure of the plant cell, accompanied by a basic diagram of the cell. They then all mentioned that these structures are made of chemicals whereby glucose is the main contributor. In addition, they referred briefly to the role of minerals absorbed from the soil. The teachers then introduced the other core idea that glucose serves to free the energy needed for carrying out biological functions through respiration. However, as there was no intention to introduce the relationship between photosynthesis and respiration to students, there was uncertainty amongst students with regard to this issue. In addition, students' responses to the teachers' question suggest that making the link between the two processes is crucial to helping students develop a holistic understanding of photosynthesis as a food making process.

To conclude this sub-section, these descriptions of the covered content might support two conclusions. Firstly, all the intended content was covered as introduced in the Worked Example. Secondly, the sequencing of the covered content also met that suggested in the Design Brief. In my view, this is not a surprising outcome when we bear in mind the fact that Saudi teachers are expected to follow the content of the textbooks and to cover every single idea.

However, needless to say, covering the content does not necessarily mean that the content was effectively introduced or even that students understood it. While the latter issue will be explored in the next chapter, finding out how the content was introduced might be made possible by examining the pedagogic strategies and mode of interactions used by the teachers, which I will be addressed in the next sub-section.

5.9.2 Pedagogies used by the teachers

I will limit my review on the use of pedagogies to those strategies that were used most frequently in the teaching. That is, conducting formative assessments to probe students' ideas, holding demonstrations and setting conflicts. In addition, given that the ways that these strategies were employed can affect their effectiveness, I review the modes of interaction employed by the teachers.

- **Formative assessment**

The Worked Example suggests probing students' ideas with regard to "What is food?", "What is the nature of plant food?" and the source of biomass. All four teachers implemented these assessments at the points at which they were instructed to do so. However, teachers varied as to how they made use of the ideas generated from the formative assessments. The aforementioned descriptions (see sections 5.2 and 5.6) showed that the teachers tended to stop at collecting students' ideas. In addition, the ideas were collected as labels or headings rather than inviting students to clarify, justify or elaborate their views. Moreover, the teachers did not allow students to comment or challenge each others' views. By contrast, some of the teachers (T1 for example) focused only on the expected ideas that were mentioned in the Worked Example. In some cases, when a student expressed a view that was expected by the teacher, the teacher's comments took the form of positive remarks as the student said what the teacher wanted to hear (see Excerpt 5.1) .

- **Teacher-led demonstrations**

Demonstrations were used to address the implausibility of photosynthesis and to complete the photosynthetic process. All four teachers implemented the planned demonstrations. It seemed also that both teachers and students enjoyed doing these demonstrations. As T3 said in his diary "…they are simple to implement in the classroom and directed to the idea". However, teachers varied in implementing the demonstrations and making use of the conclusions derived from them.

T1 and T2 started with the conclusions of the demonstration and then held the demonstration to prove the pre-advanced conclusion (see sections 5.4 and 5.5). By contrast, T3 started with the demonstration and engaged students in a post-discussion in an attempt to figure out the point of the demonstration. When he drew the conclusion, he checked whether students were in agreement with him or not. T4 took a rather different approach as he asked students to make predictions for the demonstration and then to give possible explanations. However, he employed non-interactive/authoritative talk in drawing the conclusion.

This level of variation indicates that the Worked Example was limited in guiding the teachers in the effective use of demonstrations. The Worked Example was intended to rely on teachers' expertise in implementing the demonstrations. However, these descriptions indicated that the teachers needed more guidance regarding the procedure for demonstrating, engaging students in the idea behind the demonstration and linking the conclusion to the phenomenon in question.

- **Using the specified mode of talk**

The teachers were exposed to an introductory session that briefed them on the Communicative Approach as described by Scott and Asoko (2006). In addition, symbolic annotations were presented in the Worked Example to guide the teachers with regard to the specified talk. However, there were inconsistencies between that which was specified and that which was implemented. Although this study is not concerned with characterising teacher-student verbal interaction, some distinctive characteristics can be identified.

When students were engaged in the classroom talk, their responses tended to be short and expressed as a label of the idea rather than presenting the full idea, let alone justifying it. Simultaneously, the teachers' focus was devoted to collecting the ideas instead of asking for elaboration, whether from the engaged student or from the rest of the class. In addition, teachers were limited to collecting students’ ideas rather than challenging these beliefs or inviting comment from other students. It also seems that students' talk was mostly a reaction to teachers' cues rather than emerging from students themselves. Another feature is that most of the talk was conducted in individual threads rather than being a collective classroom discussion.

Although the types of talk practiced in the teaching sequence were significantly different from usual practice, they fell short of the specifications of the Design Brief and Worked Example. Furthermore, although the teachers succeeded in probing students' ideas and making a space for several voices alongside the teacher’s voice, they could not reach interactive/dialogue communication. This is illustrated by the limited opportunities that were given to students to elaborate or justify their ideas. In terms of the non-interactive/dialogic, interactive/authoritative and non-interactive/authoritative talks, the teachers followed in the specifications of the Worked Example.

To conclude this sub-section regarding the use of pedagogic strategies, the Worked Example guided the teachers in following specifications. However, the way these strategies were communicated fell short of those specifications. In particular, interactive/dialogic talk was rarely observed during the actual implementation.

5.9.3 Assumptions advanced in the teaching sequence

The purpose of this sub-section is to determine the extent to which the assumptions advanced in the Design Brief occurred in the teaching. Although the design is informed by empirical findings on students' ideas to determine students' likely starting points, they are still assumptions until students' responses confirm that they said what they were expected to say. In addition, there were assumptions about the appropriate language and terminology used in the Worked Example. I limit my review only to the assumptions that did not work, which implies that the remaining assumptions appear to be valid.

With regard to the ideas that students hold in answer to the questions "What is the nature of food?", "What is the nature of plant food?" and the source of extra biomass, students' responses were consistent with findings documented in the literature and advanced in the Design Brief, as their expressed responses included: soil, water, minerals and fertilisers (see section 5.2). However, there were assumptions that students have limited previous knowledge of photosynthesis and linking food to energy supply criterion. As the actual teaching videos show (see sections 5.2 and 5.3), some students appeared to be aware of the reactants and products of photosynthesis. Moreover, others were able to state that food is needed for energy; yet, they were not able to apply their knowledge in some instances. An implication here is the need to revise the conceptual analysis to include previous lessons that were ignored. Also, there is an implication with regard to re-developing the Design Brief to consider more than one teaching scenario, depending on students' responses. In other words, if the students have some awareness of the photosynthetic process, what can the teacher do to respond to such awareness?

Reducing the content to the essence of photosynthesis and avoiding issues related to the relationships between photosynthesis and respiration and the role of light energy was based on insights derived from the literature (see sections 3.2.3 and 3.2.4) and was, therefore, suggested in the Design Brief. The reason behind this reduction was that the provision of more detail would be at the expense of the students grasping the essence of the photosynthetic process. However, in the actual teaching sequence, there were several cases when students asked specifically about the role of light energy, or they confused energy with heat (see section 5.5). In addition, there was uncertainty amongst students regarding the relationship between photosynthesis and respiration. To this end, it seems that it is inevitable to introduce the relationship between respiration and photosynthesis in the topic of plant nutrition.

With regard to the terminology used in the Worked Example, it seemed that some students were confused by the term "chlorophyll" as they were used to using an equivalent Arabic term. Although

I asked the teachers to check the appropriateness of the Worked Example for their students, they did not mention this term. Another issue is related to the language used with regard to Helmont's experiment. Five groups agreed with Helmont's conclusion that biomass comes from water. As T1 indicated, some students followed Helmont simply because he was described as a "scientist". He suggested in his diary that the activity will be more effective if we either eliminate the word "scientist" or suspend the conclusion and give students the opportunity to draw their own conclusions, irrespective of Helmont's actual conclusion.

To conclude this chapter, it appears that the teachers were able to cover the content introduced in the Worked Example. However, when it came to the pedagogical aspects of the design, there were some limitations. Although the teachers succeeded in probing students' ideas, they tended to collect the ideas rather than engaging students in talk that gave them space to elaborate and justify their ideas. Thus, it seems that the teacher-led demonstrations were helpful in addressing the cause of the implausibility of photosynthesis. However, they were conducted in a way which proved the scientific view, rather than developing students' understanding, which might have had a positive effect on their efficiency.

In addition, it seems that the teaching sequence was effective in developing the factual knowledge related to photosynthesis (as confirmed by findings from the *Factory Probe*, see section 6.2.1). Yet, the actual implementation revealed some limitations in developing accurate conceptual understandings concerning the role of light energy, the relationships between photosynthesis and respiration, food and energy, and photosynthesis and energy. With regard to the conceptual understandings of the source of plant food and biomass, neither the videos nor the collected classroom work allowed me to make claims in this regard. Evidence of conceptual understanding will be provided based on assessments of students' understanding by using the Food and Biomass probes, which are presented in the next chapter.

CHAPTER 6: EVALUATING THE EFFECTIVNESS OF THE TEACHING SEQUENCE IN TERMS OF DEVELOPING THE DESIRED LEARNING OUTCOMES

The purpose of this chapter is to present results related to the assessment of students' attainments of the desired learning outcomes, which answers RQ 2 and, therefore, establishes effectiveness 2 of the design. Following the introduction, this chapter is structured around three main sections corresponding to three learning outcomes, followed by a final section to summarise the key findings and highlight issues related to refining the teaching sequence.

6 CHAPTER 6: Evaluating the effectiveness of the teaching sequence in terms of developing the desired learning outcomes

6.1 Introduction

As mentioned in Chapter 2 (see section 2.5), the second RQ is intended to investigate "*To what extent did the students develop the desired learning outcomes?*" This chapter attempts to answer this research question by analysing students' responses to three written probes that were administrated to assess students' attainment of the desired learning outcomes. Moreover, as indicated in section 4.3.5, the purpose of assessing students' attainment is to measure the effectiveness of the teaching in terms of meeting its aims (as represented in the learning outcomes), which I called effectiveness 2 in the evaluation model (see Figure 4.1).

The desired learning outcomes were identified in the Design Brief (see section 3.2.3). It was expected that, by the end of the teaching sequence, the students will attain the following learning outcomes:

- *Identify that:*
  - Plants make their own food via photosynthesis from inorganic components, carbon dioxide and water.
  - Plants use energy from sunlight to power the reaction between carbon dioxide and water.
  - The products of photosynthesis are glucose and oxygen.
- *Explain the nature of plant food and how it is obtained:*
  - Plants make (or produce) their own food (or glucose, starch, carbohydrate) from the raw materials available in the environment (carbon dioxide and water) through a process called photosynthesis.
- *Explain how photosynthesis explains plant biomass:*
  - The extra biomass comes from the food (or glucose, starch, carbohydrate) that plants make (or produce, form, obtain) through photosynthesis, with small proportions of minerals absorbed from the soil.

As previously mentioned, three written probes were used to assess students' attainment of the desired learning outcomes. The first probe (*Factory Probe*) was conceptually-framed to establish whether students developed the factual knowledge related to the photosynthetic process. The second and third (*Food and Biomass*) probes were phenomenologically-framed to discover how successful students were in applying this factual knowledge to *explain* the source of plant food and extra biomass. The three probes were administrated three times in pre-, post-, and delayed-post tests with 131 students, divided between four classes (see section 4.4.3.2).

With regard to analysing students' responses, the analysis was carried out based on the coding scheme presented in section 4.4.3.3. Students' responses were nomothetically coded in one of three categories. The first category (Scientifically *Consistent*) encompasses responses that were in line with the model answer. This category includes two sub-categories (*Complete* and *Incomplete*) depending on whether responses met all or most of the features of the model answer. The second category (Scientifically *Inconsistent*) contains responses that lacked all or most of the features included in the model answer and/or showed conceptual contradiction with the scientific view. Finally, the third category (*Other*) was devoted to responses that were tautological or unrelated to the probe. In addition to this analysis, I also analysed students' responses in terms of the words that they started to use or abandoned across the three tests. The significance of the change in students' gains or word usage was compared using the McNemar's test (see section 4.4.3.3).

This chapter is structured around three main sections corresponding to the three learning outcomes and the three probes. Each section starts with a brief introduction of the probe, making reference to its advantages and limitations, and then presents a general overview of the findings, followed by a detailed analysis in terms of consistence with the model answer and the words that students tended to include in their responses. Finally, the chapter is concluded with a summary to determine the extent of the overall effectiveness of the teaching sequence, and some implications for refining the Design Brief and Worked Example.

The first section is related to students' responses to the first probe.

6.2 Students' responses to the *Factory Probe*

The purpose of the *Factory Probe* was to assess students' attainment of the factual knowledge related to plant nutrition, namely, requirements for, and products of, photosynthesis. As described in section 4.4.3.1, the probe starts with two warm up items that introduce the analogy of *Plant as a Factory* (see Figure 6.1). The purpose of these two items was to stimulate students to think about plant nutrition without direct reference to photosynthesis. Then, in the third and fourth items, students were asked to identify the products of, and requirements for, photosynthesis, respectively. It should be mentioned here that the analysis of students' responses to this probe focused on the third and fourth items, as they were specifically intended to assess students' knowledge of the requirements for, and products of, photosynthesis.

Figure 6.1: *Factory* Probe

Question 1

- Some people think a plant is a bit like a factory.

  a) In the space below explain in what ways you think a plant might be a bit like a factory. (Use a diagram or a cartoon to explain your ideas if this is easier.)

  b) If you are thinking of the plant as a factory, what is the most important part ? (e.g. root, steam, leaf, flower) Explain why you think this.
  – The most important part is:
  – The reason for my answer is:

  c) Each factory produces a product/s, what is/are the main product/s that plants produce. Explain as much as you can.

  d) In order that plants make this/these products, what do plants need? Use a diagram or a cartoon to explain your idea if this is easier.

The model answer for this probe is:

> *Glucose is the main product that plants produce, and oxygen is released as a by-product. The requirements needed for producing this main product(s), are carbon dioxide, water and light energy.*

With regard to how effective the probe was in assessing the intended factual knowledge, students' responses showed a variation of interpretations of what was intended by the first two items, as they struggled to determine what was required from them. This ambiguity can be attributed to two reasons. Firstly, Saudi students are not familiar with this style of indirect analogy-framed question. In fact, questions found in the biology textbooks are direct and focus on recalling definitions and facts.

The second reason is more specific to the probe itself, as it requires an appreciation of the food making feature in plants rather than mere recall of the requirements for, and products of, photosynthesis. If the student, for example, cannot recall the production feature, it is unlikely that he will respond to the probe as intended. This was apparent in the pre-test, as a relatively high percentage of the responses (45%, *n*=59) were coded as "Other" because students failed to detect the production feature of photosynthesis. However, when students picked up on this feature in the post-test, there was a dramatic decrease in responses (*n*=10) that were coded in the "Other" category. This meant that, even though the probe was intended to assess the attainment of the factual knowledge, only students who were aware of the production feature were able to respond as intended. In this case, a rote memorisation of the photosynthesis equation, for example, might not be helpful in responding to this probe. This can be taken as a limitation and, at the same time, can be seen as an unconventional attempt to assess only the factual knowledge that was meaningfully developed.

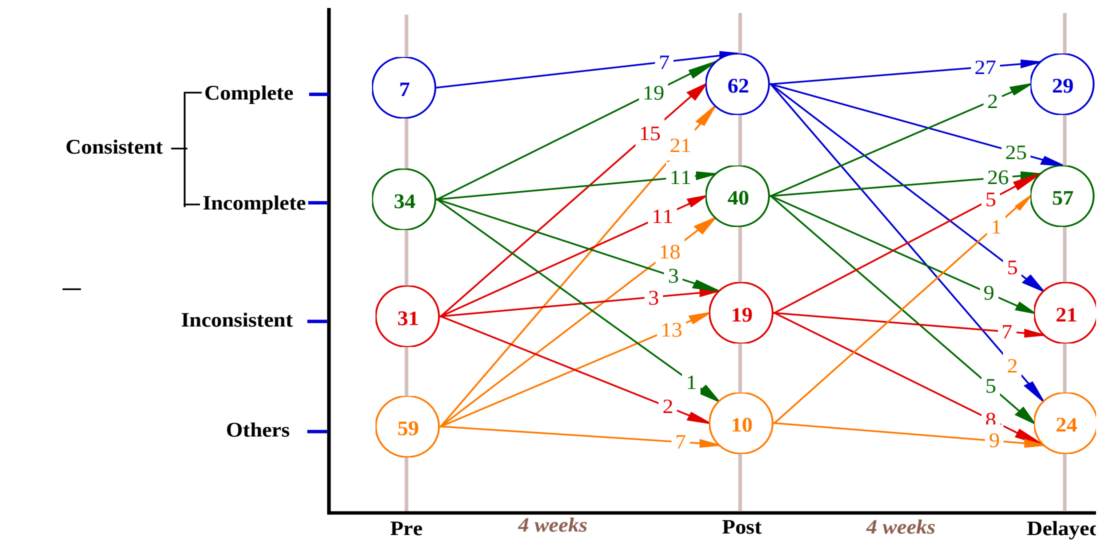
6.2.1 General overview

There was a good response rate to the first probe, namely 95%, 99% and 97% in the pre, post and delayed-post tests, respectively. This might indicate that the students were comfortable in attempting to respond to this probe, irrespective of meeting the model answer.

With regard to whether students were successful in offering the required responses, I present their responses in three main categories as specified in the coding scheme, (see section 4.4.3.3).

Figure 6.2 shows students' movement with regard to these categories, before and after exposure to the intervention, and Table 6.1 also shows frequencies and percentages of students' responses within each category.

Figure 6.2: Students' progressing moves of responses to the *Factory Probe*



As Figure 6.2 and Table 6.1 show, a key element of the pre-test is the large proportion of responses (*n*=59, 45%) that fall into the "Other" category. It seems that students' attention has leaned towards alternative aspects that were not intended in the probe, that is, environmental requirements (e.g. soil, caring, atmosphere) and/or the visible products (e.g. flowers, fruits, crops) that plants produce. As previously mentioned, this might suggest that the probe was not clear enough for the students in the pre-test, but their confusion decreased when they recognised the context in the post-test, as only 10 responses were coded in the "Other" category.

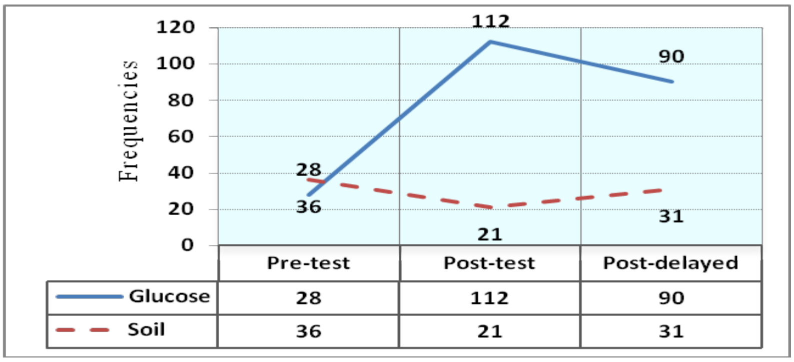
Table 6.1: Summary of students' responses to the *Factory Probe*

Category		Pre- *n*	%	Post- *n*	%	Delayed-post *n*	%
Consistent	Complete	7	*(5)*	62	*(47)*	29	*(23)*
	Incomplete	34	*(26)*	40	*(31)*	57	*(43)*
	Total	41	*(31)*	102	*(77)*	86	*(67)*
	Inconsistent	31	*(24)*	19	*(14)*	21	*(15)*
	Other	59	*(45)*	10	*(8)*	24	*(19)*
	Total	131	*(100)*	131	*(100)*	131	*(100)*

With regard to matching the model answer, Table 6.1 and Figure 6.2 show that, before experiencing the teaching sequence, only one third of the sample offered "Scientifically *Consistent*" responses regarding the requirements for, and products of, photosynthesis, whereas about two thirds of the responses were "*Inconsistent* or "*Other*". However, progression has been made in the post-test, as 77% of the sample provided "*Consistent*" responses. Moreover, 63% of the "*Consistent*" responses found in the post-test came mainly from students whose responses were coded in the pre-test as "*Inconsistent*" or "*Other*". According to the results of McNemar's test analysis, the change of the proportion of students who offered "*Consistent*" responses in the post-test (77%) was significantly higher ($p<0.0001$) than those of the pre-test (31%).

However, in the delayed-post test there was a decline in the number of "*Consistent*" responses. Of those who offered "*Consistent*" responses in the post-test (*n*=102), 14% moved to the "*Inconsistent*" category and 7% to the "Other" category. Yet, the improvement from the pre-test to the delayed-post test is still significant, despite this decline ($p< 0.0071$).

Figure 6.3: Students' use of the word "soil" and "Glucose"



In addition, another way of looking at students' progression is to consider the words that students used in their responses (whether contradictory or concurring with the scientific view). For example, it is established from the literature (see sections 2.2.3 and 2.2.4) that students use the word "soil" to refer to plant food. So, the regression of students' use of the word "soil" might be taken as an indication of development towards the acceptable view. Figure 6.3 shows that students' use of the word "soil" in the pre-test was found in 36 responses, but this has decreased to 23 and 31 responses in the post- and delayed-post tests, respectively. In contrast, the increase in using the word "glucose" can indicate students' starting to use the correct scientific terms when referring to plant food. Figure 6.3 shows that glucose was mentioned 28, 112 and 90 times in the pre-, post- and delayed-post tests, respectively, a change found to be very significant ($p< 0.0001$) according to McNemar's test analysis.

Viewed together, the progression that students made towards providing "*Consistent*" responses and their development in terms of using scientific terminology might constitute general evidence of the effectiveness of the teaching sequence in improving students' factual knowledge in terms of the requirements for, and products of, photosynthesis.

The next sub-section turns to reporting students' responses in terms of the three categories specified in the coding scheme.

6.2.2 Categorisation of students' responses to the *Factory Probe*

The following sub-sections present details of the analysis of students' responses.

6.2.2.1 Scientifically Consistent responses

Responses included in this category are divided into two sub-categories, "*Consistent-Complete*" or "*Consistent-Incomplete*".

a) Consistent-Complete responses

This category involves responses that provided all features included in the model answer. Table 6.1 shows that in the pre-test only seven students out of 41 whose responses were "*Consistent*" offered "*Complete*" responses. After exposure to the intervention, responses that were coded as "*Consistent-Complete*" increased to 47%, 23% of the sample in the post and delayed-post tests, respectively. It was expected in the delayed-post test that the "*Complete*" responses would decrease, as the probe looks for factual knowledge which is likely to be forgotten considering the time between the post- and delayed-post tests.

Looking at where the complete responses came from, Figure 6.1 shows that the development towards the "*Complete*" category in the post-test came from three categories: "*Incomplete*", "*Inconsistent*" and "*Other*". This might indicate that the teaching sequence was effective in promoting the knowledge of students who started at different points. In addition, the seven students whose responses were coded as "*Complete*" in the pre-test remained in the same category, which might suggest that the teaching sequence has no negative affect on students' learning regarding the requirements for, and products of, photosynthesis. Furthermore, the students who dropped down in the delayed-post test to "*Inconsistent*" or "*Other*" categories represented only about 10% of the total (*n*=7 out of 62), which is still expected since the delayed-post test was administrated after a month's time.

b) Consistent-Incomplete responses

This sub-category involves responses that either: refer to the requirements as raw materials without being specific regarding the nature of those raw materials, replaced carbon dioxide with air, missed oxygen, or one of the requirements (i.e. water, carbon dioxide and light). It should be mentioned that it is essential for responses coded as "*Consistent-Incomplete*" to not show any signs of contradiction with the model answer (e.g. adding soil and minerals as requirements or only oxygen as a product).

As shown in Figure 6.1, the development in the post-test towards the "*Consistent-Incomplete*" from the "*Inconsistent*" and "*Other*" categories was not as great as the development towards the *Consistent-Complete* category, 22% and 27%, respectively. On the other hand, the regression in the delayed-post test from the "*Consistent-Incomplete*" category to the "*Inconsistent*" and "*Other*" categories was double the rate of regression from the "*Complete*" category. A possible reason for this is that some students who offered "*Incomplete*" responses relied on mere memorisation compared to those whose responses were "*Complete*" as they perhaps relied on meaningful understanding.

Table 6.2: Consistent incomplete responses that missed one of either the reactants or products

	Pre-		**Post-**		**Delayed-post**	
	n	***%***	***n***	***%***	***n***	***%***
Reactants	19	*(56)*	14	*(33)*	20	*(36)*
Products	15	*(44)*	28	*(67)*	36	*(64)*

With regard to the types of incompleteness of students' responses, as Table 6.2 shows, those responses that missed one product represented 44%, 67% and 64% of the pre, post and delayed-post tests, respectively. By contrast, the percentages representing those who missed only one requirement were 56%, 33% and 36% in the pre-, post- and delayed-post tests, respectively. This might suggest that identifying products of photosynthesis was more challenging for students compared to identifying requirements. This might be explained by the time that was allocated to teaching the requirements and products. In fact, the time spent in addressing causes of implausibility (see section 3.4.3) was much greater than the time spent on teaching the nature of the products.

Moreover, when the response was coded as "*Incomplete*" because one of the requirements was missing, carbon dioxide appeared to be the most frequently omitted, representing 89%, 79% and 80% in the pre-, post- and delayed-post tests, respectively. Taking into account the fact that the teaching time allocated for developing knowledge related to carbon dioxide was more than the time allocated to water and sunlight, it is apparent that the role of carbon dioxide was problematic for students, which is frequently reported in the literature (see section 2.2.5).

In addition, when the invisibility of glucose, oxygen, and carbon dioxide is considered compared to the visibility of, and familiarity with, water and sunlight in everyday life, it is possible to see why the invisible substances were more likely to be absent in students' responses. In other words, the more substances are visible and sensible, the more likely students are to grasp and identify them, and vice versa.

Table 6.3: Results of consistent responses regarding products of photosynthesis

Nature of response	Pre-		Post-		Delayed-post	
	n	***%***	***n***	***%***	***n***	***%***
Responses that identified Glucose & Oxygen	17	*(13)*	70	*(53)*	44	*(34)*
Responses that identified only Glucose	11	*(8)*	42	*(32)*	46	*(35)*
Responses that identified only Oxygen	53	*(40)*	5	*(4)*	13	*(10)*

Also, it seems that responses that focused only on glucose as a product and missed oxygen, or those that focused only on oxygen and missed glucose, with no signs of confusion with respiration, were noticeable amongst students. As Table 6.3 shows, only 13% of the sample in the pre-test identified glucose and oxygen as products of photosynthesis, while in the post- and delayed-post tests the percentage increased to 53% and 34% respectively. Interestingly, the percentage of responses in the pre-test that considered oxygen to be the only product of photosynthesis was 40%, which corresponds with findings documented in the literature regarding the perception that the purpose of photosynthesis is to produce oxygen for the benefit of humans (see section 2.2.5). However, this dropped to only 4% and 10% of the sample in the post- and delayed-post tests, respectively. This might suggest that the intervention was effective in broadening students' views to include glucose alongside oxygen, or at least to shift students' attention towards glucose as the main product instead of oxygen. This shift is apparent when it is noted in the pre-test that over half of the sample considered oxygen to be the only product, whereas in the post- and delayed-post tests only 4% and 10% of the sample, respectively, perceived oxygen to be the only product of photosynthesis.

6.2.2.2 Scientifically Inconsistent responses

This category is allocated to "Scientifically *Inconsistent*" responses that either (1) conceptually contradicted the model answer, (2) did not identify all or most of the requirements for, and products of, photosynthesis, or both (1) and (2).

As presented earlier in Figure 6.1, and shown in Table 6.1, about a quarter (*n*=31) of the responses in the pre-test were coded as "*Inconsistent*". However, in the post-test, 84% of these "*Inconsistent*" responses moved up to the "Scientifically *Consistent*" category. Also, 68.5% (*n*=19) of the responses that were coded as "*Inconsistent*" in the post-test changed from the responses that were coded as "*Other*" in the pre-test, while only three responses dropped down from the "Scientifically *Consistent*" category to "*Inconsistent*". This might suggest that the intervention had no negative effect on students' learning, as the general trend was a movement up towards the "Scientifically *Consistent*" category, with the exception of the delayed-post test, however.

Also, as Table 6.1 shows, there was only a slight increase (14%, *n*=3 out of 21) in the "*Inconsistent*" responses between the post- and delayed-post tests. However, this should be viewed within the context of the responses that dropped down from the "Scientifically *Consistent*" responses, which means that about one fifth of the "Scientifically *Consistent*" responses in the post-test dropped down to either the "*Inconsistent*" or "*Other*" categories in the delayed-post test. In other words, about 35% of the sample did not offer "Scientifically *Consistent*" responses in the delayed-post test. Bearing in mind the problems commonly associated with delayed-post tests, it is still significant, as 65% of the sample were able to offer "Scientifically *Consistent*" responses.

Table 6.4: Reasons for coding responses as Inconsistent

Reason	**Pre-**		**Post-**		**Delayed-post**	
	n	***%***	***n***	***%***	***n***	***%***
Missing reactants of photosynthesis	2	*(6.5)*	1	*(5.3)*	1	*(4.7)*
Missing products of photosynthesis	0	*(0)*	1	*(5.3)*	1	*(4.7)*
Missing components from both products and requirements	11	*(35.5)*	3	*(15.8)*	9	*(43.1)*
Conceptual contradictions, although reactants and products were provided	0	*(0)*	2	*(10.5)*	2	*(9.4)*
Conceptual contradiction and missing either reactants or products	18	*(58)*	12	*(63.1)*	8	*(38.1)*
Total	**31**	***100***	**19**	***100***	**21**	***100***

Furthermore, as shown in Table 6.4, inconsistencies in responses appeared in five cases. The less recurrent cases were when the respondent missed either requirements or products of photosynthesis, while the more common cases were when components were missing from both the reactants and products, which happened on 11, 3 and 9 occasions in the pre-, post- and delayed-post tests, respectively.

An interesting point to note is that only a small proportion of the sample offered responses that showed conceptual contradictions (e.g. offering soil, minerals as requirements alongside carbon, water and light energy) with the scientific view, although reactants and products were correctly offered. This instance only occurred in the post- and delayed-post tests, twice in each case. It seems that when students correctly identified the requirements and products, they were less likely to pose a conceptual contradiction by including soil and minerals as being responsible for food making. In other words, conceptual contradiction was often associated with a poor identification of the requirements and products. This might suggest that the teaching sequence helped students to systemically identify requirements and products rather than advancing mere memorisation.

6.2.2.3 Other

This category includes responses that missed the intended response to the probe by suggesting environmental conditions to be the requirements (e.g. fertilisers, minerals, watering, caring etc.), considering the visible agricultural crops to be the intended products (e.g. fruits, flowers, vegetables and crops etc.) or leaving the probe unanswered.

As mentioned earlier in Table 6.1, in the pre-test about half of the responses (*n*=59) were coded in this category, which might be attributed to ambiguity regarding the intention of the probe. However, when students recognised the context intended in the probe, they were more able to achieve the intended responses, irrespective of meeting the model answer. This assumption can be confirmed by the percentages of responses that were coded in the "*Other*" category in the post- (8%) and delayed-post (19%) tests. It should be noted that this decrease in "*Other*" responses does not imply that responses moved to the “Scientifically *Consistent*” category. Rather, about one fifth of these "*Other*" responses moved to the “*Inconsistent*” category, while two thirds moved to the “Scientifically *Consistent*” category. Yet, it is difficult to prove or disprove that those students, whose responses were coded as "*Other*" would have offered “Scientifically *Consistent*” answers if they had understood the probe as intended.

6.2.3 Concluding remarks

To conclude the presentation of findings related to the first probe, three issues can be highlighted. Firstly, acknowledging the struggle amongst students in the pre-test to recognise the intended response, the probe can be made clearer by providing signs to help students recognise that the probe is related to the food making process rather than general features of plants.

Secondly, it seems that the teaching sequence was effective in enhancing the attainment of factual knowledge related to photosynthesis, as specified in the first learning outcome. This can also be confirmed by findings from collected classroom work and end-of-lesson quizzes (see sections 5.7 and 5.8). Furthermore, it seems that this attainment was underpinned by an understanding of photosynthesis rather than a mere memorisation (see section 6.2.3).

The third issue is related to the implications for refining the Design Brief or the Worked Example. As the findings show that the students were more able to identify the requirements for photosynthesis rather than its products, which might be due to the considerable time that was spent addressing the causes of the implausibility of photosynthesis, there is a need to emphasise in the teaching sequence that glucose and oxygen are the products of photosynthesis.

The next section turns to present findings related to students' responses to the second probe.

6.3 Students' responses to the *Food Probe*

The *Food Probe* is phenomenologically-framed and aimed to assess the attainment of the second learning outcome which is related to explaining the source of plant food. As Figure 6.4 shows, the probe presents three statements and students were asked to choose the statement that they think is correct, and to justify their choice. The first and third statements represent well-documented ideas from students (see section 2.2.3) that plants obtain their food from the soil or that plants do not feed like animals, while the second statement, the correct choice, states that plants make their own food. By asking students to justify their choice, it was expected that they would build their responses based on the scientific explanation learnt from the intervention.

The model answer for the *Food Probe* is:

> *Plants make (or produce) their own food (or glucose, starch, carbohydrate) from the raw materials available in the environment, through a process called photosynthesis.*

Figure 6.4: The *Food Probe*

Question 2

- Three students were talking about plant food as follows:

  Ahmad says: 'I think that plants get their food from the soil.'

  Saleh says: 'I think that plants make their food'

  While Ali says: 'I don't think plants need food at all: only animals need food.'

– I think .... (choose one of the students above) is right, and the reason is:

  ____

  ____

  ____

With regard to whether the *Food Probe* was successful in probing students' understanding, there were some advantages and limitations. Indeed, searching for explanations might be challenging for Saudi students, as assessment practices in Saudi science lessons mainly focus on assessing recall of facts, names and definitions. In addition to this feature of the Saudi context, it has been reported in the literature (Pallrand, 1993; Southerland et al., 2001) that students seem to confuse why-questions (e.g. explain, give a reason) with what-questions (e.g. describe). I can confirm this issue, as I noticed in students' responses that they tended to elaborate on the nature of plant food instead of giving explanations of how plants obtain or make food. Apparently, this confusion regarding the intention behind the probe also applies to the paper-pencil probes where there are limited chances to re-phrase the probe or ask students for specific elaboration.

The next sub-section presents a general overview of students' responses to the *Food Probe* followed by specific features of their responses in terms of consistency with the model answer.

6.3.1 General overview

Irrespective of matching the model answer, Table 6.5 shows that there was a high response rate, as only 2.25%, 1.5% and 0.75% of respondents left the probe unanswered in the pre-, post- and delayed-post tests, respectively. This might suggest that the students were comfortable in responding to this probe.

As the probe consists of two items, there was variation amongst students in responding to both items or only one of them. As Table 6.5 shows, 86.25%, 92.45% and 92.45% of the sample in the pre-, post- and delayed-post tests, respectively, responded to the two items of the probe irrespective of whether the responses were correct or not. Only a small number of the respondents across the three tests left the two items unanswered, or responded only to the first item, i.e. choosing only a statement without offering a justification. Moreover, responses that contained a choice of more than one statement constituted 7% of the sample in the pre-test, but this decreased to about half of this proportion in the post- and delayed-post tests. In fact, choosing two statements might reflect a common misunderstanding in which the student holds two contradictory views; plants *make* as well as *absorb* food from the soil (see section 2.2.3). Such responses were coded as "*Inconsistent*" as they might mirror a conceptual contradiction.

Table 6.5: The variety of students' responses to the *Food Probe*

	Pre-		**Post-**		**Delayed-post**	
	n	***%***	***n***	***%***	***n***	***%***
Responded to the two items	113	*86.25*	121	*92.45*	121	*92.45*
Left the two items unanswered	3	*2.25*	2	*1.50*	1	*0.75*
Responded only to the first part, the choice	6	*4.50*	3	*2.25*	5	*3.80*
Responded only to the second part, the reason	0	*0*	0	*0*	0	*0*
Offered two choices of statements	9	*7.00*	5	*3.80*	4	*3.00*
Total	131	*100*	131	*100*	131	*100*

As specified in the coding scheme (see section 4.4.3.3), students' responses to this probe were coded in one of three main categories: (1) "Scientifically *Consistent*", whether "*Complete*" or "*Incomplete*", (2) "Scientifically *Inconsistent*" and (3) "*Other*". The coding focused mainly on the justification item of the probe, as it contained the required explanation that the probe intended to assess (with the exception of choosing two statements as mentioned above).

Table 6.6: A summary of results related to the *Food Probe*

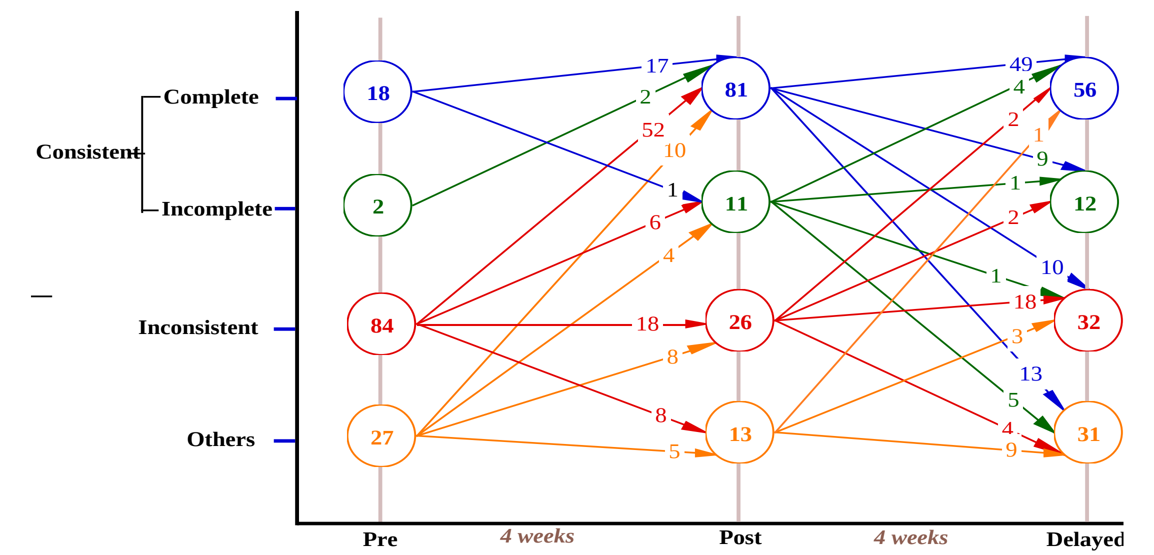
		Pre-		**Post-**		**Delayed-post**	
Category		***n***	***%***	***n***	***%***	***n***	***%***
Consistent	Complete	18	*13.5*	81	*62.0*	56	*42.75*
	Incomplete	2	*1.5*	11	*8.0*	12	*9.15*
	Total	20	*15.0*	92	*68.0*	68	*51.90*
Inconsistent		84	*64.0*	26	*20.0*	32	*24.40*
Other		27	*21.0*	13	*10.0*	31	*23.70*
Total		131	*(100)*	131	*(100)*	131	*(100)*

With regard to students' movements between the three categories across the three tests, Figure 6.5 and Table 6.6 show that only 15% of the sample offered "*Consistent*" responses in the pre-test, while the remaining 85% offered either "Scientifically *Inconsistent*" views (64%) or uncategorised responses (21%) that were coded in the "*Other*" category. After exposure to the teaching sequence, however, there were improvements in students' responses, as two thirds of the sample (*n*=92) offered "Scientifically *Consistent*" responses. According to the results of

McNemar's test analysis, the change in proportions of students who offered "*Consistent*" responses in the post-test (68%) was significantly higher (p<0.0001) than those in the pre-test (15%). In order to illustrate the source of this improvement, Figure 6.5 displays that most of these improvements came from students who offered "*Inconsistent*" responses in the pre-test.

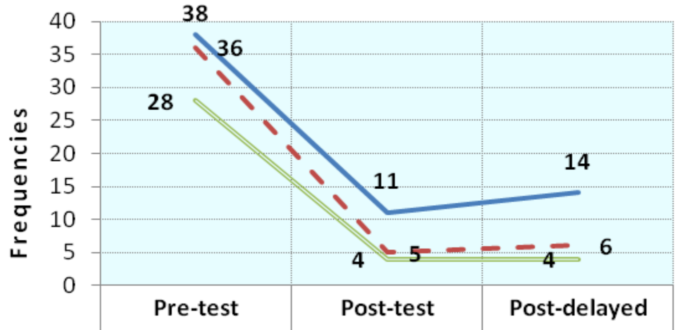
However, four weeks after the teaching sequence was completed, only approximately half of the sample (*n*=68) offered "Scientifically *Consistent*" responses, where most of the regression was in favour of the "*Other*" category. Although the improvement is still significant according to McNemar's test analysis (p<0.0001), these results might suggest that while the teaching sequence was effective in making an immediate improvement in conceptual understanding, it was less effective as a long-term effect as only half of the sample were able to offer "Scientifically *Consistent*" responses.

Figure 6.5: Students' progressing moves related to the *Food Probe*



With regard to the words that students used in their responses, Figure 6.6 shows that in the pre-test the words "soil" and "water" were the most frequently used, 38 and 36 times, respectively, while "minerals" was mentioned only 28 times. Immediately after completing the implementation, students largely abandoned using the words "water" and "minerals", whereas "soil" appeared only 11 times. The decrease in the use of these words might indicate how the teaching sequence helped students to cease using words that conflict with the scientific view. Furthermore, the use of the word "soil" across the tests might indicate how deeply it was rooted in students' beliefs, which therefore demands a particular emphasis in the teaching sequence.

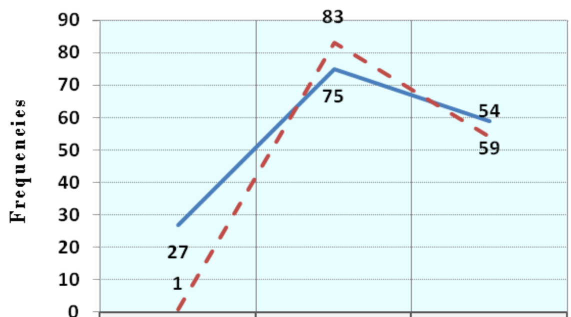
Figure 6.6: Number of responses using the words: soil, water and minerals



	Pre-test	Post-test	Post-delayed
Soil	38	11	14
Water	36	5	6
Minerals	28	4	4

In contrast, there was also a dramatic increase in the adoption of the words "glucose" and "photosynthesis" as shown in Figure 6.7. While the word "glucose" was mentioned by only one student in the pre-test, it was mentioned by 63% (*n*=83) of the sample in the post-test. Furthermore, there was an increase in use of the word "photosynthesis" between the pre- and post- tests from 20% (*n*=27) to 57% (*n*=75). However, there was a decline in the delayed-post test, as the words "glucose" and "photosynthesis" were used by only 42% and 45% of the sample, respectively.

Figure 6.7: Number of students' responses that used the words: glucose and photosynthesis



	Pre-test	Post-test	Post-delayed
Photosynthesis	27	75	59
Glucose	1	83	54

The next sub-section reports students' responses in terms of the three categories that were specified in the coding scheme.

6.3.2 Categorisation of students' responses to the *Food Probe*

The following sub-sections present a detailed categorization of students' responses according to the coding scheme.

6.3.2.1 Scientifically consistent responses

Responses included in this category are divided into two sub-categories, "*Consistent-Complete*" or "*Consistent-Incomplete*".

a) Consistent-Complete responses

Responses coded in this sub-category contained "*Complete*" responses that include all the features presented in the model answer. Table 6.6 shows that only 18 out of 131 students offered "*Complete*" responses prior to experiencing the teaching sequence. Immediately after the intervention, the number of "*Complete*" responses increased to 81 which constitute 62% of the sample. However, four weeks after the intervention was finished, only approximately 43% of the sample offered "*Complete*" responses. This decrease indicates that the teaching sequence was less effective in developing long-term understanding.

Furthermore, Figure 6.5 displays that most of the development towards the "*Complete*" responses in the post-test came from responses that were coded as "*Inconsistent*" in the pre-test. This might suggest that the teaching sequence was successful in promoting students' understanding of the source of plant food, therefore, moving students up into the category of "*Consistent*" responses. However, the drop of approximately 31% of the "*Complete*" responses in the delayed-post test raises concerns over the impact of the teaching sequence on the retention of conceptual understanding. In fact, this raises a question over whether the teaching sequence was attempting to develop conceptual understanding of the required explanations or just a mere memorisation of explanation that disappeared over time after students experienced the intervention. Perhaps a further delayed test may approve or disapprove such concerns.

b) Consistent-Incomplete responses

This sub-category involves responses that emphasise the autotrophic feature of plants, but fail to specify the nature of the food or how it is accessed. However, it is essential that the response did not contain any signs of contradiction with the model answer.

It should be mentioned, as shown in Table 6.6, that this sub-category did not constitute a large proportion of the sample compared to other categories, as only 2, 11 and 12 responses were coded as "*Incomplete*" in the pre-, post- and delayed-post tests, respectively. Furthermore, as Figure 6.5 shows, students who offered "*Incomplete*" responses in the post-test either moved up to the "*Complete*" sub-category or dropped down to the "*Other*" category. Interestingly, only one respondent moved down to the "*Inconsistent*" category. A possible reason for that is that students were in an ambivalent position where they could not offer a "*Complete-*

Consistent" response, perhaps because they were aware of erroneous views related to the source of plant food, so instead they chose to offer tautological answers that cannot be coded in any categories but "*Other*".

6.3.2.2 Scientifically Inconsistent responses

This category involves two main types of "*Inconsistent*" responses. Firstly, responses that referred to the food making process as well as obtaining food from the environment. In the pre-test, 7% of the sample chose the first and second statements as sources of plant food (e.g. plants absorb food from the environment and make it as well). It should be noted that the responses that represent this contradictory view concerning the source of plant food dropped by half in the post- and delayed-post tests.

The second type of inconsistency was when students only suggest that substances absorbed from the environment are food for plants without any reference to the food-making process. This type of consistency constituted about two thirds of the responses that were coded in this category in the pre-test. However, only one fifth of them continued to offer such responses in the post-test, and this increased to just less than a quarter in the delayed-post test.

With regard to the examples of plant food that students included in their "*Inconsistent*" responses, Figure 6.6 shows that in the pre-test "soil", "minerals" and "water" were the most commonly suggested sources. However, a dramatic decrease was noticed in the post-test. In addition, "soil" appeared to be the substance most referred to as a source of plant food across the three tests.

6.3.2.3 Other

This category encompasses uncodeable responses whereby the students offered tautological responses or left the probe unanswered. Table 6.5 shows that only a small proportion of respondents across the tests left the probe unanswered, namely 2.25%, 1.5% and 0.75%, in the pre-, post- and delayed-post tests, respectively. As previously mentioned, this might suggest that the students were comfortable with the questions asked in the probe.

Furthermore, Table 6.6 shows that, in the pre-test, only about one fifth (n=27) of the responses were coded as "*Other*", while this number was halved (n=13) in the post-test whereby the other half moved up to the "*Consistent*" category (see Figure 6.5). However, in the delayed-post test about 24% of the sample offered responses that were coded as "*Other*", which exceeded the proportions found in the pre- and post- tests. Surprisingly, more than half of these response came from the "*Consistent*" category. As previously mentioned, it seems that students were able to recognise that "soil" and "minerals" are not food for plants, but on the other hand they could not construct a scientifically acceptable explanation for the source of plant food.

6.3.3 Concluding remarks

To conclude this section, I highlight two key issues. Although the teaching sequence seemed effective in promoting students' conceptual understanding of the source of plant food, this was an immediate effect rather than a long-term effect. On the other hand, findings related to the words that students used in their responses, or movements down to the "*Other*" category rather than the "*Inconsistent*" category, might suggest that the students were aware of the scientific view, or at least recognised the erroneous view, although they were not able to construct a scientific explanation. Indeed, developing the scientific explanation involves demands that were not considered in the teaching sequence and were unfamiliar to the Saudi students.

The second issue is related to the examples that students suggested for plant food. As documented in the literature (see section 2.2.3), and showed in the findings from students' responses to the *Factory* and *Food* probes, as well as work collected from the classroom (see section 5.2), "soil" seemed to be the most common source for plant food according to students' views. This matter might deserve further research as to why students suggest soil more frequently than other substances, what they mean by soil "e.g. one source or a combination of sources", and ways to specifically target this example in the teaching sequence.

The next section presents findings related to the *Biomass Probe*.

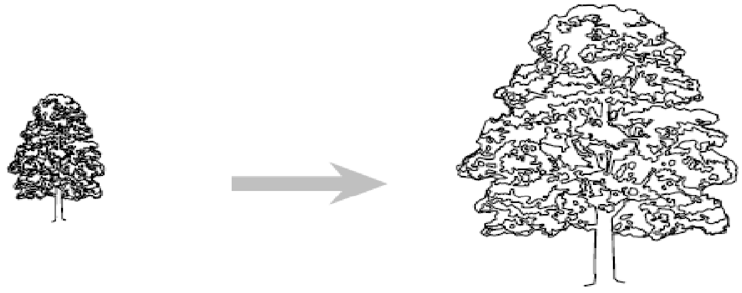
6.4 Students' responses to the *Biomass Probe*

This probe was phenomenologically-framed to assess students' attainment of the third learning outcome concerning developing an explanation for the source of extra biomass. As shown in Figure 6.8, the students were presented with a picture, based on Helmont's experiment, showing a small tree that had grown into a large tree over a period of 10 years, and the students were asked to explain the source of extra mass.

The model answer for the *Biomass Probe* is:

> *The extra mass comes from the food (or glucose, starch, carbohydrate) that plants make (or produce, form, obtain) through photosynthesis.*

Figure 6.8: *The Biomass Probe*



- A small tree is planted in a farm. After 10 years it has grown into a big tree. Where the extra mass comes from? Explain your answer as fully as possible.

It should be mentioned that during the teaching sequence (see section 3.4.5) the students were asked to perform a group activity which asked them to agree or disagree with Helmont's conclusion that the extra biomass came from water, which is similar to this probe. Interestingly, only three students mentioned Helmont's experiment in their responses, although only one of those was a "Scientifically *Consistent*" explanation.

It seems that the clarity of the probe was acceptable as only approximately one fifth of the pre-test responses were coded in the "*Other*" category (see Table 6.7). If the students, for example, were confused about the probe, they would either not respond or merely offer tautological responses, which was not the case. The clarity might be due to accompanying the probe with a picture that might have helped the students to be clear about the probe's intention. Yet, as previously mentioned in the *Food Probe*, Saudi students are not familiar with this style of assessment seeking explanations. If they had been used to this type of assessment, they would have been more able to deal with this probe.

The next sub-section presents a general overview of students' responses to the *Biomass Probe,* followed by specific features of their responses in terms of consistency with the model answer.

6.4.1 General overview

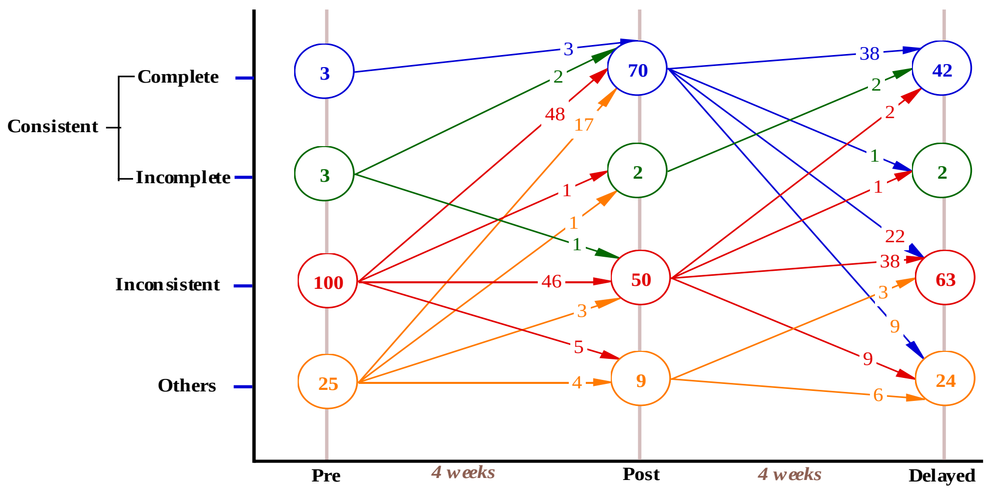
There was a good response rate to the *Biomass Probe*, namely 86%, 99% and 92% in the pre-, post- and delayed-post tests, respectively. Irrespective of whether students offered the right answer or not, this might indicate that they were comfortable in attempting to answer. According to the coding scheme (see section 4.4.3.3), results will be reported in three main categories: (1) "Scientifically *Consistent*", whether "*Complete*" or "*Incomplete*", (2) "Scientifically *Inconsistent*" and (3) *"Other"*. Table 6.7 shows frequencies and percentages of students' responses within each category, while Figure 6.9 shows students' movements between the three categories, before and after exposure to the intervention.

Table 6.7: A summary of results related to the *Biomass Probe*

		Pre-		Post-		Delayed-post	
Category		***n***	***%***	***n***	***%***	***N***	***%***
Consistent	Complete	3	*2.25*	70	*53.5*	42	*32.0*
	Incomplete	3	*2.25*	2	*1.50*	2	*1.50*
	Total	6	*4.5*	72	*55*	44	*33.5*
Inconsistent		100	*76.5*	50	*38.20*	63	*48.0*
Other		25	*19*	9	*6.80*	24	*18.5*
Total		131	*(100)*	131	*(100)*	131	*(100)*

In terms of consistency with the model answer, as shown in Table 6.7, the majority of the sample, namely 95.5% (*n*=125), did not offer "Scientifically *Consistent*" responses in the pre-test. Their responses were coded either "*Inconsistent*" (76.5%) or "*Other*" (19%) as they were uncodeable. After exposure to the teaching sequence, however, there was an improvement in students' understanding, as over half of the sample (*n*=72) offered "Scientifically *Consistent*" responses, which is a significant improvement (p< 0.0001) according to the results of McNemar's test analysis. Yet, this improvement dropped in the delayed-post test by 20%.

Figure 6.9: Students' progressive movements with regard to the *Biomass Probe*

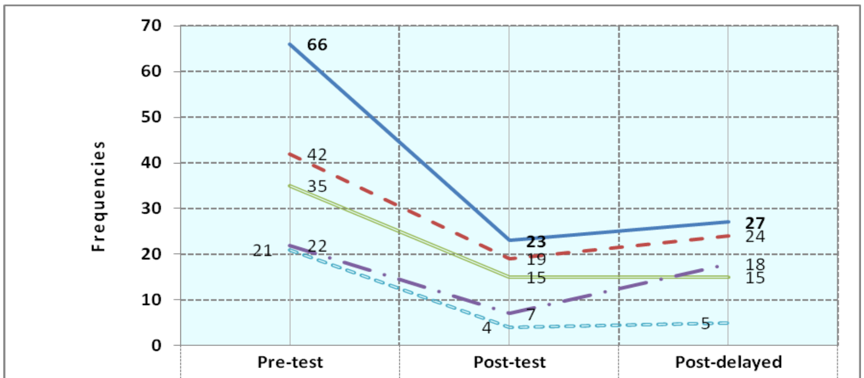


In addition, Figure 6.9 shows that most of the "*Consistent*" responses in the post-test (93%) came from responses which were previously coded as either "*Inconsistent*" or "*Other*", which might indicate how the teaching sequence helped 51% of the sample to move up to the "Scientifically *Consistent*" response. However, bearing in mind that only 55% of the sample offered "*Consistent*" responses in the post-test, this might indicate the challenging nature of this aspect of plant nutrition, as only approximately half of the sample were able to explain the source of biomass. Furthermore, 43% of the students who offered "*Consistent*" responses in the post-test failed to retain their level of response after a period of four weeks.

These results might indicate the modest number of students (*n*=72) who offered "*Consistent*" responses after immediate exposure to the teaching sequence, as well as the instability of students' understanding, as only one third of the sample retained their knowledge. However, taking into consideration the high proportion (76.50%) of the responses that were coded as "*Inconsistent*" or "*Other*" (19%) in the pre-test, it is clear that the intervention helped the students to move up towards offering "*Consistent*" responses in the post-test. On the other hand, this result might indicate how widely the source of biomass was misunderstood amongst students, and how this misunderstanding was resistant to change even after the students experienced formal teaching that was specifically designed to take account of these misunderstandings.

In terms of the words that the students either abandoned or used while explaining the source of biomass, Figure 6.10 shows that there was a decrease between the pre- and post-tests in the use of erroneous words (e.g. soil, water, care) that contradict the scientific view. However, in the delayed-post test there was a slight increase in the use of these words.

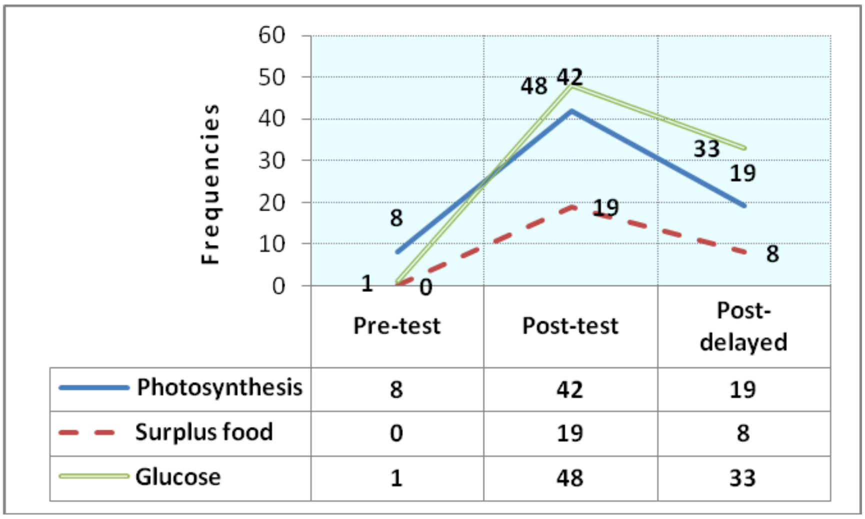
Figure 6.10: Students' use of words that might reflect scientifically inconsistent views



	Pre-test	Post-test	Post-delayed
Water	66	23	27
Light	42	19	24
Soil	35	15	15
Minerals	22	7	18
care	21	4	5

Looking deeply at these erroneous words, "water" was referred to most frequently as a source of biomass. This is not surprising when the role of water in a desert country like Saudi Arabia is considered, where direct watering is the only way to provide plants with water, as the rate of rainfall is very low. Therefore, from everyday observations, students might think that water does not only keep plants alive, but also makes them grow. This suggests that the belief that water is a source of biomass is deeply rooted amongst Saudi students, which might require specific attention when teaching the topic of plant nutrition and growth.

Figure 6.11: Students' use of the words: photosynthesis, surplus food and glucose



In terms of using words that are consistent with the scientific view, Figure 6.11 shows how students started and continued to use words such as “photosynthesis”, “surplus food” and “glucose”. With regard to the word “photosynthesis” in particular, although only eight students mentioned it in the pre-test (which might suggest previous knowledge, as mentioned in section 3.2.1), 42 students used it in the post-test.

In addition, the word “glucose” was mentioned 48 times in the post-test, which reduced to 33 times in the delayed-post test. It should be mentioned, however, that students used other synonyms such as “food” and “surplus food” when explaining the source of biomass, which is consistent with the model answer, but “glucose” and “photosynthesis” were the most used, and hence are presented here.

The next sub-section reports students’ responses in terms of the three categories, as specified in the coding scheme.

6.4.2 Categorisation of students' responses to the *Biomass Probe*

The following sub-sections present a detailed analysis of students' responses in terms of meeting the model answer.

6.4.2.1 Scientifically Consistent responses

Analysing students' responses to the pre-test shows that only 4.5% (*n*=6) of the sample offered “Scientifically *Consistent*” responses, which increased to 55% (*n*=72) after exposure to the teaching sequence (see Table 6.7). However, this increase was reduced in the delayed-post test, as only approximately one third of the sample offered "Scientifically *Consistent*" responses. Furthermore, within the "*Consistent*" category in the pre- and delayed-post tests, the "*Incomplete*" responses constituted only 2.25% (*n*=3) and 1.5% (*n*=2) respectively. This variation between "*Complete*" and "*Incomplete*" responses might indicate that offering a consistent explanation is a holistic task that is likely not to be divisible, as the components of the explanations systemically link to each other, and are therefore wholly offered. Another possibility is that the coding scheme emphasises either "*Complete-Consistent*" or "*Inconsistent*" (as they more straightforward to judge) responses at the expense of the "*Incomplete*" category. However, in applying the coding scheme, I tried to adhere to the criteria of inclusion, which might minimise such a possibility.

Results presented in this category will be reported through two sub-categories: "*Consistent-Complete*" and "*Consistent-Incomplete*".

a) Consistent-Complete responses

This sub-category involves responses that contain all the features presented in the model answer, irrespective of how they were worded. Table 6.7 shows that, prior to experiencing the teaching sequence, only three out of 131 students offered "*Complete*" responses. However, one week after exposure to the teaching sequence, over half of the sample (*n*=70) offered "*Consistent-Complete*" responses, which reduced four weeks later to about a third of the sample (*n*=42). This fall raises the question of whether the teaching sequence was effective in helping students to develop stable explanations for the source of biomass.

On the other hand, upon consideration of where these improvements in the post-test came from, Figure 6.9 shows that the "*Inconsistent*" responses were the main source, representing 68.60% of replies; in addition, about 24% came from responses that were coded as "*Other*". Hence, as previously mentioned, this result indicates how challenging the source of biomass was to students. As Table 6.7 shows, only 32 % of the sample continued to offer "*Complete*" responses in the delayed-post test, while the majority of the remainder offered responses that were coded either "*Inconsistent*" (48%) or "*Other*" (18.5%). Alongside the challenge experienced with regard to the source of biomass, it seems that insufficient remedy was offered in the teaching sequence to deal with the source of biomass.

b) Consistent-Incomplete responses

Responses coded in this sub-category did not explicitly mention that biomass comes from glucose or food produced in photosynthesis. Rather, reactants of photosynthesis or photosynthesis as a process were given as sources of biomass, provided they were free from any signs of contradiction with the consistent view.

Two key issues can be raised here. Firstly, as Table 6.7 shows, only a very few students offered "*Incomplete*" responses across the tests, namely 3, 2 and 2, respectively. As previously mentioned, when students start to believe in the scientific explanation they are more likely to offer a "*Complete*" explanation, as the components of the explanation are linked to each other. The second issue here is that the "*Incomplete*" explanations are unstable as they either moved to the "*Consistent-Complete*" or "*Inconsistent*" categories (see Figure 6.9).

6.4.2.2 Scientifically Inconsistent responses

Responses coded in this category suggest that biomass comes from water, soil and/or minerals. Also, even if these sources were not explicitly mentioned by referring, for example, to the roots, the responses were coded as "*Inconsistent*", as they reflect the view that the roots function as a mouth, which implies the plant obtains food from the soil. Other responses coded here were those that offered "glucose" alongside "soil" and "water" as sources of the extra biomass.

As presented in Table 6.7, results gathered from the pre-test showed that just over three quarters (*n*=100) of the sample offered "*Inconsistent*" responses, but only half of them (*n*=50) remained in the same category in the post-test. In the delayed-post test, however, about half of the responses from the whole sample were coded as "*Inconsistent*".

In terms of the examples that students offered for the source of biomass, "water" was the most frequently mentioned, followed by "light" and "soil", while "minerals" was less frequently mentioned. As previously discussed, considering the ecological nature of Saudi Arabia, references to "water" more than the other examples might be expected.

In addition, some students supported their erroneous explanation of why they think that water is the source for biomass with a quotation from the Quran which says "We have made every living thing from water" (The Prophets: 30). However, the quotation was misinterpreted because one of the likely interpretations could be "Every living thing is made of water, as its essential component" (Bucaille, 1980, p.124). Irrespective of the meaning of this quotation, an implication is to take account of other perspectives that students might possess whether they are derived from culture or religion. In particular, starting the topic with quotations from the Quran might interest and motivate students, as it fits with the Saudi culture and the framework of the curriculum.

6.4.2.3 Other

This category comprises uncodeable responses, whether they were tautological or the probe was left unanswered. Table 6.7 shows a drop in the percentage of the responses that were coded in this category from 19% in the pre-test to only 6.8% in the post-test. Interestingly, in the delayed-post test, 18.5% of students' responses that were coded as "*Other*" come from "*Consistent-Complete*" responses, which might confirm that students moved from "*Inconsistent*" responses to the "*Other*" category because they were not able to construct "*Consistent*" explanations.

6.4.3 Concluding remarks

To conclude this section, I highlight three issues. The source of biomass was the part of the topic that was least understood by students, and therefore the effectiveness of the teaching sequence can be questioned in this regard. However, considering that the teaching sequence succeeded in raising half of the sample from the "*Inconsistent*" category to "*Consistent*" in the post-test, it is clear that the intervention has had an impact.

With regard to the long term impact of the intervention, about one third of the students who offered the "*Consistent*" explanation in the post-test failed to retain their responses when they were assessed four weeks later. This limitation of the long term effectiveness might be explained by consideration of the activities related to the seventh KDF, which is concerned with practicing the scientific explanation (see section 3.4.7), as they were mostly directed to establishing the source of plant food rather than the source of biomass. Hence, an implication for refining the Design Brief and the Worked Example is to specifically enhance students' practice of the explanation of both the source of biomass and plant food.

The second issue is related to the competence of developing an explanation. As previously mentioned with regard to developing an explanation of the source of plant food (see section 6.3.2.4), developing an explanation might require additional practice related to the nature of an explanation and how it can be structured, which is absent from science lessons in Saudi. I will return to this issue in the discussion chapter when discussing refinement of the teaching sequence.

Thirdly, religion and science are strongly linked in Islam and, therefore, there are expectations in the curriculum that both teachers and students should bring the two perspectives together. As some students used a quotation from the Quran, the effect of this on learning science might be considered and techniques could be developed to use this source to enhance, or at least to avoid conflict, with science.

The last section presents a summary of findings related to assessing the learning outcomes and offers a general conclusion of the effectiveness of the design in meeting its aims.

6.5 Summary

Referring back to the introduction, where I asserted that the purpose of assessing the attainment is to measure the effectiveness (effectiveness 2) of the teaching in enabling students to develop the intended learning outcomes, and considering the findings that I presented in this chapter, I sum up the effectiveness of the three learning outcomes as follows:

- *1st Learning Outcome*: the teaching sequence helped the students to develop factual knowledge related to identifying the requirements for, and products of, photosynthesis. This conclusion is supported by students' responses to the *Factory Probe* which showed that 77% and 67% of the students in the post and delayed-post tests, respectively, offered the required information. In addition, students started using words associated with the scientific view (e.g. glucose, photosynthesis) and abandoned words (e.g. soil, minerals, fertilisers) that conflict with school science. Moreover, findings from students' responses to the end-of-lesson quizzes support this conclusion (see sections 5.7 and 5.8).
- *2nd and 3rd Learning Outcomes*: it seems that the teaching sequence was effective in enhancing short-term conceptual understanding related to explaining the source of plant food and mass, while it was less effective in enhancing students' ability to retain their understanding. In particular, students were less successful in explaining the source of biomass immediately after the implementation, and the majority failed to retain the required explanation after four weeks.

Furthermore, in light of these findings, several issues can be raised. To begin with, there is a need to strike a balance between developing factual knowledge and enhancing conceptual understanding. As mentioned in the last chapter (see section 5.9), the teachers covered all the required content, yet they were limited in employing pedagogic strategies in terms of interactive/dialogic talk that engages students and takes account of their ideas, and perhaps therefore enhances conceptual understanding.

Another issue is related to building students' competence in developing an explanation. Indeed, helping students to construct scientific explanations might require long practice that might go beyond designing a content-specific short teaching sequence. This raises the issue of what aspects the designer should consider when developing a content-specific design, and to what extent he can include elements that are not directly related to the content at hand, although they are crucial for developing the required outcomes. This issue will be further explored in the discussion chapter (see section 8.3.1).

In addition, there were content-specific issues that deserve consideration. For example, the word “soil” was apparent in students’ responses to the three probes across the three tests; thus, we may help students by specifically targeting this word and highlighting its limitations. In addition, the word “water” proved to be challenging, although not to the same extent as “soil”.

Moreover, in terms of the factual knowledge that students offered, they seemed more able to identify the requirements for photosynthesis than its products. Given that more time was devoted to deal with the requirements (see section 3.4.3), a further consideration of the products of photosynthesis would help students to develop the required knowledge.

These conclusions are drawn from analysing and assessing students’ responses to the written probes. However, what would the students and teachers say after experiencing the teaching sequence? This is presented in the next chapter (Chapter 7).

CHAPTER 7: TEACHERS' AND STUDENTS' PERCEPTIONS OF THE TEACHING SEQUENCE

This chapter presents findings related to teachers' and students' perceptions of the teaching sequence, which answers the 3rd RQ. The purpose for exploring their perceptions is to complement the findings obtained from analysing the actual implementation and assessing learning in order to inform refinement of the design; moreover, they will also enable me to suggest preliminary insights into how to approach schools with innovative initiatives in Saudi. Following the introduction, this chapter is structured around two main sections comprising teachers' and students' perceptions that include their stories, follow the emerging issues, and present a summary of their perspectives in terms of complementing other findings and implications with regard to reforming science education in Saudi Arabia.

7 CHAPTER 7: Teachers and students' perceptions of the teaching sequence

7.1 Introduction

As mentioned in Chapter 2 (see section 2.5), the third RQ is intended to investigate the question of "*How did the teachers and students respond to the key conceptual and pedagogical aspects of the teaching sequence?*", Hence, this chapter is devoted to answering this research question by analysing data gathered from teachers' and students' semi-structured interviews. As previously discussed (see sections 2.4.3.2 and 4.1), the purpose for exploring teachers' and students' perceptions of the teaching sequence was twofold. On one hand, issues raised by teachers and students may complement judgements about the effectiveness of the teaching sequence and decisions about what parts of the sequence need to be refined. One the other hand, as the Ministry of Education is reforming science and mathematics education, the preliminary insights drawn from this study can offer guidance on how to approach schools with innovative initiatives.

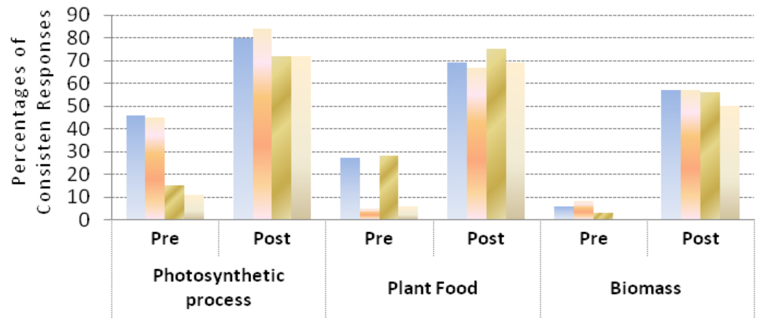
The main source for data used to answer this question was interviews conducted with the teachers and students one week after administrating the post-test; students were interviewed first. As indicated before (see section 4.4.4.4), both interviews were videotaped and transcribed for later analysis. The transcriptions were then qualitatively analysed by comparing similarities and differences within each group in the case of students, and between individuals in the case of teachers.

Following this introduction, this chapter is structured around two main sections related to teachers' and students' perceptions. Each section starts by providing an overview to capture the profile of the interviewees; it then delves into a detailed analysis of the views of the individual teachers or groups of students. At the end of each section, the emerging issues are consolidated in terms of the design's strengths and limitations, as well as issues related to the Saudi context.

Finally, at the end of this chapter, a summary is presented that brings together teachers' and students' views and outlines what their views can say with regard to refining the design and making suggestions for reforming science education in Saudi Arabia.

Before presenting teachers' and students' stories, this section will first briefly comment on students' achievements. As Figure 7.1 below shows, students' achievements in the post-test were alike across the three learning outcomes. This might suggest that students' experiences were similar in terms of teaching and learning with regard to this specific intervention. Therefore, it can be claimed that perceptions of the teachers and students resulted from similar experiences of the sequence rather than being affected by the teacher, in the case of students, or by students, in the case of the teachers.

Figure 7.1: Percentages of students' consistent responses



	Photosynthetic process Pre	Photosynthetic process Post	Plant Food Pre	Plant Food Post	Biomass Pre	Biomass Post
T1/N=26	46	80	27	69	6	57
T2/N=37	45	84	5	67	8	57
T3/N=32	15	72	28	75	3	56
T4/N=36	11	72	6	69	0	50

7.2 Findings from teachers' interviews

As previously mentioned (see section 4.4.4.4), the main data source for findings presented here was semi-structured interviews that were conducted individually one week after the post-test was administered. In addition, interview data was augmented by teachers' diaries, when appropriate. As presented in Table 7.1, a set of pre-prepared guided questions were used in the interviews. Each individual interview lasted for approximately 30 minutes on average.

Table 7.1: Guided questions used in teachers' interviews

1. How did you feel about the idea of teaching plant nutrition in a way that differs from your usual methods?
2. How did you feel after you had implemented the design?
   - How did you feel about yourself?
   - How did you feel about your students?
   - How did you feel about teaching biology?
3. Which aspects of plant nutrition were effectively taught? Why?
4. Which aspects of plant nutrition were poorly taught? Why?
5. How do you think the following strategies contributed to promoting students' understanding, and in which way:
   - Exploring students' ideas, Setting a conflict, Using an analogy, Group discussions and work, Interactive talk.
   - Which of the techniques mentioned above were most challenging? In which way? For whom (you, students, the topic, time etc.)? And why?
   - Which of the techniques mentioned above were most effective, and why?
   - Which of the techniques mentioned above would you want to use in your teaching, and why?
6. How do you rate the sequence in comparison to your usual teaching?
7. How did you rate students' engagement with the sequence?
8. Are there any ideas that you would like to talk about?

In terms of the analysis, as mentioned before (see section 4.4.4.4), I worked on the transcripts by highlighting the key points of interest related to conceptual and pedagogical aspects of the teaching sequence that were found in each individual's transcript. I then compiled an individual coherent story of each teacher.

The next sub-sections present the individual stories of each of the four teachers in four sub-sections. Each sub-section begins by providing a brief profile of the teacher linked to my observations of his performance and how his students performed in the written probes, as summarised in Figure 7.1. The purpose of providing these profiles is to enable the reader to make sense of the teachers' views in light of his profile and students' performance. Individual stories are then presented, supported by quotations in the teachers' own words, whether from interviews or diaries. Finally, looking across the individual stories, the section concludes by consolidating the key issues shared by the four teachers.

7.2.1 T1's story

T1 has been teaching high school biology for nine years (see Table 4.3, section 4.3.4.3). He seemed to be the one amongst the four teachers who agreed to participate in the study as a result of the researcher's position, as educational supervisor. In addition, he thought that his participation in this intervention would contribute to improving his practice. Indeed, he was committed to implementing the design as planned. As he said, he read through the teacher's guide for each lesson the night before, which I can confirm from my observations of his teaching. In terms of his actual performance, he was confident in the class and had full control of students' behaviour. Furthermore, he appeared to have a good relationship with his students, which can be confirmed by the friendly atmosphere in his class.

In terms of his usual teaching style, the lesson I videotaped prior to the actual implementation showed that he usually starts with a brief review of the previous lesson and asks students to recall the facts and definitions. This can be confirmed from the interview too, as he admitted that students are rarely taught biology practically. He gave two reasons for the lack of practical work, stating that:

> "First, equipment and apparatus aren't available, if I needed ten pieces of equipment, for example, nine of them won't be available in the lab. This is the biggest problem. The second thing is the lab itself. We're three biology teachers teaching three modules: Bio1, Bio2 and Bio3. The priority for using the lab is biased towards the advanced modules: Bio2 and Bio3. But because I teach Bio1, it most unlikely I will get a chance to do practical work in the lab".

With regard to T1's students' achievement in the post-test, Figure 7.1 shows that his students came second amongst other classes. However, before the implementation he was anxious about students' engagement and did not expect to see them as active participants:

> "I was surprised by their motivation. Some students rarely give attention to the lesson, even if they do, they do it only for the presence of the teacher, but this time they were really willing to participate".

Furthermore, he thought that students' engagement affected him as well, and improved his performance:

> "My performance in this intervention was better than normal, definitely better. I found a big difference because students were engaged and interested. One of the things that disappoints the teacher is when he feels that students aren't interested. But the teacher becomes motivated when he finds students active, engaged and ready for everything, which I found in this intervention".

When I asked him specifically about the features of the intervention that affected him and his students, he pointed to the learning activities that students were asked to take part in during the lessons:

> "It's the way in which the ideas were presented. Ideas can be presented orally and passed to the students, but it's rare when they get it. But in this intervention, they were involved in motivating activities like the one modelling glucose".

Specifically, regarding the activity of building a model of glucose, he quoted one of his students who appreciated the effect of this activity:

> "…students won't forget the shape of the glucose, and will remember how it is formed. As one of the students told me "I didn't know that chemical reaction is…I mean, this simple, just by breaking down atoms of carbon dioxide and water, and then re-arranging them differently to make up a different molecule, glucose. I was confused about chemical reactions, but when we made up the glucose and got oxygen as a leftover, I understood what is meant by a chemical reaction".

In addition, he particularly emphasised the practical work that was conducted in the form of teacher-led demonstrations. He thought that:

> "Practical work delivers the idea directly to the student without putting pressure on them nor presenting too many theoretical facts, it keeps students focused naturally and fully".

To illustrate his point regarding the impact of demonstrations on students' learning, he mentioned the demonstration illustrating that carbon dioxide has weight:

> "…students grasped concepts in the demonstration that would otherwise be difficult if you just tell them about it. I can recall one of the students saying "I didn't know that air has weight, it's impossible, but the experiment really proved that".

This demonstration, which was not directly related to the content introduced in the textbook, made T1 realise that there are demands that ought to be addressed to help students understand biology; as he put it:

> "The intervention helped in improving students' understanding of concepts that go beyond plant nutrition *per se* to other chemical and physical concepts, which are essential to understanding biology".

As a result of these features of the teaching sequence, it appeared that his approach to teaching biology had also improved. He explained by saying:

> "The only problem with biology is that it's a theoretical subject which differs from chemistry and physics where most of the teaching is based on experiments. Biology is mostly delivered through talk, introducing theoretical facts that students should memorise. But after the intervention, my view has changed. There is a chance to do 50% of the teaching through practical work. But as I said early, there are difficulties involved in doing practical work in our school".

Indeed, his participation gave him an opportunity to reflect on his usual practice and the way biology was taught. As he clearly stated:

> "We teach biology, and maybe all subjects, through lecturing, writing on the board and then asking students to copy down and memorise. The same procedure is repeated everyday".

In contrast, he saw this new approach as promising in terms of making a shift from traditional teaching:

> "We hope that we can find innovations like this intervention that can change the theoretical way of teaching biology. We wish to reach a day when students believe that biology cannot be learnt through memorisation. Rather, it's a subject that should be learnt through understanding, like math and physics".

However, he believed that there are barriers to transferring biology teaching to such an innovative style. Apart from the unavailability of labs and the shortage of equipment he mentioned earlier, he pointed out other two problems. The first barrier was:

> "…the amount of facts presented in the textbook enforces use of the lecturing style. But teaching in this approach requires working with a small number of concepts over a sufficient amount of time. I teach photosynthesis, for example, in one lesson of 45 minutes, while I taught it in this intervention in five lessons. Students are taught a lot of facts and they have no time to study them for understanding, so they just memorise".

Another problem that limits using this approach was the assessment regime:

> "We only use paper-and-pencil tests in biology. So even if we do practical work, students won't pay attention because they know it won't be tested. However, if we say to students '*you will be tested on practical work*', only then will they pay attention".

When he was asked if there were any challenges he encountered while teaching the design, he thought that the challenges were pedagogical rather than conceptual:

> "…the challenge lies in the method used, lesson flow and movements between ideas and concepts. I found it new for me to teach through groups and to manage students' questions and ideas. Students are not familiar with this approach too, so there was pressure in making a sudden shift to this approach".

Of the pedagogic strategies incorporated in the design, he thought that eliciting students' ideas was the most challenging as "…students weren't used to being asked about things that they haven't been taught. They expect you to ask them about the previous lesson". He added that he needed more time to prepare himself for probing students' ideas "…as students hadn't come across such techniques, I needed to devote more time to preparing how to start and close the eliciting question". Indeed, as presented in Chapter 5 regarding the actual implementation, his style of eliciting ideas appeared to be collecting students' ideas rather than elaborating and building on the ideas accumulatively (see Excerpts 5.1 and 5.9).

In terms of the limitations of the design with regard to promoting students' understanding, he mentioned that the design was limited in tackling the role of light energy. He stated:

> "I'm not sure if the students understood the role of light energy in photosynthesis. I think they didn't get it. What we said was that sunlight is used in photosynthesis. But how it's used, this is still a mystery and we need to work further on this. Maybe you can add an activity to explain this important aspect".

In addition, in his diary he pointed to another problem with the activity regarding Helmont's experiment because Helmont was described as a "scientist"[1] which might have affected students' reasoning about the validity of his conclusion:

> "It was hard for them [*students*] to believe that a science scholar like Helmont was wrong in his conclusion. I would suggest that he is not described as a scientist or scholar, or just keep the issue open without any conclusion and let the students make up their own minds".

7.2.2 T2's Story

As shown in the teachers' profile (See table 4.3, section 4.3.4.3), T2 appeared to be the least experienced of the participating teachers, with only four years practice of teaching high school biology. In addition, based on my observations of his actual teaching, he was the least enthusiastic as his teaching of the teaching sequence relied, as he admitted, only on what was presented in the introductory sessions. During the teaching, however, he appeared confident both in terms of managing the class and introducing the content of the teaching sequence.

As shown in the video that I recorded prior to the actual implementation, T2's usual teaching style is to begin by reviewing the previous lesson and ask students to respond to short oral questions. He then starts the new lesson by first introducing the title of the topic, and maybe raising a question as an entry point. His style of teaching can best be described as lecturing supplemented by teacher's questions and students' short answers. However, most of these questions are only used to present new scientific ideas rather than to engage students in dialogue. Furthermore, he said that most of his teaching took place in the classroom rather than science labs, as they were devoted mostly to physics and chemistry lessons.

In terms of how his students performed in the written probe, Figure 7.1 shows that they gained the highest results with regard to the first probe, while they were at about the same level as the others in the other two probes. However, prior to the implementation, he was not optimistic about students' active participation in the intervention. As he put it:

> "I didn't expect the students to be interested in, and engaged with such a demanding approach; to be honest; students do not want to make big efforts".

In addition, he was not optimistic about his performance either. He expressed his concern over taking part in the intervention due to a "…lack of a full understanding of the content of the

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[1] In Arabic, the words "scientist" and "scholar" are used interchangeably, and the word "scholar" is used historically to describe religious scholars who have an authoritative voice when it comes to religious matters. Therefore, it was possible that students were thinking of this authority even in the context of science.

teaching sequence". So, perhaps because of that, he suggested including in the introductory sessions "…something tangible like, for example, presenting short videos of a teacher, teaching according to this approach". In addition, he preferred making the teaching sequence more prescribed by adding:

> "…some annotations to determine precisely when during the teaching to explain an idea, to hand over responsibility to students or to ask questions and so on".

However, after the implementation, he changed his opinion of students' engagement, saying that "…students had benefited from the sequence and learnt things they hadn't ever thought of". When he was asked about the aspects of the design that were beneficial, he pointed to the:

> "…active participation, students were offered opportunities to share ideas which enhanced self-confidence, as students voice their ideas irrespective of they were correct or not".

He went further by making comparisons between this new approach and the usual practice, where students are:

> "…accustomed to a dictation teaching style wherein the student is a receiver and his only role is to copy what is presented by the teacher. But when they come to be active participants, even without a textbook, they felt that they owned the lesson themselves, that it did not belong to the teacher who delivers the lesson and leaves the class".

In particular, T2 stressed the activities used in the sequence, as they were:

> "…concrete not theoretical, so students were engaged with them. In fact, students don't pay attention unless they see something concrete…[*and*] conducting these activities through group-work kept students motivated, engaged and competitive".

He also thought that the teaching sequence was not only beneficial for students; he found it helped him too in improving his own knowledge of content related to photosynthesis. In particular:

> "…with regard to the question 'Do plants release carbon dioxide during the daytime?' The knowledge we have and present to students is that plants respire during the night while they photosynthesise during the day. These were basics in my view. But to say that respiration occurs during the day too, and releases carbon dioxide, there is a lot of confusion here, even I am confused".

As a result of these advantages, he will teach photosynthesis next year according to this approach, but "…won't follow the same sequence of the lessons and timing". When he was asked why he did not wish to follow the full package, he mentioned the restraint imposed by the amount of content presented in the textbook, which cannot all be covered using this new approach. In addition, he said that there is another barrier related to the time needed to adopt such an approach, as:

> "…this approach is time consuming and we have only 45 minutes allotted to teach photosynthesis, so what to focus on and what can be discussed?"

7.2.3 T3's story

T3 is experienced with 16 years practice of teaching high school biology (see Table 4.3, section 4.3.4.3). In addition, he is an award holder for distinct science teaching in the Gulf countries[2]. Due to his outstanding performance, he has been involved in several local projects established and run by the Science Department at the General Directorate for Education in the Riyadh region. Apart from other duties in the school, he is the senior science teacher and is responsible for teaching Year 12 classes, which is usually entrusted to the most highly qualified teacher in the school.

When I visited the school to ask them to participate in the study, the headteacher left the decision to T3. Once he was convinced by the programme, he arranged an informal meeting with the other teachers to discuss the details. Throughout the introductory sessions and actual implementation, he made all the necessary arrangements. His personality and long years of experience have provided him with self-confidence, which was apparent in his ability to manage his classes which gives the advantage of quality teaching.

Figure 7.1 shows that his students were slightly better than other students with regard to providing consistent views of the nature of plant food, and they were the ranked second in comparison with other classes in offering consistent responses for the source of biomass.

In terms of his view of the teaching sequence, he seemed very positive. When he was asked to rank the programme he stated that

> "The overall results exceeded my expectations; I would rank it [*the programme*] as very good, maybe excellent in some aspects with some students."

Although he did not specify the areas in which his students were good or excellent, he found that "…the intervention was useful in enhancing learning and better than usual practice".

Although T3 was enthusiastic about participating and very supportive, he did reveal that he was worried about his success. He attributed that to his own personality "I'm always worried

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[2] The *Gulf countries* include countries located in the area surrounding the Arabic Gulf, namely, Kuwait, Oman, Qatar, the Kingdom of Bahrain, the Kingdom of Saudi Arabia, and the United Arab Emirates.

when I’m asked to participate or contribute to any programme". In addition, he was not sure how he would perform because:

> "…the programme was new for me, it might not be new as content, but maybe the teaching approach, I wanted to implement it appropriately as required, without amendments".

In terms of the differences between his usual practice and the new approach, he identified two variants. Firstly, he said that he uses an interactive teaching style like the one in the new approach, however:

> "…the dialogue I adopt is different from the one in this programme. I used to distribute students into groups and assign a topic to each group to teach the rest of the class".

The other thing that was different is:

> "…the activities used in the programme, they are new and creative, we might mention a few of them in our normal teaching, but have never implemented them in the way described in this sequence".

In particular, he mentioned that these activities were useful due to some features, like being:

> "…student-centred and specifically motivating passive students, who I really want to engage, so they can write something in exams rather than handing in blank exams sheets".

Alongside the effect that the teaching sequence had on students, he believed the process also had an effect on him. He thought that the intervention had affected him in two respects:

> Firstly, "…the thing that I was most impressed by is the teaching/learning activities used to introduce and develop the scientific ideas".

In addition, he said that the sequence contributed to clarifying his content knowledge with regard to the concept of food:

> "To be honest I found a variation between my own understanding of what food is and the one introduced in the sequence".

Apart from these advantages, he noticed a limitation in terms of the time allocated for teaching the sequence which seemed to be insufficient, so he suggested adding one more lesson:

> "I was under time pressure to cover the content and conclude the lessons, I think if the sequence was taught through six lessons instead of five, this would release the pressure and give the teacher some space to follow up some ideas".

In terms of whether he was challenged by some aspects of the teaching sequence, he pointed to the style of the pedagogic strategies incorporated in the teaching. In particular, he believed that:

> "…eliciting students ideas could be challenging if the teacher wasn't prepared. For example, I tried to elicit Grade 12 students' ideas, in a different topic though, but I was struggling, then I gave up. I realised that I needed to have some knowledge of their ideas before exploring them, which requires some research about students' ideas on this particular topic".

When he was asked whether he plans to use this intervention next year, he confirmed that he will, but preferred to implement the sequence with his own plan and timing:

> "I could do it [*the teaching*] better if I was not restricted to a certain plan or time, if I can't, for example, conclude an idea in this lesson, I'll carry it on in the next lesson".

7.2.4 T4's story

As shown in Table 4.3 (see section 4.3.4.3), T4 has five years of experience of teaching high school biology. At the time of the study, he was undertaking an MSc in environmental sciences. His attitude to the intervention was positive. In addition, he seemed to come prepared to the lessons and try to follow the sequence scenarios as fully as he could. With regard to his students' achievements, Figure 7.1 shows that they were slightly lower than those of other classes. In addition, he was struggling to manage students' behaviour during the group activities and to give them equivalent opportunities to share their ideas.

In terms of his expectations prior to the implementation, like the other three teachers, he expressed his worries because of the nature of the approach and how students might respond. As he put it:

> "When I first looked at the materials you gave us I was shocked by the number of activities and the time allocated to implement them in the class … [*also*] I didn't expect students to actively participate in the intervention, however, they were highly engaged and motivated, which was really very nice".

When he was asked whether he saw any differences between the new approach and the usual practice, he pointed to a significant feature of the teaching sequence in which:

> "...the focus on enhancing understanding. Unfortunately, biology is being learnt through 90% memorisation and only 10% understanding. Teachers teach biology theoretically through introducing mere facts. This is what we have in our schools, and we really need to use such activities to change this situation".

Furthermore, he mentioned some of the features that made students motivated and engaged:

> "…the learning activities, eliciting students' ideas, dialogic teaching and group discussion were the most effective techniques used in the intervention….[*in particular*] the learning activities were designed to enhance understanding rather than factual recall".

Specifically, he stressed the importance of eliciting students' ideas. He described this importance:

> "…in this strategy, you explore students' ideas deeply, and then build on these ideas to guide students to the intended concept. Also, conducting this strategy through groups gave all students the opportunity to express their ideas. … [*However*], it's a challenging strategy as the teacher might get ideas from the students that he didn't expect, which can be embarrassing".

Furthermore, in addition to the effect of the teaching sequence on students' learning, he felt the sequence affected him in terms of improving his content knowledge with regard to the reason why plants convert glucose into starch. He stated:

> "The reason that plants convert glucose into starch, this was new for me. Although we learnt it in university, we learnt it quickly and vaguely".

However, despite the advantages of the teaching sequence, he thought that there was a limitation in terms of the time allocated. He felt that he was under time pressure because needed during the teaching:

> "…to implement the activity and to give students the opportunity to present their ideas. There's no time for all of that. We might need to re-sequence the activities and teach the intervention over six lessons instead of five".

In terms of whether he was planning to use the teaching sequence to teach photosynthesis next year, he confirmed he will use it "…because I implemented it and saw how students were effective and engaged". However, he thought that:

> "…there is a time limit as the allocated time in the timetable doesn't allow using this approach, including all its features".

7.2.5 Emerging issues from teachers' stories

The purpose of this sub-section is to consolidate the key issues shared by the four teachers. Four main issues were identified with regard to how the teachers respond to the design: the difference between their usual practice and the new approach, implications that can inform refinement of the design and whether and how they will use it in the future. Within each issue, I provide my own reflections as well.

7.2.5.1 From worry to surprise

It seemed that all four teachers were enthusiastic about participating in the study, although they were worried as a result of the features of the new approach as well as how students might respond. This might be understandable when we consider that both teachers and students are immersed in a context which is lecture-based and teacher-led in which factual recall is favoured at the expense of developing conceptual understanding. Therefore, the teachers were concerned about the negative impact of usual practice on the effective implementation of the teaching sequence. As T1 put it:

> "We are both, teachers and students alike, accustomed to traditional teaching in which we lecture and students copy, but suddenly you asked us to use group discussion and activities".

In addition to the effect of conventional teaching, the teachers were worried about their competencies to meet the demands placed by the new approach in terms of its "…theoretical base and associated methods" (**T3**), as well as the practicality of implementing the teaching sequence considering "…the number of activities and the time allocated to implement them" (**T4**).

Another source of concern might be caused by the content of the teaching sequence, although it was not so apparent or explicit. Only T2 explicitly mentioned the "…lack of a full understanding of the teaching sequence". He particularly pointed to the confusion between the occurrence of photosynthesis and respiration during the day and night. Other teachers, however, mentioned the content only in the course of how the teaching sequence contributed to improving their content knowledge with regard to some problematic aspects of photosynthesis such as the concept of food (**T3**), and the reason that plants convert glucose into starch (**T4**). In fact, this might suggest that the teachers were not fully aware of these details of the content; therefore, they were concerned about their own understanding of the content presented in the teaching sequence.

These causes of concern might reflect their first impressions when they were first introduced to the teaching sequence. However, these worries and low expectations disappeared after the implementation. Indeed, all the four teachers expressed that students were "…highly motivated to participate""(**T3**), "engaged""(**T1**) and "…did very well"(**T3**). They believed that students' engagement was real rather than artificial or due to the teacher's authority. In fact, students

"…were given space to talk and were not restricted; in addition, there were new activities which added some actions in the class" (**T3**).

To conclude, it seemed that the teachers were worried, on one hand, by the effect of the conventional practice and the pedagogical and conceptual features imposed by the teaching sequence. So, how can the designer help the teachers to meet these challenges? As suggested by T2, the teachers might need to see exemplary teaching that was performed using the features of the teaching sequence, so they can see that it does work in natural classrooms. In addition, the teachers mentioned time pressure. Factoring in extra time may help teachers to develop their competencies and confidence in both the pedagogical or conceptual aspects. Also, they can be supported by spelling out the problematic aspects of the content, or the underlying principles of the design itself, which might enhance their confidence.

7.2.5.2 It's different and useful, although demanding

When the teachers compared the usual teaching and the new approach, they were aware of some of the limitations of the traditional teaching such as emphasizing the passive role of the students (**T1**) and calling for factual recall at the expense of encouraging understanding (**T4**). On the other hand, they recognized that the new approach had certain useful features such as "[*the*] active participation [*in which*] students have opportunities to share ideas…irrespective if they were correct or not"(**T2**). In particular, they attributed the usefulness of using learning activities as the activities were "new and creative"(**T3**), and aimed at "…enhancing understanding rather than factual recall"(**T4**). Furthermore, they thought that eliciting students' ideas was very useful. However, they believed that it requires prior preparation to find out what sort of ideas students might possess (**T3**), otherwise "…the teacher might get ideas that he didn't expect, which can be embarrassing"(**T4**).

Alongside supporting students' learning, they found that the teaching sequence also helped them to improve their content knowledge (**T1**). Examples of these improvements were related to some problematic aspects such as the concept of food (**T3**), the fact that plants respire in the day and at night, (**T2**) and the reason that plants convert glucose into starch (**T4**). In addition, it seemed that their images of biology teaching and learning were improved. While the stereotypic image of biology teaching rests on delivering facts and definitions though lecturing, they now believe "…that there is a chance to do 50% of the [*biology*] teaching through practical work"(**T1**).

To conclude, the teachers' attitudes towards the design were very positive. Furthermore, they recognised one of the distinct features of the design which is taking account of students' prior ideas, and they appreciated how useful it was in supporting students' learning. They were also aware of the demands placed by using such an approach, particularly when it was associated with interactive/dialogic talk. As presented in the analysis of the actual implementation, the teachers tended to stop at collecting students' ideas rather than building on the ideas or asking students for elaboration (see section 5.9.2).

On the other hand, it seemed that the effect of the intervention extended to improving teachers' content knowledge and image of biology teaching and learning. So, to what extent can such an intervention be used as a professional development approach? Considering that the actual time spent with regard to this intervention was about 12 hours (introductory sessions plus the implementation), this can be comparable to the time spent on a professional development courses. However, in this intervention there was a two-way effect on both teachers and students simultaneously. To this end, it might be useful to target the areas of biology which prove to be difficult to understand by developing teaching sequences to be implemented in schools. In such a way, alongside generating useful kits to be used in the classrooms, both teachers' and students' learning will improve.

7.2.5.3 Some revisions are needed

It seemed also that after the implementation the teachers were in a position to make suggestions with regard to refining the design. The first suggestion concerned the time pressure imposed by the design, as they were asked to implement the sequence in only five lessons. Three teachers (**T1, T3, and T4**) suggested that it would be more realistic if the design was implemented over six instead of five lessons. The reason for the extra lesson was to free teachers from pressure and to find time to listen to students' ideas. Yet, whether the required extra lesson was necessary due to a real shortage of time caused specifically by the amount of content and associated activity or the general novelty of the new approach in which teachers needed more time to adapt and understand, is open to question. In this respect, as the design was only implemented in one cycle, it is difficult to make a judgement in terms of the time limit.

In terms of suggestions that were related to refining specific aspects of the teaching sequence, the teachers raised two points. Firstly, it seems that a cultural characteristic should have been taken into account in terms of Helmont's experiment. In particular, describing Helmont as a "scientist" might have affected some students. As T1 put it "It was hard for them [*students*] to believe that a scholar like Helmont was wrong in his conclusion". Indeed, students live in a culture where scholars are knowledgeable, so it is not likely that a wrong conclusion would be reached. As a result, students chose to follow Helmont's conclusion rather than to challenge it.

A possible way to resolve this problem, as suggested by T1, is to keep the activity open without referring to Helmont's final conclusion.

The second specific point about refining the design was related to the role of light energy in photosynthesis. This issue was also confirmed by the analysis of the actual implementation (see section 5.9.3) as well as students' interviews (see section 7.3.4.3). As this aspect was briefly touched upon in the teaching sequence, students might know that light energy is important for photosynthesis but "…how it's used, this is still a mystery and we need to work further on this"(**T1**).

To conclude, referring back to the fact that the purpose of exploring teachers' perceptions about the teaching sequence is to inform decisions on refining the design, the teachers raised concerns that could not be solely revealed by findings from the analysis of the actual implementation or from assessing students' learning. For example, the time issue will be more appreciated by the people who enacted the teaching in the classroom.

Furthermore, I have identified a limitation that arises when a design is implemented and evaluated in only one cycle, which leaves some questions unanswered. A second cycle might help in validating the changes that were made in the light of the evaluation of the first implementation.

7.2.5.4 I'll use it, but…

Although the teachers appreciated the positive impact that the design brought about, whether on themselves or on their students, and they did plan to re-use the teaching sequence or at least parts of it, they "…won't follow the same sequence of lessons and timing" (**T2**), and would teach it over six lessons (**T3**).

In addition, it seems that personal willingness to use the teaching sequence in future was dominated by the system in which they participated. For example, the textbooks impose an approach that emphasizes telling facts in order "…to cover the content"(**T2**). Moreover, there were problems related to the availability of "equipment and apparatus" and places to carry out science experiments and hands-on activities (**T1, T2**). Above all, the assessment regime indirectly favours using factual teaching, since students will only pay attention to elements that are included in exams (**T1**).

The constraints imposed by the context can limit adoption of the teaching sequence in the long-term. It appeared that it was not enough for the teachers to appreciate that a given approach is effective in enhancing students' learning. In fact, they work in a system where they are affected by several factors. Indeed, improving practice is not only a matter of developing well-designed teaching sequences and enabling teachers to enact them. Rather, it involves making a systemic change that starts out to include, amongst other things, making resources available and adapting assessment practices.

The next section present findings from students' interviews which are compiled in three categories: high, average and low achievers. It concludes with some issues shared by the three groups.

7.3 Findings from students' interviews

As mentioned in section 4.3.4.2, a total of 131 students, aged 15-16, from four different classes (in two different schools) took part in the study. Students are usually distributed between classes in equal proportions, according to their achievements in the previous year's examinations, and all abilities are represented in all classes. Therefore, classes seem relatively equal, whichever class is selected.

As mentioned before (see section 4.4.4.1), the source for data presented here was from semi-structured interviews conducted with students as groups according to their performances in the post-test. A total of 48 students were interviewed, which represents 36% of the whole sample. Each group were interviewed for 15-20 minutes, but it should be noticed that the high achievers' interviews were longer and richer. As shown in Table 7.2, a set of pre-prepared questions were used to guide the interviews.

Table 7.2: Guided questions used in students' interviews

1. Did you realise that the teacher's practice was different from his usual teaching?
   - What was new?
   - What was the same?
2. How do you rate your learning in plant nutrition compared to other topics in biology? Better, the same, worse?
   - Which parts do you think understood very well? "Look at your notes of the lessons".
   - Which parts do you feel couldn't understand? "Look at your notes of the lessons".
3. Which of the following did you like or dislike and why?
   - Being aware of your ideas.
   - Group discussion.
   - Talking to the teacher and other students.
4. Which one of the techniques above affected your learning, and in what way?
5. How do you see learning biology after experiencing the sequence?
   - Compare biology to other science topics.
   - What kinds of study skills are required?
6. Are there any ideas you would like to talk about?

In terms of analysing students' interviews, as mentioned in section 4.4.4.4, I started with the transcripts from the high achievers and moved on to those of the average and low achievers, successively. I first highlighted and labelled the key points related to the conceptual and pedagogical aspects of the design. Then I developed a story for each group that consolidates the key points shared across the three groups at the same level.

This section begins by presenting the story of the high achievers, followed by the average and low achievers. Within each story, I include quotations from students' words making reference to the group's level (**H**= high, **A**= average, **L**= Low), the number of the group within the level (**G**=Group 1, 2 or 3) and a digit to denote the number of the students within the group (**S**=students 1, 2 or 3). Then I present the shared issues emerging from the three stories.

7.3.1 High achievers' story

When the high achievers were asked about the differences between the new approach and teachers' usual practice, they pointed out some of the limitations of the teaching they experienced in normal biology lessons. They described a lesson that is led by a teacher who;

> "…writes the title and then starts lecturing, there is no discussion and we barely participate. Before the end of the lesson, the teacher asks us to write the information down in our notebooks, and we might get the chance to ask for clarification if we didn't understand something" (**H, G1, S2**).

In fact, this represents the most common procedure that teachers follow in Saudi schools. In addition to this approach, some teachers can fall short of this procedure and only "…write on the board or dictate" (**H, G3, S1**), or focus only on the textbook and ask students "…to underline the key ideas…and memorise them"(**H, G2, S1**). To sum up what happens during the lessons, the students focus on the teacher as the one who has the authority, does most of the talking and gives orders. As the students put it, the teacher "…talks and talks and talks and the information is poured down on us"(**H, G3, S1**). It seems that the perceived problem was all about the teaching methods, not the content *per se*, because students thought that "…the content is good but the problem is how to teach it"(**H, G3, S1**).

As a result of these conventional practices, the students portrayed an image of biology as "…a memorization subject where teachers lecture and we record and recall"(**H, G4, S2**). Indeed, learning and maybe even schooling was affected by the ways that teachers teach, so "…studying becomes boring and you know, you dislike that, when you only write and memorize"(**H, G3, S1**).

This is how students perceived usual practice in biology lessons. So, how did they find the new approach? It seemed that the students first experienced changes within the teaching itself. As one of them put it, it was the "…first time that I have seen a teacher who teaches in this way…the method was different, and nothing is comparable"(**H, G1, S2**). While the traditional teaching was teacher-dominated and fact-driven, in the new approach the teacher stopped "…say[*ing*] the facts directly, actually he asked us to work in groups and find out" (**H, G1, S3**). As a result of the change in teaching, the students' role was different too as they became

> "…engaged with the teacher, all students were responding to the teacher's questions, not just, like other lessons, four or five are participating while the rest are asleep" (**H, G2, S3**).

In such teaching, students play several roles that go beyond receiving information only "…to receive and practice, and students support each other"(**H, G4, S3**). Within such practice, they believe that learning will be built differently because:

> "There is nothing that comes straight away, things come gradually and step by step, when things come easy they go easy, but when they come gradually they stay" (**H, G1, S1**), and learning became "…like building a house; brick by brick" (**H, G3, S4**).

When the students were asked about the features of the new approach that contributed to making this change, they pointed to "…using activities, group discussion and ideas exploration" as responsible for this shift (**H, G3, S4**).

In terms of the activities that were used in the teaching sequence, the students thought that they have some positive features such as being:

> "…simple and related to everyday life, like using grapes and fizzy water and so on. Photosynthesis, therefore, was not just a chemical reaction you have to recall" (**H, G3, S1**), … [*the activities also*] were introduced in every lesson and they were different every time. For example, modelling glucose was excellent as a way of delivering the idea, and it will make the idea settle in my mind" (**H, G1, S2**).

In addition to the activities themselves, they thought that the way they were introduced "…made information more settled" (**H, G2, S3**),… [*and*] "…stuck in my mind not in the textbook" (**H, G1, S1**). Furthermore, the activities were effective as they integrated different techniques, so the students "…listen, see, and practice, like what happened in modelling the glucose" (**H, G2, S1**).

The second thing they mentioned was using group discussion. They believed that group discussion was advantageous to them and an "excellent strategy" (**H, G1, S2**). It helped them to "…get ideas from here and there so as to develop a better idea" (**H, G1, S2**) In addition, in the group discussion the purpose was to share "…ideas irrespective if they were right or wrong" (**H, G1, S3**). Another advantage was related to engaging the whole class:

> "…all students were participating in the lesson, not like before where you would find only about 20% who participate; this change occurred because of group discussion which makes students engaged, and interested in participating" (**H, G2, S1**).

They also went further to acknowledge a specific advantage of group discussion for students who "…don't take things from the teacher, but accept them from other students" (**H, G4, S2**). Finally, they think that group discussion had an effect on the teacher because he started to "…listen to our ideas and discussions" (**H, G3, S1**).

Despite these advantages, they thought, however, that group discussion was "…time consuming" (**H, G4, S1**) and "…some students don't work, rather they are burden on the group members" (**H, G4, S2**).

The third feature that they liked about the teaching sequence was exploring their ideas because "…in this way we know our mistakes, so we correct them" (**H, G2, S2**). They thought that starting from their ideas was effective because "…the one who knows his mistakes won't ever forget them (**H, G2, S3**), **[***and therefore*] the right ones will stabilise in our minds" (**H, G1, S1**). In addition, the teacher stopped saying "…this is wrong and this is right…and started to help us to see our mistakes by ourselves" (**H, G2, S1**).

As a result of these features, their image of biology changed from "…a memorization subject where teachers lecture and we record and recall… [*to a subject where*] we practice, think and understand" (**H, G4, S2**). They believe now that "…70% of biology learning is actually understanding" (**H, G2, S1**). Indeed, with such learning "…when it came to the test, I only needed to refresh my knowledge because the ideas were still here [*points to his head*]" (**H, G4, S3**). In fact, they were aware of this significant change when compared to traditional learning. As one of them put it:

> "…other topics require memorization, but here it had changed. I didn't need to go back to my records or the textbook. Rather, I relied on the knowledge I gained during the teaching and I understood, I feel that I learnt here better than other topics" (**H, G4, S2**).

Because of the aforementioned features of the teaching sequence, they wish they "…can use the same strategies in other science subjects to make us think and understand" (**H, G1, S1, S2**), (**H, G2, S1**). They think that if other subjects use the same strategies, "…students will like the subjects and the teacher as well" (**H, G3, S1**).

However, it seemed that they were dominated by the assessment regime and the idea of the importance of recording the ideas that were presented in the lessons. Therefore, they asserted the importance of recording the content of every lesson:

> "When we didn't record what we had learnt in the first lesson, in the next lesson some students forgot some of the ideas…so we must record so we won't forget" (**H, G2, S1**).

When they were asked about specific conceptual aspects regarding the teaching sequence, the concept of plant food was amongst those mentioned. One of the students described the development of his understanding of the concept of plant food and said:

> "My idea was that water and minerals are plant food, but I was wrong, I recognised this by myself through the discussion and not from the teacher" (**H, G2, S1**).

Another example was related to:

> "…plant respiration [*which*] is unknown for many people, I thought that plants only photosynthesise, but I changed this view " (**H, G4, S2**).

However, there were aspects of the teaching sequence that they did not understand. For example, they felt that "…converting glucose into fat and protein was not clear enough" (**H, G2, S1**). In addition, they thought that the role of light energy might need more clarification. One of them described his understanding:

> "I don't know precisely what's the role of light, we know that combining carbon dioxide with water will form glucose, but didn't understand how the light contributes to this reaction" (**H, G2, S3**).

7.3.2 Average achievers' story

When the average students talked about biology teaching in their usual classrooms, they pointed out some limitations. They described usual teaching as "…lecturing, where teachers receive only one or two questions from students" (**A, G1, S3**). They thought that the lecturing style was enforced by "…the amount of content presented in the textbook" (**A, G4, S2**). In a class like that, students' participation is limited as there are "…only five or six students who pay attention to the teacher" (**A, G1, S3**).

However, when they were asked about the difference between the usual teaching and the new approach, they believed with "…no doubt the programme is better" (**A, G1, S3**) as students were "interactive and engaged" (**A, G1, S3**) and you can see that "…the whole class was participating"

(**A, G1, S3**). In addition, "The teachers' manner was different" (**A, G1, S3**) and "…there was a chance to talk and share your ideas" (**A, G3, S1**). Indeed, they thought that talking and sharing ideas was important because when "…you see and practice, things settle in your mind, but with only talk from the teachers, we might get confused" (**A, G1, S1**). When they were asked specifically about the features that contributed to this change, they mentioned "…activities and group discussion" (**A, G1, S3**).

They thought that the activities were useful because they "…were designed as a dialogue between students, i.e. Suleiman said this but Ahmad said that etc." (**A, G3, S2**).

With regard to group discussion, they thought that:

> "Group discussion motivates cooperation, ideas exchange and makes you try to be better than other groups. And it means you consider other students in your group to be peers not competitors, so we share and exchange ideas, and it's better than working alone as you can't get help then" (**A, G4, S3**).

In addition, group discussion means for them "…listening to more than one opinion" (**A, G3, S1**) and tends "…to bring about a summary of ideas to arrive at the right one" (**A, G3, S1**). However, they were bothered by "…some students… [*who*] didn't work" (**A, G3, S1**) or those who "…held [*the group discussion sheet*] for himself and didn't read it loudly" (**A, G3, S2**).

As a result of the positive features of the teaching sequence, they thought that "This programme was better because it's taught differently" (**A, G4, S1**) and they "…wished that all subjects are taught in this way" (**A, G4, S3**), (**A, G1, S1**). They saw the benefit of this new approach when they prepared for the post-test, as they "…needed only a quick review" (**A, G4, S1**) while some of them just relied "…on the knowledge that was gained during the lessons" (**A, G4, S2**).

When they were asked about the ideas that they did not understand, they pointed to how plants obtain the requirements needed for photosynthesis. As one of them put it, "I struggled to understand how plants absorb light, how water enters into plant and how plant takes in carbon dioxide" (**A, G2, S1**). Also, they needed more illustration of "…how plants convert the surplus glucose into fat and protein" (**A, G2, S2**). Another problematic concept was "…the relationship between photosynthesis and respiration during the day and night" (**A, G4, S3**), and maybe the whole "gaseous exchange" (**A, G4, S1**).

In terms of the limitations of this approach, they criticised:

> "…the teacher in the first lesson when he listed our ideas on the board, but didn't show us what was wrong or right, we need the teacher to say which one was the right idea" (**A, G2, S3**).

Also, they expressed the need to "write down [*in their records*] what has happened in the lesson so we won't forget" (**A, G2, S3**).

7.3.3 Low achievers' story

The transcripts showed that the low achievers' responses were less elaborate than the other two groups when they talked about their experience during the intervention, and they were maybe less aware of the features of the teaching sequence. For example, when they were asked if they noticed any differences between the normal method of biology teaching and the one used in the intervention, there was a variation in their views as some thought there was "…nothing new, the same teaching strategies were used in both approaches"(**L,G1,S1**) so "…there was no difference" (**L, G3, S1**), while others thought that "…everything had differed" (**L, G2, S1**) ranging from learning in "….a different place" (**L, G3, S2**), to "using group discussion" (**L, G4, S3**) and "activities sheets" (**L, G4, S3**). So, there was a "…space to express your ideas" (**L, G1, S3**) and "…students appeared interactive" (**L, G4, S1**).

Some of those who recognized that there were differences mentioned that the group discussion helped them "…to arrive at the correct answer" (**L, G2, S1**). However, they were not happy about the method of distributing students into groups as "…good students were together in the same groups" (**L, G3, S2**). In addition, like high and average achievers, "The thing that was troubling is that we didn't make records of information taught in every lesson" (**L, G2, S3**).

When they were asked whether they understood the key ideas presented during the intervention, they said that they "…understood everything" (**L, G3, S1,2**) and "…nothing was difficult" (**L, G4, S1, 2, 3**). However, when I asked them about the nature of plant food and how it is obtained, they expressed misunderstandings like "Plants get food from the soil and make it themselves, oxygen and glucose can be food as well" (**L, G4, S1**) and "Plants get food from the soil through the roots" (**L, G4, S2**).

With regard to extending the approach used in the intervention to other subjects, some wished that it was possible "…because there was an exemplification of each idea in concrete form, like modelling glucose, which makes us understand better" (**L, G2, S1**). Yet, some did not wish that "…because it demanded more work" (**L, G1, S1**).

7.3.4 Emerging issues from students' stories

This sub-section consolidates the key issues raised by the students in the three stories. As mentioned before, I should assert that interviews with high achievers were longer and richer than others, and, therefore, perceptions presented here might be biased towards the high achievers rather than being representative of all abilities.

The issues represent the most common topics linked to the design itself rather than the individual characteristics. This section begins by presenting how they thought that the intervention was different and better than usual teaching, and then elaborates on what made it better. It then goes on to consider the conceptual aspects that the students did not understand.

7.3.4.1 It's different and better

Students recognised that the intervention had some features that were considerably different from usual practice. They perceived the latter "…poured down" (**H, G3, S1**) content because the teacher just "lectures" (**A, G3, S1**), "dictates" (**H, G3, S1**) or asks students "…to underline the key ideas" (**H, G2, S1**) presented in the textbook. Within such context, students "…barely participate" (**H, G1, S2**) and their role was limited to only "…record and recall", in which "…studying becomes boring" (**H, G3, S1**) and biology was portrayed as a "…memorization subject"(**H, G4, S2**). Although they believed that textbook content is good "…the problem lies in its amount, which enforces memorization" (**A, G4, S2**).

In contrast, during this intervention they experienced a totally different practice and it was their "…first time…to see a teacher who teaches in this way…, and nothing was comparable" (**H, G1, S2**) with usual practice. In particular, "[T]he teacher's manner was different" (**A, G1, S3**) as he stopped taking control over the class saying "…this is wrong and this is right" (**H, G2, S1**) or presenting "…the facts directly" (**H, G1, S3**). Rather, he started to "…share out the lesson" (**H, G4, S3**) with students.

These changes on the part of the teachers made students "…interactive and engaged" (**A, G1, S3**) as they got "…space to express [*their*] ideas" (**L, G1, S3**). Moreover, students started to learn comprehensively in the sense that they "…practice, think and understand" (**H, G4, S2**) as well as learning from each other, rather than relying on the individual reception of facts. So, they believed that with "…no doubt, the programme is better" (**A, G1, S3**) than usual practice.

These views on the positive effects of the teaching sequence might complement the judgment of the effectiveness of the teaching sequence. It might be argued that the positive attitudes that students have about an intervention reflect their satisfaction with what the intervention had offered them. In addition, with all the limits that surround students' views and judgments, they can be used as indicators of what was going on in the classroom and how pleased they were. In particular, if they can justify their judgment, they might be more valuable. So, what features of the teaching sequence made students develop such positive views?

7.3.4.2 What made it better?

Students stressed the usefulness of group discussion as well as using learning activities. In terms of group discussion, they believed that it was useful as it gave students a space "…to express and share ideas" (**H, G1, S**1/**A, G3, S1**) irrespective of their correctness (**H, G1, S3**). In addition, the teachers themselves were affected by group discussion as they started to listen more (**H, G3, S1**).

In terms of the learning activities, they were authentic and real life-based, which makes photosynthesis more than a chemical reaction that should be memorized (**H, G1, S2**). Also, they liked the way the activities were presented to depict a conversation between students (**A, G3, S2**).. Within such activities, students started to think, practice and understand, and therefore made "…things settled in [their] mind" (**A, G1, S1**).

7.3.4.3 We got the basic idea

The high and average achievers thought that they got the basic idea that "…combining carbon dioxide with water in the presence of light will result in glucose" (**A, G1, S1**). This also can be confirmed by the analysis of students' responses to the *Food Probe* that showed that the majority of them developed the required factual knowledge (see section 6.2.1). However, the low achievers were still having misunderstandings such as believing that plants get food from both the soil and make it by themselves, or plants just obtain it "…from the soil through roots" (**L, G4, S2**), which can be confirmed by the findings from students' responses to the written probes (see sections 6.2.2.2, 6.3.2.2, 6.4.2.2).

On the other hand, students mentioned some aspects of the content that they did not understand, so more clarification is needed. These aspects can be summarised into: converting surplus glucose into fat and protein (**H, G2, S1**/**A, G2, S2**), the role of light energy in photosynthetic process(**H, G2, S3**), how plants take in water and carbon dioxide (**A, G2, S1**) and the gaseous exchange during the day and night (**A, G4, S3, A, G4, S1**). As noticed when analysing the actual implementation and students' interviews, the role of light energy and the relationships between photosynthesis and respiration need more clarification.

7.4 Summary of teachers' and students' perceptions

Referring back to the purpose of exploring teachers' and students' perceptions (see section 7.1), I present a summary of issues that complement findings from other sources or inform refinement of the design, as well as suggesting preliminary insights for reforming science education in Saudi.

In terms of complementing other findings and informing refinement of the design, I highlight the following:

- It seemed that the students were emotionally engaged in the intervention and enjoyed their experience. As mentioned in section 2.4.3.2, evidence of the emotional engagement can be directly investigated in students' interviews.
- There is a consensus amongst both teachers and students on the effectiveness of the teaching sequence in terms of the impact of its pedagogic strategies. In particular, the learning activities, group discussion, interactive teaching and eliciting of students' ideas appeared to impact on the development of positive views about the teaching sequence.
- However, the teachers stated that eliciting students' ideas was challenging due to several reasons. This concurs with what was presented in the analysis of the actual implementation that the teachers tended to collect students' ideas rather than ask for elaboration or build the ideas cumulatively (see section 5.9.2).
- As shown by the findings related to assessing the learning outcomes in terms of attaining factual knowledge (see section 6.2.1), students also felt that they attained the essence of the photosynthetic process.
- Yet, they mentioned some aspects that they did not understand. These aspects were the role of light energy in photosynthesis, the relationships between photosynthesis and respiration, converting glucose into starch and forming proteins and fats from glucose. They asked for more detail and clarification.
- Moreover, there was a cultural issue related to the effect of the word "scientist" on students' conclusions with regard to the activity of Helmont's experiment. Making the activity open without providing any conclusions might resolve this issue.
- In addition to promoting students' learning, the teaching sequence optimised teachers' content knowledge of some of the problematic aspects of photosynthesis such as the concept of food, converting glucose into starch and the relationships between photosynthesis and respiration. Therefore, developing a teaching sequence might be a useful approach for professional development programmes.

With regard to informing science education reform in Saudi, teachers' and students' views can offer the following insights:

- It seemed that both teachers and students were aware of the limitations of conventional methods of biology teaching. On the other hand, they appreciated the impact of innovative aspects of the design on promoting teachers' content knowledge and students' learning. This might suggest that they are ready to adopt reforming initiatives to help them optimise their practices.

– Yet, any reform should consider other affective factors that go beyond promoting teaching and learning practices. As mentioned by both the teachers and students, there were barriers related to the availability of resources, the large amount of content presented in the textbook and traditional assessment practices. To enable teachers and students to adopt new initiatives, the reform should be systemic in the sense that it considers all the affective factors.

The next chapter (Chapter 8) pulls the key findings of the study together, and discusses issues related to refinement of the design, developing a set of domain-specific guidelines to teach plant nutrition in Saudi, and offers reflections on the strengths and limitations of the Leeds Model and the model of evaluation.

CHAPTER 8: DISCUSSION

This chapter begins by summarising the key findings of this study with regard to the three research questions. These findings are then used to draw out some refinements to improve the original design, and develop a set of domain-specific guidelines to teaching plant nutrition in the Saudi context. Finally, some reflections are offered related to the model of design (the Leeds Model) and the model of evaluation used in the study.

8 CHAPTER 8: Discussion

8.1 Introduction

As mentioned in Chapter 2 (see section 2.3.1), design studies provide tangible materials to be used in practice and domain-specific guidelines for teaching specific content. Chapter 3 of this study presented the Design Brief and Worked Example, which I consider to be materials that can be used in practice. However, as the design was implemented through only one cycle, I underline here some revisions for refining the design (see section 8.3) with the purpose of improving its effectiveness. I also suggest a set of domain-specific guidelines related to teaching plant nutrition in the Saudi context (see section 8.4).

In addition, since my research is design research, I broadly examine underling issues relating to the use of the Leeds Model to develop the design (see section 8.5.1), as well as aspects regarding the evaluation model used to appraise the designed sequence (see section 8.5.2).

However, in order to link this discussion to the findings of this study, this chapter first revisits the research question linked to the key findings to highlight issues related to developing teaching sequences or teaching and learning biology in Saudi.

8.2 Key findings of the study

As set out in Chapter 2 (see section 2.5), the main aim of this study was *to develop a teaching sequence about plant nutrition for the Saudi context.* Science education in Saudi is in need of such studies directed towards improving teaching and learning science. As previously mentioned, Saudi students' low scores in science in the TIMSS 2007, and the lack of studies directed to designing curriculum with the purpose of improving teaching and learning (Alkathiri, 2002), may assert the importance of pursuing this aim. Moreover, as the Ministry of Education is planning to reform science education, such a study might shed light on some issues related to designing or adopting instructional materials from other contexts (e.g. textbook) and approaching schools to implement them.

Three secondary aims and three questions emerged from this main aim:

- **Research aim 1**: To use the Leeds Model to design a teaching sequence about plant nutrition for male Saudi school students aged 15-16. This aim was followed in Chapter 3 by developing the Design Brief and Worked Example.

- **Research aim 2:** To determine the effectiveness of the teaching sequence in terms of meeting its design intentions and achieving the expected learning outcomes. This aim involved finding out:

  1. *To what extent was the planned design implemented as intended?*
  2. *To what extent did the students develop the desired learning outcomes?*

  - **Research aim 3:** To determine how the teaching sequence and associated teaching practices were perceived by Saudi teachers and students. The question which emerged from this aim was:

  3. *How did the teachers and students respond to the key conceptual and pedagogical aspects of the teaching sequence?*

The following three sub-sections present the key findings relating to the three research questions listed above. Section 8.2.1 summarises the match between the intended and implemented teaching in terms of content that was covered, as well as the pedagogic strategies that were used. Section 8.2.2 concerns the attainment of the learning outcomes and suggests possible reasons for the limited long-term effect of the teaching sequence in terms of enhancing conceptual understanding. Finally, section 8.2.3 is concerned with Saudi teachers' and students' perceptions of the teaching sequence.

8.2.1 How the teaching was implemented

This section presents the key findings regarding implementation in terms of covering the required content and the pedagogic strategies that were used by the teachers. It then underlines some issues related to ensuring effective implementation.

- *To what extent was the content covered?*

With regard to covering the content, tracing teachers' actions showed that the content was covered as presented in the Worked Example. Although the Worked Example contained some aspects of content that went beyond information introduced in the textbook, and it was different from the methods to which teachers are accustomed, it seemed that the teachers did not find the content demanding *per se* during the teaching (although they expressed some concerns when they were first introduced to the teaching sequence). Even though the teachers themselves misunderstood some details of the content (e.g. the gaseous exchange in plants, see section 7.2.2), they corrected their own understanding before the implementation and introduced the content as required.

However, it should be noted that *coverage* does not necessarily imply that the teachers *delivered* the content as intended or even that students attained the desired learning outcomes. For example, all the four teachers covered specific details about the structure of the plant cell, as well as the chemicals of which the cells are composed (see section 3.4.5) with the intention of helping students to understand how the glucose produced in photosynthesis contributes to the formation of these chemicals. However, although the teachers introduced the intended content, they did not make explicit links to refuting Helmont's conclusion that water is the source of extra biomass. So, although the teachers did cover the content, they did not make explicit the reason for introducing this content, which is to show students that biomass comes mainly from glucose produced in photosynthesis rather than soil, water or minerals. Perhaps as a result, about two thirds of the sample did not offer scientific explanations for the source of extra biomass in the delayed-post test (see section 6.4.1).

In fact, covering the content was not a challenge for the teachers. As T3 clearly put it "*The challenge lies in the method used, lesson flow and movements between ideas and concepts*" (see section 7.2.1). So, to what extent did the teachers follow the specifications of the pedagogic strategies?

- *Following specifications of the pedagogic strategies*

Findings presented in Chapter 5 show that there were limitations inherent in following the pedagogic strategies as intended in the Design Brief and Worked Example. In order to give examples, I will focus on the three main strategies that were used in the sequence, namely, formative assessment, teacher-led demonstrations and employing different categories of communication to address different teaching purposes.

With regard to formative assessment, although the teachers used the formative assessments at the points that were specified in the Worked Example, their expectations of these assessments seemed to be fixed regarding what they already expected students to express rather than being open and responsive to all possible views (see section 5.9.2). Furthermore, it appeared that there was a focus on conducting assessments more than maintaining the *purpose* behind probing students' ideas. To this end, the teachers tended to collect students' ideas and list them on the board rather than inviting students to elaborate or justify their own ideas, or to comment on the ideas of others.

In terms of teacher-led demonstrations, the teachers also followed the Worked Example in conducting all the required demonstrations. However, they performed them through a conventional approach that was, on most occasions, limited to only proving the scientific view or advancing a direct transfer of scientific facts (see section 5.9.2). The alterations that teachers made to the implementation of the demonstrations concurs with findings in the literature that teachers tend to modify novel strategies to fit with the instruction to which they are accustomed (Ogborn, 2002).

With regard to employing different classes of communication, although there was evidence that the teachers used an interactive approach to communicate with students, it tended to be interactive/authoritative more than interactive/dialogic (see section 5.9.2). Moreover, communication in general was teacher initiated and led, and narrowed to meet teachers' expectations. Furthermore, students' responses were mostly short and expressed in the form of labels for ideas that lacked elaboration or justification.

Given these limitations, one might wonder what caused the limitations that prevented teachers from performing the pedagogic strategies as intended. Considering the positive attitudes that teachers showed towards the teaching sequence (see section 7.3.4.1) and their commitment to introducing the specified content, there is no reason to assume that the teachers did not follow the pedagogic strategies as intended because they did not believe in their effectiveness. Moreover, there is no evidence to suggest that students played any role in limiting teachers from employing the pedagogic strategies as intended. Perhaps the limited implementation might be due to other factors such as a lack of knowledge and skills regarding how to implement the intended modes of communication or to insufficient support from the designer to enable teachers to enact them. These factors are further discussed below.

- *Helping teachers to implement the teaching as intended*

Rowan et al. (2009) stressed the importance of ensuring an effective implementation of the intended design. To meet this requirement in this study, I provided annotations in the Worked Example to guide the teachers in employing the required class of talk and the nature of the teaching/learning activities. However, it appeared that the amount of details provided was not sufficient.

Confrey (2006) stresses the importance of providing detailed guidance to ensure the design is implemented as intended in order "…to avoid 'lethal mutations' during the implementation" (p.143). On the other hand, Collins et al. (2004) point out that it is impossible to specify all the related details of any design because "…any implementation of a design requires many decisions that go beyond the design itself" (p.3). So, are there particular cases when the provision of detailed guidance is crucial to ensure effective implementation?

Given the limited implementation of interactive/dialogic talk and teacher-led demonstration, I can detect two cases where a detailed specification is needed. Firstly, a case where the pedagogic approach, like interactive/dialogic, proven to be demanding and there are notable observations that teachers' practices often fall short of reaching the desired level (Scott et al., 2006a; Leach et al., 2006). Secondly, when the teachers are accustomed to traditional teaching practices or are unfamiliar with the desired approach, even if it is not necessarily as demanding as the first case.

A lesson to learn from both cases when implementing a novel approach is not to overestimate teachers' expertise; therefore, there is a necessity to find ways to ensure that teachers are able to enact the pedagogic approach or to enable them to do so. In this study, this constitutes a "design decision" towards making the Worked Example more responsive to the needs of Saudi teachers, an issue which will be further elaborated in section (8.3.2).

Moreover, an analysis of the implementation can highlight other factors related to achieving effective implementation. As showed in Chapter 5, both teachers and students were making efforts to use the pedagogic strategies and teaching/learning activities. In particular, students were behaviourally and intellectually engaged during the teaching and findings from the interviews showed that they were emotionally engaged as well. In terms of the teachers, all four welcomed the teaching sequence, despite its novelty and the fact it differed from their usual practice. On the other hand, both the teachers and students were aware of the limitations of traditional practices of teaching and learning. These positive attitudes and behaviours were critical in enhancing the implementation of the teaching sequence. This is also relevant to reforming science education in Saudi, which may suggest that both Saudi teachers and students are ready for science education reform.

The relationships between the design and its implementation also have implications for refinement of the design that was developed in this study, which is discussed in section 8.3.2.

8.2.2 The recorded learning outcomes

This section revisits the key findings concerning the attained learning outcomes. As specified in the Design Brief (see Appendix A and section 3.2.3), three outcomes were expected to be observed in students' responses after exposure to the teaching sequence. These three outcomes were assessed using three written probes. This sub-section revisits the findings with reference to the effectiveness of the teaching sequence, and examines what the results of the assessment can say about Saudi students' ideas about plant nutrition.

- *The effectiveness of the teaching sequence in terms of improving learning*

Findings from students' responses to the *Factory Probe* in the post-test (supported by collected classroom work) show that about three quarters (n=131) of the students identified the requirements for, and products of, photosynthesis. Although this result reduced to two thirds of the sample in the delayed-post test, these findings still suggest that the teaching sequence was effective in enabling students to acquire the relevant factual knowledge.

In terms of conceptual understanding, students were assessed using two probes with regard to plant food and biomass. Findings from students' responses to the *Food Probe* show that 68% of the sample offered the required explanations for plant food in the post-test, while only 51.90% did so in the delayed-post test (see section 6.3.1). This might question the effect of the teaching sequence in enhancing long-term understanding. However, given that there was an increase in *Consistent* explanations from only 15% in the pre-test to about 52% in the delayed-post test, in which the change appears to be statistically significant, it is clear that the teaching sequence was effective to some extent in terms of long-term impact.

With regard to offering explanations for the source of biomass, findings from students' responses to the *Biomass Probe* (see section 6.4.1) show that more than half of the sample offered *Consistent* explanations in the post-test. This decreased to only one third of the sample in the delayed-post test. If only about half of the sample attained the desired learning outcome in the post-test and then about one third of this half failed to retain their understanding for only a month after exposure to the intervention, it appears dubious to suggest that the teaching sequence was effective in enabling students to offer *Consistent* explanations about the source of biomass.

- *Causes of limited conceptual understanding*

Given the findings presented above, it is unclear whether the explanations offered in the post-test were based on a conceptual understanding or were simply memorised for the test so the knowledge then disappeared in the delayed-post test. In this respect, findings from the delayed-post test showed an increase towards offering tautological responses (e.g. reformulation of the question) or descriptions of the photosynthetic process that cannot be coded as *Consistent*, but on the other hand did not contain any views that conflict with the views proposed in the model answer (see section 6.3.1). This might suggest that the students were aware of their erroneous views, but could not offer the required explanations. On the other hand, literature related to analysing students' explanations shows that a tendency to offering tautological or mere descriptions might reflect a surface understanding of the phenomenon under consideration

(Chin and Brown, 2000). So, "What was missing from the teaching sequence that minimised developing long-term explanations?"

Returning to the literature with regard to supporting students to develop scientific explanations, Chin and Brown (2000) mentioned some characteristics of the teaching that uphold such purposes. They suggest that the teacher should engage students with "how and why" questions, offer continual practice in constructing explanations, inform students of the components of a good explanation and offer conceptual guidance through reflection prompts. In addition to these suggestions, Davis (1996) stresses the importance of inviting students to elaborate their ideas and integrate their reasoning.

Looking back at the implemented teaching, such qualities were hardly observed in the teachers' actions. Given that a large number of students could not offer long-term explanations for the source of plant food and biomass, although they recognised that soil, water and minerals cannot be regarded as plant food or sources for extra biomass, it might be concluded that students need extended opportunities to practice the construction and extended use of explanations. In turn, this might suggest that the limited effect of the teaching sequence, in terms of enhancing a long-term conceptual understanding, was due to the lack of use of appropriate pedagogies. This confirms the findings above which indicate that relying on teachers' expertise is not enough and sufficient support is needed to enable the teachers to enact the teaching as intended. This issue will be revisited in sections 8.3.2 and 8.3.3 in terms of refining the design.

- *Saudi students' ideas regarding plant nutrition*

To my knowledge, there are no specific studies directed to investigating Saudi students' ideas of plant nutrition or photosynthesis. Literature on students' ideas suggests that students share similar ways of thinking about the natural world (Driver et al., 1994a), which can be confirmed with regard to the Saudi students' reasoning about plant nutrition.

Although my study was not directly related to probing Saudi students' ideas of plant nutrition with the objective of documenting their reasoning, their responses to the three written probes (see Chapter 6) and collected classroom work (see Chapter 5) can offer some general insights. Similar to findings from the literature (see section 2.2), Saudi students also consider substances absorbed from the soil to be food for plants and sources for extra biomass. Amongst these absorbed substances, water seemed to be the most frequently referenced as a source for extra biomass (see section 6.4.2.2). This reaction might be predictable from students who live in a country where direct watering is the only means of supplying plants with water because there are no rivers or lakes and the annual rainfall is very low. Moreover, soil has also proved to be difficult for students to abandon as a source of plant food and biomass (see sections 6.3.1 and 6.4.1). However, it is not clear if students regard soil as one substance or a combination of several elements (e.g. water, minerals, and fertilisers). Based on the literature I reviewed about students' ideas, no specific attention has been directed to investigating the meaning that students assign to the word "soil". Therefore, conducting such research might inform our knowledge of how to help students to overcome this misunderstanding.

8.2.3 Teachers' and students' perceptions of the teaching sequence

Both the teachers and students showed positive attitudes about the teaching sequence and associated pedagogic strategies. They were also aware of the limitations of conventional ways of teaching biology where the classroom is dominated by the teacher's voice, there are limited opportunities available for students to interact with teachers or peers and the lecturing style is used to teach. It seems that this dissatisfaction with existing practices played a role in the teachers welcoming and using the novel approach, despite it being demanding in its pedagogic aspects.

In terms of demanding strategies, the teachers thought that eliciting students' ideas was challenging (see section 7.2.5.2) as it requires prior research about their ideas to be conducted and potentially may cause embarrassment if the teacher has limited subject knowledge. In addition, eliciting students' ideas involves an interactive/dialogic approach that is challenging in its nature, not just for Saudi teachers, but for teachers in other parts of the world as well (Scott et al., 2006a). This refers back to the limited support that was offered to the teachers to enable them to understand and then enact the required class of communication. In order to support teachers to meet the required satisfactory level of maintaining interactive/dialogic talk, considerable assistance is needed in the form of oral guidance prior to the implementations, as well as detailed written guidance linked to specific content towards the intended practice.

However, the provision of professional development and instructional materials will not assure that all desired practices will be integrated in everyday teaching. As mentioned by the teachers (see section 7.2.5.4), there are barriers such as the assessment regime, lack of resources and the large amount of content presented in the textbook that may prevent teachers from integrating the novel practices into everyday teaching. In particular, research confirms (e.g. Davis, 2003) that obstacles such as a lack of time and testing practices can prevent teachers from changing their instructional approaches. With regard to the Saudi context, since the

Ministry of Education is currently reforming science education, there is a need to consider that isolated initiatives in the form of producing new textbooks or professional development are unlikely to change the classroom practices. Rather, change requires considering other affective factors and preparing a holistic plan that treats these factors as "…a meal not as a menu" (Fullan, 2007, p.44).

After revisiting findings related to the three questions of the study, the next section considers the use that can be made of these findings with regard to refining the designed teaching sequence and developing a set of domain-specific guidelines for teaching plant nutrition in Saudi.

8.3 Refining the designed teaching sequence

It should be noted that this study constitutes a first attempt to implement the designed teaching. As pointed out by Millar and Osborne (2009, p.53), "…it is unlikely that a first implementation provides useful evidence of the effectiveness of any intervention". In some studies, (e.g. Brown and Clement, 1992), significant effectiveness is only achieved after making "*major revisions*" to the original design. In order to point out the required revisions, this section attempts to address the question "What changes can be made to overcome the limitations reported above in order to make the design more effective?"

Refinement of the design represents an essential feature of design studies (see section 2.3.1), as development of a given design involves an iterative process of designing, implementing, evaluating and then re-designing in an attempt to improve teaching/learning a specific content. Although this study did not go through a second cycle in which the original design is refined, implemented and evaluated, it is still fruitful to highlight possible improvements to make teaching more effective.

To this end, I offer refinements related to improving the Design Brief, Worked Example, introductory sessions (i.e. to introduce the designed teaching for teacher), and the probes used to assess learning outcomes. The reason for considering all these elements is that I view the design as a "packaged product" which encompasses these elements. This is because a change made to one element affects the others. In other words, anything advanced in the Design Brief must be translated into the Worked Example, the teachers need to be introduced to the content and pedagogic strategies specified in the Worked Example, and the desired learning outcomes are affected by specifications in the Worked Example and how teachers understand them.

8.3.1 Refining the Design Brief

As mentioned in Chapter 2 (see section 2.4.1.3), the Design Brief specifies the design intentions and justifies the decisions in terms of content, content aims, sequencing and pedagogic strategies. In this section, I underscore some possible improvements to the Design Brief in order to address the limitations that were revealed by the findings from the analysis of the implementation and students' responses to the written probes.

A key issue in this design is related to the limited effect on enhancing long-term conceptual understanding. As reported when evaluating the learning outcomes (see section 8.2.2 above), analyzing students' delayed responses to the *Food* and *Biomass* probes showed that only about half of the sample offered acceptable responses to the question "What is the nature of plant food?", while only one third satisfactorily explained the source of biomass. Therefore, how can the Design Brief be improved to encourage students to construct the required explanations?

In an attempt to determine the steps involved in being able to develop a scientific explanation, McNeill et al. (2006) suggest, among other things, the importance of developing a proper understanding of the relevant content as well as knowledge of what constitutes an explanation. I will consider now whether the specifications advanced in the Design Brief addressed these two conditions.

With regard to the inclusion of relevant content knowledge needed to construct an explanation of plant food, the findings showed that there was confusion amongst students in terms of the relationships between food and energy (see section 5.7). This was perhaps caused by limited information and discussion concerning the relationship between photosynthesis and respiration (food as a source of energy). The intentional avoidance of this relationship was advised in the Design Brief (see section 3.2.3) with the view of making the topic of plant nutrition less complex by reducing the content. However, it seems that an understanding of the role of glucose, as fuel for respiration from which energy is liberated, requires a prior understanding of the following points:

- Plants need energy to carry out biochemical functions;
- only organic substances supply energy;
- glucose produced in photosynthesis is the only organic substance available for plants;
- the necessary energy is liberated in respiration from glucose;
- these relationships between photosynthesis and respiration imply perceiving a plant as a system.

By means of connecting this information, and understanding that the two processes, photosynthesis and respiration, combine to supply the required energy for plants (Brown and

Schwartz, 2009), students should be able to construct an explanation regarding the role of glucose as a source of energy. It should be noted, though, that the introduction of respiration is still problematic and, therefore, requires tackling common misconceptions; for example, the belief that photosynthesis is a plant's way of breathing or that plant respiration is inverse to animal respiration (Canal, 1999).

The other issue mentioned by McNeill et al. (2006) to help students in the construction of explanations is an understanding of what constitutes an explanation. Looking back at the design, this requirement was not targeted in the Design Brief. Furthermore, I can claim, based on my experience of science education in Saudi, that both teachers and students rarely experience the construction of explanations because science lessons are usually delivered through lecturing, which presents scientific content as facts to be memorized. Therefore, if this is the case, then it might be useful to target explicitly helping students with this aspect.

Lizotte et al. (2004) found that defining explanations in terms of three components (claim, evidence, and reasoning, see Table 8.1) helps students to construct stronger explanations. In order to help students understand the nature of explanation, McNeill and Krajcik (2008) advise that the teacher should model domain-specific examples of how to construct an explanation that contains the three components, and should also give students opportunities to compare scientific to everyday explanations. I will further illustrate how to address constructing an explanation in terms of the Worked Example (see section 8.3.2 below).

Table 8.1: Components required to construct an explanation for plant food

Component	Description	Application to plant food
Claim	A conclusion about a problem	Only glucose produced in photosynthesis constitutes plant food
Evidence	Data that supports the claim	1) Inorganic substances absorbed from the soil cannot supply a plant's need for energy. 2) Scientists found that plants produce glucose from raw elements (carbon dioxide and water) and light.
Reasoning	A justification for why the evidence supports the claim	Plants need food to provide energy needed to carry out biochemical functions. Energy can only be liberated (in the case of green plants) in respiration from glucose, and photosynthesis is the only way that a plant can obtain this glucose. Inorganic substances (e.g. water, minerals and fertilisers) cannot be regarded as food because they do not supply energy.

Another possible refinement to the Design Brief concerns making the teaching sequence more flexible and responsive to students' ideas. As mentioned in Chapter 5 (see section 5.2), there were cases when students expressed aspects of the scientific view, while the assumption made in the Design Brief is that they will only posses spontaneous views. I tended in the Design Brief to envision the teaching/learning process as a singular scenario rather than being open to other possibilities that emerged from students' responses. To this end, the design was too linear in the sense that I only anticipated students would have the same starting points, would offer certain responses and the teaching, therefore, goes in only one direction. Although I use a model that adopts the view that knowledge is socially constructed by both teachers and students (see section 2.4.1.3), I was limited in translating this view in terms of considering the variety of students' responses and keeping the teaching responsive to what students might offer.

In order to overcome this limitation, the design should anticipate that some students possess a prior knowledge of photosynthesis while others do not, and both should be taken into account. In this manner, the design will transform from being singular and linear with one scenario of teaching/learning processes to being differentiated and responsive to what happens in the classroom. Avoiding constructing a linear, closed design is often discussed in instructional design environments in the context of educational technology (e.g. Willis, 1995), and we, as designers of teaching sequences, can find useful insights that inform the design of domain-specific sequences.

8.3.2 Refining the Worked Example

As mentioned in Chapter 2 (see section 2.4.1.3), the Worked Example is one possible way to address the principles set out in the Design Brief, which means that making changes to the Design Brief entails the same for the Worked Example. In addition, limitations of the implemented teaching can be attributed to a limitation in addressing the Design Brief through the Worked Example rather than a limitation in the Design Brief *per se*. This means that more refinements would be needed for the Worked Example than for the Design Brief. This sub-section presents some possible refinements to the Worked Example, either to meet the changes made to the Design Brief, or to make the Worked Example better address the Design Brief and be more responsive to the needs of Saudi teachers.

As mentioned in the previous section, there is a need to refine the Design Brief with regard to enhancing the construction of explanations. In the Worked Example also, teaching/learning activities can be used to enhance students' understanding of the content and develop their knowledge of what constitutes an explanation. I only focus on improving the Design Brief with regard to constructing an explanation of the nature of plant food. Similar principles can apply to biomass.

In terms of the content, it seems that an explanation of plant food should rest on establishing a scientific definition of food. In this respect, the Design Brief suggested conducting a formative assessment and drawing an analogy between food and fuel (see section 3.4.1). However, it appears that further clarification was needed to emphasise the relationships between food and energy and what energy really means in the context of nutrition. To address this need, students' knowledge and understanding of the relationship between food and energy can be brought together when they consider different types of nutrients and the energy they provide in calories (i.e. units of energy). As Appendix E shows, students, for example, can examine several products to determine the numbers of calories they provide as written on the nutrition fact labels. To emphasise that some products supply energy while others do not, the chosen products might include packet of table salt, a bottle of water, a bar of chocolate and a bottle of fruit juice. Water and salt in particular can be extended later on to the context of plants to show that they do not supply energy even to plants. Then, a combination of the fuel analogy and comparing food in terms of energy supply can enhance students' conceptualisation of food which would help them towards constructing the required explanation.

In addition to introducing the relevant content, the other requirement is to improve the Worked Example regarding what constitutes an explanation in the context of plant food. Firstly, the teachers can guide students to identify the components of an explanation (see Table 8.1 for an example in the case of plant food), emphasising cases, for example, where one of the components is missing and how this affects the quality of the explanation. Another activity might be student-centred where students can be asked to compare a scientific explanation of plant food with an everyday explanation in light of the three components. This activity can ignite discussion and also dialogue if the activity involves students evaluating the explanations of others based on the availability of the three components. After developing students' capacity to construct explanations, an activity can be planned to practice explaining plant food and biomass. In fact, the activity used in the Worked Example was only directed to consolidate students' knowledge of photosynthesis rather than to practice explaining plant food and biomass (see section 3.4.7).

Another refinement of the Worked Example concerns meeting students' responses as to whether they agree or disagree with the scientific view. As noted earlier, teachers were more prepared to receive responses that conflict with the scientific view. However, when students raised photosynthesis as an explanation for plant food or when they linked food to energy, the teachers simply ignored such views because the scenario that was suggested in the Worked Example only focused on everyday ideas. To this end, the Worked Example needs to include flexible activities that are responsive to students' responses and, therefore, encourage teachers to consider different possible ideas. If students, for example, express conflicting ideas on the source of sweetness, the teacher should challenge them. In contrast, if students suggest photosynthesis, the teacher should acknowledge this view and then try to challenge this idea as well to find out how well students understand it. In some cases, the teacher might use the two activities to work on the two views.

In addition, some students referred directly to the need to clarify some aspects of the content such as the role of light energy in photosynthesis, the relationships between photosynthesis and respiration, the conversion of glucose into starch and the formation of proteins and fats from glucose (see section 7.4). Aside from students' own feelings about the limited knowledge that was attained in relation to these aspects, more clarification might enhance their ability to construct explanations, as this is affected by the availability of related content knowledge, as mentioned above.

Thus, the Worked Example needs refining in terms of meeting cultural expectations and terminology used in Saudi school. As mentioned by the teachers (see section 7.2.1), students experienced problems with the word "chlorophyll" and "scientist". The word "chlorophyll" proved to be difficult for students because some of them learnt about chlorophyll with a different Arabic term. On the other hand, the word "scientist" was used in Helmont's experiment activity to probe students' ideas about the source of biomass (see section 3.4.5). Employment of the historical background of Helmont's experiment when teaching photosynthesis has been suggested in the literature (Wandersee, 1985; Eichman, 1996). However, as reported in the findings, some students accepted Helmont's conclusion because he was described as a "scientist" (see section 3.4.5). In fact, the meaning and authority assigned to the word "scientist" in the Arabic culture might differ from that ascribed in Western culture where the activity is first suggested. As stressed by Lee and Fradd (1998):

> *Learning science vocabulary becomes more complex when comparable terms and parallel ways of considering ideas do not exist across languages. The words of one language cannot always be completely translated into another. Meanings must be understood within cultural contexts* (p.16).

With regard to the terms "chlorophyll" and "scientist", language and cultural effects might have limited students' engagement with the teaching. As an aid to refining the Worked Example, it can be improved if chlorophyll is introduced by the English and equivalent Arabic name, whereas avoiding the word "scientist" might help students to engage with the activity by employing their reasoning rather than following Helmont's conclusion.

In addition, some students used quotations from the Quran to support their views regarding water as a source of plant food and biomass (see section 6.4.2.2). Given that quotations from the Quran are used in the official textbooks with the purpose of linking Islam to science, as both are strongly linked in the Islamic view, it is possible to use such excerpts to open up discussions related to the quotation that was used by some students.

To conclude, a key issue here is the need to make the Worked Example more responsive to the Saudi context. The original design that I drew upon was developed in the EPSE project for English students and teachers. Although I made modifications to the sequence to meet the targeted content and fit with the assumptions I advanced in the Design Brief (see section 3.3), tasks were left undone in terms of clarifying and prescribing the pedagogic strategies, enhancing the construction of explanations and meeting cultural and language expectations. All these, together, entail in the first instance making design decisions in terms of the Design Brief and then translating them into the Worked Example to meet the needs of the Saudi context.

8.3.3 Refining the introductory sessions

Findings from analysing the implemented teachings and teachers' interviews highlighted the limitations and difficulties related to the pedagogical demands of the teaching sequence. In particular, the limitations are related to engaging students through interactive/dialogic talk and performing demonstrations

In terms of enhancing different classes of communication, according to the teaching purposes, I did introduce the Communicative Approach in the introductory sessions and provided the teachers with handouts based on Scott and Asoko (2006). However, the interactive/dialogic feature of teacher-student interaction was limited to collecting students' ideas and listing them on the board, a level that Scott et al. (2006a) described as low interanimation. Similar results regarding the limited use of interactive/dialogic talk were reported by Leach et al. (2006) who evaluated teaching interventions that were informed by the Communicative Approach (Scott and Mortimer, 2003). So, what was the reason for the lack of interactive/dialogic talk?

Although the teachers in this study tried to follow the teaching sequence and they did make progress towards engaging students, it seems, however, that adopting interactive/dialogic communication goes beyond a short teaching intervention. In attempting to suggest factors related to employing interactive teaching (dialogic in particular), Scott et al. (2006a) point to teachers' views on: teaching and learning, the knowledge and skills related to anticipating and responding to students' ideas, the knowledge and skills necessary to engage students, and sufficient time to plan and practice the desired type of interaction. Given these factors, it appears that achieving interactive/dialogic talk requires targeting teachers themselves and supporting them in transforming their practice throughout an extended period. Leach et al. (2006) also suggest using video resources containing exemplary interactions of the intended content to model the desired practices for the teachers. Wong et al. (2006) report a positive impact of using videos of teachers' own practice or that of others where the videos were analysed with the objective of improving specific aspects of the desired instruction.

With regard to the ways that the teachers enacted teacher-led demonstrations, the Worked Example did not, in fact, offer specific guidance. Rather, it relied on teachers' expertise. However, as presented in Chapter 5, the teachers varied in their approaches, and some of them were limited to simply stating the scientific view and using the demonstration to prove it. It appears that the teachers needed guidelines directly specified to encouraging an effective use of demonstrations. In this respect, as suggested by O'Brien (1991), this might include providing a short introduction prior to the demonstration to focus students' attention, advancing a "Let's see what happens approach", including asking students for predictions and engaging students with questions about the demonstrated phenomenon. However, looking back at the implemented teaching, only some of these features were observed on some occasions during the actual implementation (see section 5.9.2).

Given the content of the introductory sessions (see section 4.3.4.3), it seems that the teachers need more support regarding appropriate knowledge and skills to engage students through interactive/ dialogic talk as well as performing demonstrations. As previously discussed, teachers can watch and reflect on exemplary practices regarding teacher-student interactions and the performance of demonstrations. Another strategy is to invite teachers to reflect on their own practices related to the designed teaching. Davis (2003), for example, found that science "…teachers learn new content and pedagogy as a result of their reflections on their practice" (p.24).

To allow for such reflections, the design can be implemented in two stages: the pilot and the actual implementation. In this case, the purpose of the pilot is to let teachers try out the pedagogic strategies and then allow them to reflect on their enactments with the purpose of improving them so they meet the design intentions. Another approach that might help bring teachers' enactments closer to the design intention is to involve a few teachers in the development of the design alongside the researcher. This might fulfil a twofold purpose. On one hand, the designed teaching might better address teachers' need in terms of the required details and support to enact the design as intended. On the other, as their engagement in the development makes them aware of the purpose behind a certain strategy, they will consider the purpose while using the strategy in the classroom.

In addition to the need for design decisions in terms of making the designed teaching sequence more responsive to the Saudi context, maybe methodological decisions can contribute to achieving an effective implementation of the desired practice. This involves inviting teachers to take a serious look at the design prior to the implementation with the objective of establishing expected difficulties so as to resolve them. Moreover, allowing sufficient time to implement the design in more than one cycle may help to gain more knowledge about Saudi teachers' needs and, therefore, to refine the design accordingly.

8.3.4 Refining assessments of learning

Assessment of students' learning in this study was achieved in two ways. The first was the written probes that were used in the pre- and post- tests that aimed to measure the effectiveness of the teaching sequence in terms of attaining the desired learning outcomes. The other was end-of-lesson quizzes that were intended to establish the level of in-action engagement and preliminary understanding.

With regard to the limitations of the written probes, the intention of the *Factory Probe* was not clear to students as a large number (45%) of responses in the pre-test were coded in the "*Other*" category because students focused on the general features of plants rather than food-making. If the probe is to be used again, signs can be added to the first two items to help students recognise the food making process. In addition, the use of the second and third probes (*Food and Biomass*) could be improved if some students were orally assessed alongside the paper-and-pencil assessments. As the two probes were intended to assess students' explanations, relying only on writing might limit discovery of the conceptual difficulties that limit students from offering the desired responses. Given that conducting interviews is time consuming (Cohen et al., 2007), the researcher may focus on specific issues that were noticed in students' responses to the written probes and interview a small number of students who offered such responses. Such follow up assessment would augment findings derived from the written responses (Bell et al., 1985).

The end-of-lesson quizzes were helpful in revealing students' engagement and understanding with some aspects of the teaching. In addition, with regard to analysing the implemented teaching, there were cases where I suggested using end-of-lesson quizzes to help establish students' understanding. For example, the jigsaw activity was used to address the concept of the cycling of matter by showing students that glucose is made of atoms derived from carbon dioxide and water, albeit with a different arrangement. However, there was no direct evidence to see whether the activity had achieved its purpose. Therefore, a quiz to assess students' understanding of the cycling of matter might fulfil this need (see section 5.4). Another example is related to the role of minerals in plant nutrition. The Worked Example suggested introducing the role of minerals when discussing the role of glucose to assimilate plant biomass. However, there is a need to see whether students recognised the role of minerals or whether they were still holding the common idea that minerals are sources of biomass (see section 5.6). Assessing students in this respect might shed light on the effectiveness of the way that the role of minerals was approached.

8.3.5 Summary and conclusion related to refining the design

Looking at the refinements required to improve the design (summarised in Table 8.2), it can be seen that most of the revisions are directed towards improving the treatment of content from the point of view of enhancing the construction of explanations. This, in turn, entails making changes in terms of how to address this need in the Design Brief and Worked Example, and how to enable teachers to enact the intended approach rather than to just cover the content. In fact, the content *per se* was not the main challenge for the teachers in this study (see section 7.2.1). There is a lesson to learn here; namely, as a design developer or evaluator, it is necessary to anticipate the limitations in the pedagogic dimension. It is also a lesson for reformers of science education to direct their initiatives to improving pedagogic practice at the same time as improving the content, whilst also taking into account challenges imposed by the context and educational regime (Barab and Luehmann, 2002).

Table 8.2: Summary of revisions required to improve the teaching sequence

Element	Revisions
Design Brief	- Targeting the enhancement of the construction of explanations by introducing the relevant factual knowledge related to a given explanation, and knowledge and skills regarding what constitutes an acceptable explanation. - Making the design more flexible and responsive to take account of different starting points of students (e.g. both the spontaneous and initial scientific views regarding sources of plant food and biomass).
Worked Example	- Enhancing the construction of explanations, some factual knowledge should be introduced regarding the relationships between food and energy and what energy really means in the context of nutrition, the role of light energy in photosynthesis, the relationships between photosynthesis and respiration, the conversion of glucose into starch and the formation of proteins and fats from glucose. In addition, the teacher may guide students through the construction of explanations by identifying the components of an explanation and comparing scientific and everyday explanations. - Making teaching more responsive, planning activities where students' everyday and initial scientific ideas are taken into account.

	- Meeting the cultural (e.g. avoid using the word "scientist") and language (e.g. chlorophyll) expectations.
Introductory Sessions	- Supporting the employment of interactive/ dialogic talk by showing teachers exemplary videos or recordings of their own teaching so they can reflect on them. - Providing guidance with regard to performing effective demonstrations. - Involving a small number of teachers in developing and reviewing the designed teaching
Assessments of learning	- Adding signs to the *Factory Probe* to help students detect the context of plant nutrition. - Conducting interviews with a small number of students about specific conceptual issues that arose in the written responses. - Adding end-of-lesson quizzes to check students' understanding of the cycling of matter in the context of forming glucose and the role of minerals.

Another issue that should be highlighted here relates to other possible improvements to the teaching which can be made by considering factors that go beyond the design *per se*. Although I will only focus here on interactive/dialogic talk, the issue can, however, be extended to other pedagogies used in the teaching. As previously mentioned, engaging students in interactive/dialogic talk requires sufficient time to plan and practice dialogic teaching (Scott et al., 2006a). Given, on one hand, that class time in the Saudi school timetable is limited to 45 minutes of 6-7 blocks per day, and, on the other, that interactive/dialogic talk involves a series of questions and answers from both the teacher and students, and maybe group-discussions of a given conceptual issue, we can imagine how the teaching would be rushed and fragmented over more than one lesson to achieve the required interaction. In fact, both time and how it is organised can affect teaching and learning. A recent review of the effect of block scheduling suggests that students may achieve greater knowledge in science when they are taught through extended block schedules compared to traditional schedules (Dickson et al., 2010). Evidence like this might suggest re-scheduling the school timetable in Saudi schools in order to bring about extended opportunities for discussion and engage students in interactive/dialogic talk.

This chapter now turns to the second sub-section that concerns making use of the findings in order to draw out domain-specific guidelines for teaching plant nutrition.

8.4 Domain-specific guidelines for teaching plant nutrition

One of the fruitful outcomes of design studies is to develop domain-specific guidelines regarding teaching and learning a given area of content (see section 2.3.1.2). While some researchers call them specific design principles (Linn et al., 2004), domain specific theories (Gravemeijer and Cobb, 2006) or heuristics (Design-Based Research Collective, 2003), I prefer to follow Confrey (2006), and call them guidelines to emphasise their preliminary nature, as they:

> *…are not intended as recipes for success, but to help others select and apply the most appropriate substantive and procedural knowledge for specific design and development tasks in their own settings* (McKenney et al., 2006).

In line with the notion of their preliminary nature, Brown and Clement (1992) assert, after reporting some principles for enhancing students' understanding of mechanics, that these principles must remain as "*grounded hypotheses*" rather than conclusive inferences. If the desire is then to make them more solid, further evaluation of their effectiveness is needed, focusing on limited variables and gathering real time data (e.g. studying classroom interaction). Towards this end, as the design in this study was evaluated only in one cycle with a small number of teachers, it might be safer to regard the resulting domain-specific theories only as guidelines.

In this study, a sequence concerning teaching plant nutrition to Year 10 Saudi students (aged 15-16) was designed, implemented and then evaluated. Bearing in mind the features of the designed teaching sequence (see Chapter 3), how the sequence was implemented (see Chapter 5), and the key findings summarised above, I propose the following set of guidelines for teaching plant nutrition in the Saudi context. It should be noted that the guidelines are linked to each other because they directed at specific content, and there are variations between them in terms of the details they specify (i.e. they offer large- and fine-grain sizes of detail).

- *Requirements for generating explanations*

As reported in assessing learning outcomes (see Chapter 6), the teaching sequence did not help students to generate long-term explanations for the source of biomass and food. Therefore, it can be claimed that, if the teaching does not emphasise, for example, the relationship between respiration and photosynthesis, students would not be able to offer solid stable explanations, although they may become aware of their erroneous views regarding how plants obtain food. In order to enhance the construction of explanations, the teaching sequence needs to introduce the required specific knowledge, knowledge of what constitutes an explanation in general and the desired explanations regarding plant food and biomass, and opportunities to construct and practice the learnt explanation.

- *The required factual knowledge*

One of the assumptions advanced in the Design Brief was to reduce the content with the purpose of helping students to grasp the essence of photosynthesis and plant nutrition. Content reduction might have helped to keep students focused on the main issues related to plant nutrition. For example, omitting the content related to the technical mechanism of light/dark reactions might be justified on the grounds of the amount of technical details that are not fundamental for the construction of explanations. However, some of the aspects that were omitted (e.g. the relationship between photosynthesis and respiration, the role of light energy) appeared to be fundamental to enable students to construct the required explanations. A key decision that the teacher or the designer needs to make is related to the amount of factual knowledge to which students should be exposed in order to understand plant nutrition. Obviously, this will vary depending on the desired learning outcomes. Given the learning outcomes specified in the Design Brief, the teacher should introduce and clarify details concerning the photosynthetic process including the role of light energy, the chemicals of which cells are made, the role of light energy, relationships between food and energy, relationships between photosynthesis and respiration, some physiological aspects related to gaseous exchange and cellular respiration, and the structure of roots, stems and leaves.

- *Addressing the pre-requisite concepts*

As mentioned in the literature (Simpson and Arnold, 1982a) and drawn out from analysing the learning demands (see section 3.2.3), there are pre-requisites that should be addressed to help students appreciate photosynthesis as an explanation for plant food and biomass. That is, establishing a definition of food as fuel for respiration from which energy is liberated, the fact that carbon dioxide has mass and can contribute to making other substances, and understanding cycling of matter in terms of rearranging atoms of carbon dioxide and water to form glucose molecules. Although the evaluation of the implementation and learning did not provide direct evidence to support this guideline, one of the teachers mentioned in the interviews (see section 7.2.1) that students hold conceptual problems related to these pre-requisites and the teaching sequence helped them to overcome these problems. However, it should also be mentioned that the method of addressing these pre-requisites is crucial to achieving the purpose of addressing them. It is unlikely that traditional methods of fact communication will help students to correct their views about how they perceive gas or matter. In this particular study, for example, although teacher-led demonstrations were employed, they were enacted through a non-interactive/authoritative approach, which may have limited their impact.

- *Starting with the simple and postponing the complex*

This guideline concerns minimising the complexity of photosynthesis by the introduction of a simple model (i.e. carbon dioxide and water combine to form sugar) as a possible explanation for plant food; further details were then gradually added to complete the simple model.

Findings from the evaluation of the actual implementation showed that students did not find the model to be incomplete when it was introduced in its simple form. Moreover, as the main focus was on glucose as the main product of photosynthesis, postponing adding oxygen and introducing it as a by-product might have prevented the erroneous idea that photosynthesis is a gaseous exchange process by which plants balance oxygen in the ecosystem. This can be confirmed by findings from students' responses to the first probe which showed (see section 6.2.1) that responses naming oxygen as the main product of photosynthesis dropped to only 4% and 10% in the post- and delayed-post tests, respectively, while it was named by 40% of the sample in the pre-test. In addition to adding oxygen at a later stage, other details related to the need for light energy, the trapping of energy by chlorophyll and converting glucose into starch seemed to be working, as students and teachers did not raise concerns about postponing them.

- *Eliciting students' ideas about food, plant food and biomass*

Three formative assessments were used to probe students' ideas about food, how plants obtain food and the source of extra biomass. Evidence has been reported in the literature about the general effect of formative assessment on improving learning (Black, 1993). In this study, findings from analysing the implemented teaching suggest that using formative assessments was beneficial in informing teachers of students' starting points, as well as making students aware of their thoughts. Some of the ideas that students expressed focused on the views that food is needed to keep us healthy and alive, plants take in food from the environment and food can be produced through photosynthesis as well as taken from the surrounding environment. Given that students hold such views, it would not be effective to start introducing plant nutrition without externalising and then challenging these ideas. On the other hand, the assumption that students approach the sequence without prior knowledge of "the nature of photosynthesis" appeared to be inaccurate with regard to Saudi students at high school level. The formative assessment showed that students did have some knowledge about photosynthesis, albeit fragmented, and a number of them could link food to energy.

- *Challenging students' ideas about the source of plant food*

This guideline considers setting a conflict to show students the limitations of their everyday ideas about plant food. The technique of conflict creation is usually employed to make students dissatisfied with their ideas (Posner et al., 1982) so they can be helped to recognise their limitations in order to explain the phenomenon at hand. The teacher then attempts to help students resolve this by introducing how the phenomenon can be explained through the scientific view (Scott et al., 1992). In this study, after making students aware of their ideas, a conflict was evoked by asking students to think about the sweet taste found in fruit, which cannot be explained by absorption of water and minerals. After setting the conflict, the argument presented by the teacher was "If soil, minerals and water aren't sweet, where does the sweetness come from?" The analysed classroom work and videos showed that setting the conflict helped students to recognise the limitations of their ideas and to consider photosynthesis as a possible source for plant food.

- *Highlighting and then addressing causes of implausibility*

This guideline concerns highlighting and then addressing the conceptual problems (How can a weightless gas contribute to forming other molecules? How can combining gas with liquid form a solid? Do chemical reactions take place in plants?). It seemed that the primary step in which the causes of implausibility were made explicit was essential because students did not recognise these problems by themselves, although they held erroneous views about them. The teaching sequence then moved to address the fact that gas does have mass using three successive teacher-led demonstrations. Then, cycling of matter was addressed by a teacher-led demonstration and the activity of building a glucose model from atoms of carbon dioxide and water. Evidence from video analysis and interviews suggests that these techniques fulfilled their purpose. However, teacher-led demonstrations were used in a traditional manner as the teacher did not attempt to invite students' predictions or questions. As previously discussed (8.3.1.2), it would be more effective if the teachers engaged students prior to, during and after holding demonstrations.

8.4.1 Summary and conclusion related to the domain-specific guidelines

This sub-section concludes by highlighting three issues relating to the nature, quality, transferability and practicality of these guidelines. First, however, it should be asked "To what extent can these guidelines be perceived as evidence-informed?" Given that the Design Brief was informed by empirical findings on students' ideas and the Worked Example was tried out in natural classroom settings, they meet the requirements necessary to call them as such (Scott et al., 2006b). Moreover, these guidelines are *partly* supported by evidence from videos of the actual implementation, assessments of learning and interviews with teachers and students. In addition, classroom written work was used to augment findings from these sources. The word "partly" should be stressed here because, as can be noticed from the guidelines presented above, it is not possible to formulate a given guideline in a way that ensures every aspect of it is supported by evidence. Rather, these guidelines are formulated and supported by insights from literature, my initial assumptions and evidence from implementation and evaluation.

Given these limitations, it is clear that it is very unlikely to be possible to offer sole evidence-based practice in education in the sense of providing detailed prescriptions (Millar and Osborne, 2009). This kind of limitations perhaps led Hargreaves (1999) to suggest using the term "evidence-informed" instead of "evidence-based" practice in the context of educational research.

Furthermore, it is not possible to be certain about the effectiveness of these guidelines, given the small scale of the study, the reported modest impact in terms of enhancing long-term conceptual understanding, and acknowledging that the design was conducted in one cycle. However, they do offer specific insights for Saudi teachers regarding where to expect difficulties and how to approach these difficulties, as well as highlighting cautions that should be avoided (e.g. separating photosynthesis from respiration and linking food to energy).

In terms of the transferability of these guidelines to other contexts, it is necessary to assert that the guidelines resulted from a design that addressed a specific aspect of particular content in order to achieve specific learning outcomes, introduced to students of a particular age, taught by characteristic teachers working within an educational system with specific customs and expectations. Having clarified that aspect, it is acknowledged in design studies that making judgments of transferability "…requires conscious choices and value judgments" (Ejersbo et al., 2008, p.150). In order to ease using the guidelines in different contexts, it is first the responsibility of the design researcher to "…provide the database that makes transferability judgment possible on the part of the potential appliers" (Guba and Lincoln, 1985, p.316). I believe that such data was provided in the appended Design Brief (see Appendix A) and the descriptions of implementation presented in Chapter 5. However, it is still the responsibility of others who wish to use these guidelines to make judgements about the shared characteristics between contexts (i.e. the context of this study and their own context) and to identify the parts of the design that meet their local needs (Leach et al., 2009).

The final issue concerns the extent to which these guidelines can inform Saudi biology teachers' decisions in teaching plant nutrition. Although they guide the teacher in some of critical aspects of teaching plant nutrition, they are not sufficient on their own. Rather, they should be accompanied by ways of approaching these specific guidelines, as set out in the Worked Example. Furthermore, there is still a wide range of decisions based on professional judgements relating to what, when and with whom to use these guidelines.

8.5 Reflections on the design and evaluation models used in this study

The purpose of this section is to reflect on the design and evaluation models used in this study. The first sub-section (8.5.1) reflects on my use of the Leeds Model in an attempt to consider its strengths and limitations in terms of designing and communicating teaching sequences. The second sub-section (8.5.2) reviews my evaluation in order to highlight the strengths and limitations of the model and methods of evaluation employed in this study.

The reason that I focus on the design and evaluation is that they underline the main outcomes resulting from conducting the design study. As stated by Confrey (2006), the success of design studies can be judged on the basis of "…how well they can specify what kinds of knowledge they seek to produce, and the warrants for the knowledge they do produce" (p.148).

8.5.1 Reflections on the use of the Leeds Model

I claimed in Chapter 2 (see section 2.4.1.4) that the Leeds Model meets the characteristics of design studies and helps to achieve the expected outcomes from such studies. Here, I examine the usefulness of the Leeds Model, whether it addressed the characteristic of design studies in terms of enabling me to formulate and articulate the rationale and intentions of the design, translate the intentions into a teachable form, communicate the design and inform the evaluation.

In design studies there are two demands that run alongside each other. The first demand is to formulate a local instruction theory in order to address how to teach or learn a given topic (Gravemeijer and Cobb, 2006). The second is to achieve this formulation through systemic and articulated accounts, which constitute a significant characteristic of a design study (Gorard and Taylor, 2004; Confrey, 2006). As stressed by Barab (2006), the articulation allows "…others to understand how to reconceptualise the theory-in-context with respect to their local particulars" (p.156). So, how did the Leeds Model address these two demands?

First of all, it is widely acknowledged that such formulation and articulation are difficult jobs and involve considerable intellectual effort (e.g. Leach et al., 2009; Cobb and Gravemeijer, 2008). The Leeds Model was helpful in breaking down tasks concerning formulation and articulation at multiple levels and types of specifications. For example, the first part of the Design Brief considers the context of the teaching in terms of content, students, teachers and institutional constraints. As I mentioned in Chapter 2 (section 2.4.1.3), such contextual specifications help the designer to sustain the context while making design decisions. On the other hand, it helps others to consider the context in which the design was operated while making judgements regarding the transferability of the resulting domain-specific guidelines.

The Design Brief turns more specific in the second and third parts which are directed towards content aims and pedagogic strategies. These areas are where I found the Learning Demand tool (see section 2.4.1.3 part 2) useful in sharpening my focus on the problematic aspects that hinder students from appreciating the plausibility of photosynthesis. Departing from this concentrated focus, the teaching goals were mapped out with the intention of establishing a scientific definition of food, showing that carbon dioxide does have mass, and addressing that combining liquid with gas can form a solid. Moreover, the Learning Demand tool was helpful in assisting me in seeing the links between the concepts to be targeted, challenges that might prevent students from learning these concepts, and how to target these challenges. However, I was struggling to map out a set of teaching goals that cover all the intended concepts as a result of only using the Learning Demand tool. Therefore, I used the task analysis tool that was introduced by Gagne (1974) for the purpose of breaking down the key ideas and I then recognised the embedded pre-requisite concepts that should be targeted in the teaching sequence (see section 3.2.3).

Another strength of the Leeds Model that should be mentioned at this point is that developing the specifications into tabulated sections kept me focused on making links and developing a coherent design. This coherence is important in the following stages of translating the design into the Worked Example, implementation and evaluation. As pointed out by Ruthven et al. (2009), the iterative process of implementing, evaluating and refining a design is affected by "…the quality of the original design and by the clarity and coherence of the intentions it expresses" (p.329). In addition, the clarity and coherence of a given design can enhance the communication of the rationale to other designers who want to judge its validity or transferability.

With regard to how the Leeds Model helped me to translate the Design Brief into a teachable form and communicate the design to the teachers, the model is less explicit regarding how the Design Brief can be put into practice, whether in terms of developing the Worked Example or considering the implementation. While I see that the authors of the Leeds Model have succeeded in clarifying purposes, components and procedures to develop the Design Brief, they have not provided equal attention to the Worked Example. If we consider the Worked Example to be the medium of putting the Design Brief into practice, it would be helpful if the Leeds Model is extended to consider issues related to developing the Worked Example in terms of the amount of specifications so as to help the teachers follow the design intentions or address potential challenges that might emerge during employing pedagogic strategies. In particular, the need to address these two issues was apparent in this particular study.

In terms of how the Leeds Model addresses issues related to evaluating the designed teaching, I used the specifications that were articulated in the Design Brief to check the effectiveness of the actual implementation in order to establish the match between what was intended and implemented. To guide the process of matching, I developed a set of KDFs (see Chapter 5) that summarise the essential design decisions, and then I traced the actions of teachers and students. Based on this analysis, I concluded with claims about the match between the designed and enacted teaching with regard to content and pedagogic strategies. To this end, I found the level of specification that was articulated in the Design Brief assisted me in tracing teachers' actions and students' engagement. I believe that only with this level of specification was I able to come up with outcomes (i.e. refinements and domain-specific guidelines) of my study that "…provides others with insights into the challenges and opportunities that might emerge in their own context" (Barab, 2006, p.154). However, although the level of specifications drawn out by the Leeds Model can inform the evaluation, the Leeds Model fell short of guiding the evaluation process as a whole. Therefore, I needed to look for an evaluation model to guide the process of evaluation.

Moreover, given that the Leeds Model does not explicitly account for how to translate the Design Brief into a Worked Example or how to effectively implement the Worked Example, it could be concluded that the main interest of the Leeds Model is to formulate and articulate a given design rather than addressing issues related to translating the design into a teachable form or consider the process of implementation or evaluation. So, what can be said about the usefulness of the Leeds model and how can it be improved?

Before answering this question, I would like to make a distinction between the Leeds Model and my use of the Leeds Model, employing the distinction that Confrey et al. (2002) make between "models-of" and "models-for" in the context of implementing interventions in science and mathematics education.

Drawing upon Confrey et al.'s (2002) distinction, the "models-of" are those design models that have been constructed as a result of successive research and can be generalised to different local designs with some modification. On the other hand, the "models-for" are local models that use a "model-of" in a given context or conditions while maintaining the critical components of the adopted "model-of". In this sense, the Leeds Model can be considered to be a "model-of" whereas my usage of it is as a "model-for". It should be mentioned that the "model-of" evolves into many "models-for" that validate its usefulness and develop its theoretical underpinnings as well as its practical features.

Considering this relationship, I want to highlight two points. On one hand, given that the Leeds Model was applied in designing a teaching sequence for the Saudi context which differs, to some extent, from the context where the Leeds Model was developed, this can be taken as strength of the general applicability of the Leeds Model.

One the other hand, although I used the Leeds Model in the way in which it was intended, I made an addition in the course of identifying the key ideas to be taught. While this task may be straightforward in the English context, as the ideas to be taught are already specified in the English Curriculum, the content in the Saudi context is dominated by the textbook. Therefore, a filtration of the ideas was needed because the content presented in the textbook was limited, fragmented and contains some misconceptions (see section 3.2.2). This is a case where I made an addition to the Leeds Model to meet a particular need.

Moreover, the Leeds Model might be extended to account for the processes of *developing* a teaching sequence that goes beyond the *design* phase. In my view, because the development of a design goes through an iterative process that should involve putting the design into a teachable form, implementation, evaluation and making refinements to the original design, a "model-of" will be more useful if it guides the designer through these phases. The Leeds Model would be more useful if it offered more explicit theorisation concerning how to bridge from the Design Brief to the Worked Example, how to implement the Worked Example, and how to evaluate the teaching with the purpose of refining the Design Brief and Worked Example.

This chapter now turns to the second sub-section that concerns the model of evaluation that I used in this study.

8.5.2 Reflections on the use of the evaluation model

The purpose of this section is to review the evaluations conducted on this study in order to highlight issues related to evaluating teaching sequences in general, and to underline the strengths and limitation of the model and methods of evaluation used.

In this study, I used a model to evaluate the effectiveness of the teaching sequence (see section 2.4.3.1). Following Madaus and Kellaghan (2002), I defined the model of evaluation as a construct of:

> *…the main concepts and structure of evaluation work serving the function of providing guidelines for using these concepts to arrive at defensible descriptions, judgments, and recommendations* (p.20-21).

In the model I extended from that of Millar et al. (2002), I intended to measure the effectiveness of the teaching sequence in terms of the match between what was intended and implemented as well as the match between what was intended and attained. To make these measurements, I developed a set of KDFs (see section 5.1) that summarise the essential design decisions as specified in the Design Brief. I then analysed videos of the actual implementation to determine the extent to which these KDFs were met. In addition, I explicitly specified the desired learning outcomes in the Design Brief and then used three written probes (see 4.3.3) to assess students' attainment.

As mentioned in Chapter 2 (section 2.4.3), evaluation constitutes an essential component of any design activity. In fact, any claims of effectiveness must be supported by evidence derived from evaluation. In addition, refinements and the development of guidelines for teaching specific content should be supported by evaluation as well (Barab, 2006). Therefore, the more the evaluation process is made explicit and the more its strengths and limitations are shown, the more others will be able to judge the recommended guidelines and to draw upon the designed teaching. To this end, providing consolidated accounts of the evaluation process might increase the trustworthiness of the findings and may encourage others to make use of them.

This section will attempt to provide some accounts of how the evaluations were conducted. Although some accounts were provided in terms of the quality of the research in the methodology chapter (see section 4.5), at this point my concern is directed towards the evaluation rather than the research in general. In order to highlight the strengths and limitations of the model and methods of evaluation that I used in evaluating the teaching sequence, I draw upon the notion of meta-evaluation, as proposed by Scriven (1972) and extended by Stufflebeam (2000).

According to Scriven (1972), "A meta-evaluation is an evaluation of an evaluation" (p.84). It can be used to determine the merit of the evaluation by reviewing the extent to which it meets the requirements of a sound practice (Stufflebeam, 2000). The meta-evaluation results can provide the researcher with feedback as to the quality of their evaluation and point out the required improvements to their evaluation models and methods. In addition, the results help the readers of the evaluation to decide whether to accept or reject the conclusions advanced by the evaluator, or to re-read the results bearing their context in mind (Stufflebeam, 2000). Moreover, the meta-evaluation will prevent the delivery of faulty findings or the making of unsound decisions based on these findings.

Although the notion of meta-evaluation is mostly conducted by external evaluators, it can be still beneficial, with adaption, to review the evaluation of the short teaching sequences. For example, Kemmis (1982) recommends employing a meta-evaluation in the context of curriculum development in order to optimise the self-criticality of the developer's own practices. Moreover, while the quality of meta-evaluation will be more valuable if it is conducted by an independent evaluator, Scriven (1991) mentions that it is still useful if the evaluators themselves carried it out. I should mention here that I did not conduct a formal meta-evaluation as outlined by Stufflebeam (2000). Rather, I only attempt to review my own evaluation in the light of the criteria used in literature concerning meta-evaluation.

In order to conduct a meta-evaluation, Stufflebeam (2000) proposes four main requirements, including specific standards and criteria that should be checked to judge the soundness of a given evaluation. These requirements are:

(1) *Propriety*: the evaluation is conducted in an ethical manner,

(2) *Feasibility*: the evaluation process and methods are practical and cost-effective,

(3) *Accuracy*: the process of evaluation and findings are valid and usable, and

(4) *Utility*: the evaluation findings are informative and influential.

Given the purpose for conducting a meta-evaluation in this study, I can see that the accuracy and utility requirements are more relevant to my study since they are directly linked to the evaluation process *per se*. Tables 8.3 and 8.4 summarise the standards included in these two requirements, how they were met in my evaluations and where to check them in this thesis.

8.5.2.1 Meeting the accuracy requirement

To find out whether the accuracy requirement is met, Stufflebeam (2000) suggests employing a set of standards as shown in Table 8.3 below.

The first standard concerns programme documentation, which is one of the essential standards used to judge the quality of design studies (Gorard and Taylor, 2004). In order to meet this standard in my evaluation, the Design Brief provides justified specifications and decisions regarding the intended teaching that make explicit the rationale of the design. Moreover, descriptions of teachers' and students' actions were reported to determine the extent of meeting the intended design, and comparisons were made between what was intended and implemented to report any discrepancies with regard to content, pedagogy and learning. In addition, students' attainment was assessed and described in terms of attaining factual knowledge as well as developing conceptual understanding. However, there was a limitation in documenting the programme with regard to the Worked Example, as I only presented outlines of the lessons and teaching/learning activities. As I mentioned in section 3.3, since the Worked Example was only developed in Arabic, translating it into English was demanding.

Table 8.3: Meeting the accuracy requirement

Standard	How it was met	Relevant sections
Programme Documentation	By reporting the design intention and rationale through the Design Brief and Worked Example, the implementation of the teaching sequence, findings of attainments and teachers and students' perceptions	3.2 / 3.3 / appendix A chapters 5, 6, 7
Context Analysis	By providing descriptions of the institutional and physical	3.2.1 / 4.3.4.1 / 4. 3.4.2 / 4. 3.4.3

	characteristics of the context and participants.	
Described Purposes and Procedures	By providing descriptions, rationale and administration of the written probes, making descriptions of actual implementations, and presenting the questions used to guide the interviews.	4.4.3 / chapter 5 / 4.4.4
Defensible Information Sources	Information was obtained from teachers and students using several methods such as written probes, video, classroom written work and semi-structured interviews	4.4
Valid and Reliable Information	The rationale for the evaluation was discussed in detail, describing how it will be addressed through relevant data. The analysis of the data was described and justified. The reliability of analysing students' responses was checked by an independent coder. Limitations were highlighted as well.	4.4 / 4.4.3

The second standard is concerned with the context within which the programme was evaluated. This is important in design studies because making judgments about the transferability of the domain-specific guidelines to other contexts requires an understanding of the context where they were first tried out and tested (Barab, 2006). In my research, the institutional characteristics were described in the first part of the Design Brief (see section 3.2.1). I also provided profiles of the participating schools, teachers and students. Moreover, findings derived from the videos and interviews highlighted some issues related to the contextual influences on the effectiveness of the teaching. Finally, views of teachers and students were explored with regard to the quality, limitation and potential adaptations of the teaching approach in Saudi schools. I believe that these descriptions are useful for people who want to judge the effectiveness of the teaching, who may possibly use the design to teach plant nutrition according to their local needs, and make the necessary refinements.

The third standard is devoted to describing the purposes and procedures of the conducted evaluations. The evaluation models guided me in maintaining a tripartite focus of intentions, actions, and attainment and in gathering data related to each facet. In terms of setting out the intentions and evaluating the implementation, I specified the rationale of the design, as well as descriptions of the seven KDFs that were used to trace teachers' and students' actions, and how these actions were traced using data from videotaped lessons and classroom written work (i.e. activity sheets and end-of-lesson quizzes). With regard to the assessment of learning outcomes, I used three written probes which I fully described in the methodology chapter in terms of their purposes, design and administration. In addition, I was clear about the limitations relating to the written probes, the short period between the post and delayed-post tests and the uncertainties of my interpretations of some parts of students' responses.

The fourth standard considers using defensible information sources, which is a main characteristic of design studies (see section 2.3.1.3). This was met by gathering data from different sources and of different kinds. The evaluation model I used brings together the actual implementation and learning outcomes. With regard to the actual implementation, I traced teachers' actions as well as students' behavioural and intellectual engagement based on video and written classroom work. With regard to assessing attainments, I used three written probes and augmented them with end-of-lesson quizzes and classroom written work as well. In addition, students were directly asked about aspects of the content that they found difficult to understand or did not understand. I also used semi-structured interviews to explore teachers' and students' perceptions of the strengths and limitations of the teaching sequence. Furthermore, I justified in the methodology chapter the rationale behind the sources and methods used to collect data. In particular, I was clear about the limitation of teachers' diaries (see section 4.4.5) and using data from interviews with average and low achievers (see section 7.3).

The fifth standard considers the validity and reliability of the obtained information. In terms of validity, the evaluations focused on the research questions related to reporting the actual implementation (RQ1), assessing learning outcomes (RQ2), and teachers' and students' perceptions about the teaching sequence (RQ3). I described in the methodology chapter how each question was addressed. In addition, I described how the data were collected, analysed and interpreted. In terms of the written probes, the content validity was checked by two biology education supervisors. I also attempted to support my inferences with relevant data. For example, in each chapter I highlighted in the form of summaries: concluding remarks and issues raised due to the recurrent points that I observed in the data. With regard to the reliability of the analysis of the written probes, I provided an Arabic graduate student with the coding scheme, the probes and their purposes, and students' responses. He independently checked the reliability of the coding scheme in 10% of the sample. In addition, I was clear about the short period between the post and delayed-post tests. However, findings derived from videos and interviews were limited only to my analysis. It would be better if my descriptions of actual implementations were checked against videos, or if the stories of teachers and students were checked by the participating teachers.

8.5.2.2 Meeting the utility requirement

This sub-section considers reviewing the evaluation in terms of meeting the utility requirement. Stufflebeam (2000) proposes a set of standards, as shown in Table 8.4 below and I present my review with regard to them.

The first standard is concerned with the information scope and selection. As stressed by Gorard and Taylor (2004), there is a need in design studies to "…collect, combine and unproblematically make use of data of different sorts" (p.107). The evaluation model rests on the importance of collecting data from teachers and students, as the actions of both affect their shared efforts with regard to the construction of knowledge (Driver et al., 1994b). In terms of collecting data related to the teachers, teaching enactments were linked to the KDFs and then were traced by analysing the videos. Actions of the teachers were first followed individually to highlight differences and then collectively to capture the whole picture. The main interest was to determine the extent to which the design of the teaching sequence was met in terms of content and pedagogy. In addition, teachers' views were explored through individual semi-structured interviews. The purpose of the interviews was to raise issues related to the strengths and limitations of the design itself, and issues related to adopting such an approach in Saudi schools. Some interesting issues were presented in both respects. Alongside the interviews, small pocket notebooks (teachers' diaries) were designed to encourage teachers to report their views and feelings about the teaching sequence immediately after implementing each lesson. However, it seemed that the teachers only filled in the notebooks after they finished the five lessons, and they offered limited reflections.

Table 8.4: Meeting the utility requirement

Standard	How it was met	Relevant sections
Information Scope and Selection	Sources and coverage of information: data gathered from both students (pre- and post-test, end-class quizzes, worksheets, videos, interviews) and teachers (videos, interviews, diary)	4.4. 3/ 4.4.1 / 4.4.4,/ 4.3.4/ 4.3.5
Report Clarity	Analysis of findings presented in three chapters. Analysis of the implementation was linked to the Design Brief through seven KDFs. Learning outcomes were reported and augmented by the words that students used. Teachers' and students' perceptions were compiled in stories that reflect the key issues.	Chapters 5, 6 and 7
Evaluation Impact	Some improvements were suggested to optimise the effectiveness of the teaching sequence	5.9.2 / 5.9.3 / 6.4.3 / 6.5

In terms of the students, the learning outcomes were assessed before and after exposure to the teaching sequence using three written probes that were conceptually and phenomenologically-framed. Moreover, the in-action attainments of some aspects of the content were assessed using end-of-lesson quizzes. In addition to assessing the learning outcomes, their behavioural and intellectual engagement was traced from the videos and activities worksheets. In terms of emotional engagement, their views were explored in semi-structured interviews that were conducted in groups according to their performances (high, average, low).

The second standard of utility is concerned with the clarity of reporting with regard to the findings of the evaluation. The clarity of reporting in terms of the findings can be reflected by the extent to which the relevant findings were presented clearly when necessary (Stufflebeam, 2000). In design studies, such standards of reporting and clarity are critical to enable others to judge the quality of the work and make connections to their own contexts (Barab, 2006). In reporting the evaluations conducted in this study, accounts were provided in terms of students' attainment (Chapter 6), the actual implementation (Chapter 7) and teachers' and students' perceptions (Chapter 8). Firstly, the quantitative findings of students' attainments were presented in three sub-sections that correspond with the desired learning outcomes as specified in the Design Brief. Moreover, findings were presented in tables and figures to enhance the clarity and help the reader makes sense of the changes across the three tests. With regard to implementing the teaching, the findings were reported in terms of the seven KDFs. Within each KDF, the rationale and related activities were first presented and then followed by the teachers' actions and students' engagement, and were also supported by excerpts from teacher-student interaction and classroom work. Finally, with regard to teachers' and students' perceptions of the teaching sequence, individual stories were first compiled and followed by some reflections. In addition, in this chapter (see section 8.3) I made use of the evaluation results with regard to refining the designed teaching.

The third standard of utility is concerned with the impact of the evaluation. Indeed, this is essential in design studies to meet the iterative characteristic (see section 2.4.1.1) by making revisions to the original design. The evaluation yielded some useful insights into improving the Design Brief, Worked Example, introductory sessions and written probes. However, there was a limitation in meeting this standard, as the suggested refinements did not extend to examining their validity, as the research was designed in only one cycle due to a practical reason related to the limited time and resources available to replicate the design.

To conclude this part, based on this meta-evaluation I can underline the strengths and limitations of the model and the methods used to evaluate the teaching. In terms of its strengths, I used an evaluation model that brought together measurement of the actual implementation as well as the learning outcomes. In addition, findings from these two sides were augmented and triangulated by findings from the interviews. Given the detailed descriptions of the design, its implementation and evaluation, other designers can judge and maybe use the guidelines I advanced in section 8.4. In addition, the evaluation findings informed refinement of the designed teaching sequence to make it more effective. In terms of limitations, the impact of the suggested refinements can only be regarded as initial hypotheses that should undergo validation.

8.6 Concluding remarks

The main point I wish to highlight from the above discussion is the importance of the explicit articulation and documentation of a given design in terms of design, implementation and evaluation of teaching sequences. Only with such detailed articulation can the designer develop validated possible refinements and domain-specific guidelines. As a result of such articulation, researchers can then draw on each other's work. In addition, rather than practising this research in a loose manner, it might be more useful if design researchers were to develop or adopt models of design and evaluation that support coming up with "…defensible descriptions, judgments, and recommendations" (Madaus and Kellaghan, 2002, p.21). The more their models are holistic, the more their work would be systemic and informative.

In the next chapter, I make some general conclusions on the overall study, and underline the contributions and limitations, suggest some implications and ideas for future research, and highlight the lessons I learnt.

CHAPTER 9: CONCLUSIONS

This chapter begins by presenting an overview of the study, highlighting the key conclusions, and goes on to underline its contributions, followed by an outline of its limitations. Furthermore, some implications for science education in Saudi and ideas for future research are suggested. Finally, it concludes by establishing two lessons linked to developing science textbooks in Saudi.

9 CHAPTER 9: Conclusions

9.1 Introduction

This chapter begins by presenting an overview of the study, highlighting the key conclusions, and goes on to underline its contributions, followed by an outline of its limitations. Furthermore, some implications for science education in Saudi and ideas for future research are suggested. Finally, it concludes by establishing two lessons that I plan to bear in mind when I return to my practice of developing science instructional materials for Saudi schools.

9.2 Overview of the study

In this study, I developed a teaching sequence about plant nutrition for Grade 10 male Saudi students aged 15-16. My choice of plant nutrition was influenced by the significance of this topic in school biology and the widespread misunderstandings about it held by students. Given that there is a need to improve Saudi students' understanding of science, and there is a lack of studies regarding the design of science instructional materials, I decided to conduct a design study and implement the resulting design in Saudi schools. I believe that such a study will not only shed light on designing science instructional materials in Saudi, but also on how Saudi teachers and students respond to novel materials and teaching approaches that differ considerably from their usual practice.

Some of the key conclusions that can be drawn from this study are revisited below.

Designing teaching sequences

This study started by reviewing literature related to students' understanding of plant nutrition, namely, the nature of plant food, the source of biomass and their knowledge of photosynthesis. However, *it was not possible to inform* teaching plant nutrition solely by such empirical findings. Therefore, I used the Leeds Model to guide the process of designing the teaching sequence by the means of two design tools. Firstly, the Learning Demand tool was used to map out the teaching goals that address the very intellectual difficulties that students face when photosynthesis is used to explain plant food and biomass. As the Learning Demand tool does not fully specify what is involved in learning plant nutrition, I turned to the notion of task analysis to meet this need. The other tool was the Communicative Approach that specifies the appropriate class of communication with which to address a specific teaching purpose.

While the Leeds Model helped me to articulate the rationale of the design and specify the teaching goals, pedagogic strategies, and the sequence of the teaching, *it does not explicitly focus on how to put* these specifications into practice in terms of designing the teaching/learning materials, implementation and evaluation. However, the level of specifications offered by the Leeds Model guided me in developing the Worked Example (adapted from an existing teaching sequence by Hind et al., n.d.) and the process of evaluation.

Evaluating teaching sequences

To meet the specific need of evaluation, I extended an evaluation model proposed by Millar et al. (2002) to assess laboratory work. The model that I developed brought together the design intention, actions of the teachers and students in the classroom, and the assessment of the learning outcomes. Combining these three facets enabled me to measure the effectiveness of the designed teaching sequence. Findings from the evaluation provided useful insights about the effectiveness of the teaching, possible revisions to improve its effectiveness, a set of guidelines for teaching plant nutrition in the Saudi context, and general insights concerning Saudi teachers and students' perceptions of the teaching sequence.

The effectiveness of the teaching

In terms of the effectiveness of the teaching, the findings suggest that the sequence helped students to acquire factual knowledge related to photosynthesis, as well as to develop a short-term conceptual understanding of the nature of plant food and the source of extra biomass. Yet, it was less effective with regard to long-term conceptual understanding. The limited effectiveness may be caused by overlooking the relationships between photosynthesis and respiration, food and energy and the limited focus on the construction and practice of scientific explanations.

The nature of required revisions

The necessary revisions can be summarized into three key points. Firstly, in order to design a sequence that enhances a long-term conceptual understanding and the construction of explanations, it is not only sufficient to think about specific content (e.g. plant nutrition) and how it should be approached in the classroom. Rather, in addition to introducing all the related subject information, the sequence should consider introducing knowledge and skills regarding what constitutes a scientific explanation, and plan opportunities for students to practice the learnt explanations.

The second point concerns making the design more responsive to take account of all possible ideas, whether they are everyday ideas or initial scientific views developed from previous teaching. Because the teaching will be more demanding, the teacher should be supported by various activities to meet students' possible reactions. More importantly, issues relating to staging the teaching in a way that addresses the two possible routes should be examined.

The third point concerns enabling teachers to enact the design as intended by providing support and specifications about teaching techniques that seem to be demanding (e.g. interactive/dialogic talk) or those to which teachers are not accustomed (e.g. teacher-led demonstrations), but which are not necessarily demanding, like the former.

It should be noted that all these revisions are not directly related to the topic of plant nutrition; therefore, it appears that designing a domain-specific sequence involves making design decisions that go beyond the specific content *per se* to include decisions about the nature of intended outcomes (e.g. constructing explanation) and the needs of a specific audience of teachers and students. As can be seen from this study, unless these needs are met, teachers will not be able to implement the teaching as intended, and students will not attain the desired learning outcomes.

Guidelines for teaching plant nutrition in Saudi

Considering the design specifications, as well as the evaluation results, I suggested a set of domain-specific guidelines for teaching plant nutrition in the Saudi context, and I highlighted the difficulty of offering guidelines that are supported by evidence that accounts for every detail included in a given guideline. The proposed guidelines concern the amount of detail that is required in order to teach the topic of plant nutrition at Grade 10 in Saudi schools, emphasizing the construction of explanations, the sequencing of content and techniques for addressing the pre-requisite concepts (i.e. food, mass and matter). Moreover, I asserted guidelines relating to eliciting students' ideas about plant food and biomass and then challenging these ideas. I mentioned also the limitations of these guidelines due to conducting the design in only one cycle. Yet, teaching plant nutrition using these guidelines may help teachers to address conceptual difficulties and develop conceptual understandings.

Science education in Saudi

In terms of the Saudi context, although the teaching approach differed from the usual practice of teachers and students, students appeared to be engaged and teachers appreciated the effectiveness of the teaching approach in improving learning. On the other hand, given that both teachers and students were aware of the limitations of traditional practice, this may suggest that they are ready for reform. However, the teachers raised concerns about contextual constraints such as the amount of content presented in the textbook and assessment practices, which will limit the adoption of novel approaches. This may suggest that designing domain-specific teaching sequences is only one factor in improving teaching and learning in science, and it is important to consider other affective factors if change is to take place.

9.3 Contributions of the study

This section outlines the contributions of this study to science education in general and in the Saudi context with regard to developing teaching sequences and teaching plant nutrition.

Contribution to developing teaching sequences

It is clear that my study can point to areas where improvements are needed in terms of developing teaching sequences. Firstly, although existing attempts to theorise and instrumentate the design of teaching have succeeded in providing design models to guide the articulation of the design intention, there is still a need for more information about how to translate the design intentions into a teachable form and how to enable teachers to implement the design as intended. Secondly, although there is a consensus about the importance of evaluating the designed teaching and the types of data to be collected, limited theorisation has been directed to address this importance. The evaluation model that I developed and used in my study is an attempt to fulfill this need. This tripartite model brings together the design intentions, actions of teachers and students and learning outcomes. Apart from measuring the effect on improving students' learning, evaluation findings can help to point to the validity of the design intentions and necessary revisions.

Contribution to teaching plant nutrition

Plant nutrition is one of the most researched topics in biology education and several teaching sequences have been designed to teach this topic. However, in this study I developed and articulated a rationale accompanied by justified design decisions at a fine grain size of detail. With such articulation, others who research the design of biology teaching can judge the validity and transferability of the designed sequence. The resulting design can be recognised as one of the few attempts in the field of designing domain-specific teaching sequences.

Contribution to science education in Saudi Arabia

Given the lack of design studies in Saudi, this thesis constitutes a pioneering and novel attempt to design science instructional materials. In particular, this study used a particular design model to draw upon insights about learning and teaching science and empirical findings about students' ideas to inform teaching. This approach could be a basis for other studies focusing on designing science teaching in Saudi. On the other hand, employing a design study approach could be fruitful in measuring the effectiveness of a given design, and improving understanding in Saudi of how teachers and students respond to innovative initiatives. In addition, this study sheds light on the kinds of ideas that Saudi students hold about plant nutrition. Findings from students' responses confirm that Saudi students had similar alternative ideas to those reported in the literature. Yet, there were some small social and cultural differences. For example, many studies have shown that students see water as the source of plant food (Driver et al., 1994a); the very dry Saudi climate may give a visible link between water and survival of the plant, which therefore strengthens and re-enforces this view in Saudi students.

Nonetheless, there were limitations to this study that are presented below.

9.4 Limitations of the study

The key limitation to this study is the fact that the resulting design was only trialed in one cycle. As a result, some questions about the effectiveness of specific aspects of the design were left unanswered. Moreover, the possible revisions are still in the form of "guess work" and should be validated by actual teaching. Given that the suggested domain-specific guidelines are only supported by evidence from first implementation, their effectiveness is still open to question.

The other limitation is related to the small number of teachers and students who participated in this study. Indeed, conducting the design with only four teachers will limit the generalisability of the domain-specific guidelines and the workability of the designed teaching sequence in other contexts.

In terms of limitations related to methodology, learning outcomes were assessed using only written probes. Given that conceptual issues were noticed in students' responses, it would be better if these issues were investigated by following up with oral probes with a small number of students. Another limitation is found in the results gathered from students' interviews, as they represent the high achievers whose interviews were richer and longer. Although all students were interviewed using the same questions and settings, average and low achievers would have expressed more ideas if additional prompts were used. Another limitation is related to using teacher-student interaction to evaluate the implementation. While findings from the interactions were used to augment other findings, a focused analysis of the interactions might reveal issues about the effectiveness of specific aspects of the design.

9.5 Implications for science education in Saudi

The findings of this study suggest some implications that should be considered in order to improve science education in Saudi Arabia, particularly since the Ministry of Education plans to reform science and math education.

Improving science textbooks

The conceptual analysis of the biology textbook shows that the focus is on introducing facts and definitions rather than targeting conceptual understanding or taking account of students' prior ideas. In addition, the content seems to be fragmented, as well as advancing some misconceptions. Given the key role of textbooks in the Saudi context, the content should be improved in order to enhance conceptual understanding and the construction of explanations.

The process of improving textbooks is similar to the practice of developing teaching sequences described in this study. It should draw on empirical findings on students' ideas, as well as contemporary perspectives on learning and teaching. The resulting textbook should then be piloted in classrooms, and the results from the pilot should be used to improve the textbook. The process of evaluation might undergo successive cycles until the textbook reaches a level that is satisfactory enough to be widely used. Moreover, the evaluation should consider the textbook itself and its usage in the classroom.

In addition, given the limited research conducted in Saudi with regard to designing science instructional materials, which necessitates drawing upon research conducted in, or sequences and textbooks designed for, other countries, there are cultural and language differences that should be considered. As shown in this study, overlooking such differences might limit the effectiveness of the instructional materials.

Preparing teachers for novel teaching approaches

Given the novelty of the teaching approach adopted in this study, preparing teachers to implement the teaching as intended was an essential requirement. However, as shown in this study, teachers' expertise should not be overestimated. Although teachers welcomed and appreciated the novel pedagogies and activities used in the teaching sequence, it appeared that they were in need of further support in some basic techniques like demonstrations to which science teachers are supposed to be accustomed. If teachers lack proficiency in such basic techniques, one wonders about teachers' competencies in the more advanced methods. Analysing the training needs of the Saudi science teachers might help to determine their pedagogical starting points and then professional development programmes can be planned accordingly.

Professional development can be organised through direct programmes or by involving teachers in the implementation of initial teaching sequences or the piloting of textbooks. As shown in this study, teachers' involvement contributed to improving their subject knowledge, learning novel pedagogic strategies for teaching specific content, and changing their perceptions of teaching and learning biology.

Reforming science education

As the Ministry of Education is in the process of reforming science, this study showed that both teachers and students are ready for reform. However, improving practice is more than offering instructional materials or professional development. The Ministry of Education should consider improving the assessment regime to encompass more than assessing recall, re-organizing the school timetable in longer blocks to allow for extended classroom interaction and providing resources for practical work.

9.6 Suggestions for future research

This study can suggest some areas to be considered in future research. Starting with Saudi students' ideas about plant nutrition, findings showed that "water" and "soil" are the most suggested sources for plant food and biomass. In order to design a teaching sequence that addresses these ideas, understanding why students suggest these sources, as well as what they mean by "soil", might be helpful.

In addition, issues concerning the insertion of the articulated design into instructional materials and helping teachers to implement the design as intended are in need of more clarification. The expected outcomes from such research can be in the form of rubrics to guide the design process. While there are examples of such rubrics (e.g. Brophy and Alleman, 1991), they are very general; therefore, producing specific rubrics for science education may be more productive.

Furthermore, acknowledging the difficulty of developing domain-specific guidelines that can be recommended for teachers with confidence in their effectiveness, I suggest focusing on designing short versions of sequences (one or two lessons) that embody a small number of hypotheses. The resulting designs can be implemented by the same teacher with different classes or by different teachers. The effectiveness can be measured using data from teacher-student interactions and students' engagement with the teaching/learning activities. In such small focused studies on certain hypotheses, it may be possible to understand how students respond to a certain pedagogic technique and, therefore, it would be much easier to formulate a domain-specific guideline informed by evidence from different data sources.

9.7 Final reflections: *Lessons learnt*

By conducting this study, I gained knowledge and developed skills regarding performing scientific research. In addition, designing a teaching sequence and conducting a design study taught me lessons that can be linked to my work practice in Saudi. As I work in the General Directorate of Curricula at the Ministry of Education, my job involves designing science curriculum documents (e.g. setting out main goals and syllabuses) and authoring and reviewing science textbooks. When reviewing textbooks, for example, my colleagues and I work as a team and divide the textbook units between us (4-6 authors), according to our subject backgrounds and personal preferences. Each author prepares his work based on his own experience and insights found in other international science textbooks, usually authored in the United Kingdom and the United States. Then, the prepared units are discussed and revised within the team before a final version is compiled that goes out to schools. However, as a result of conducting this study, I can complete this work within a different framework. In the first instance, literature on students' ideas and designing a teaching sequence can inform such activities and make them more evidence-informed rather than relying on experience and other international textbooks, which were actually designed for different contexts. In addition, the workability of the prepared textbook cannot be limited to the authors' views. Rather, the final say should be in the classroom where teachers and students experience the textbook and disclose its strengths and limitations. In this sense, it is unlikely that a final version of a textbook will be achieved without undergoing cycles of implementation, evaluation and refinement.

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Appendix A: The Design Brief

Part 1: Description of the context for the designed teaching

Key aspects	*Descriptions*
***Curriculum**: descriptions of the biology textbook and the key ideas with regard to plant nutrition.*	Year 10 is the first year in which biology is taught as a separate subject, two classes per week of 45 minutes each. Textbooks are usually the main source for content, teaching and assessment. The biology textbook that is used consists of 10 units that must be taught over two semesters. Each unit focuses on a relatively broad topic which can be taught over four to six lessons. At the end of each unit, a set of questions are presented and these are usually assigned for the students to complete as homework. Teachers may also use some of these questions in exams. The topic of plant nutrition has not been taught previously, as a separate targeted topic. But the words photosynthesis, chlorophyll and plant nutrition were briefly mentioned in Year 7 and in the 1st semester of Year 10. Therefore, the first time that plant nutrition is introduced is in Year 10. In addition, it is revisited in Year 11 with more technical details related to light/dark reactions. At the time of introduction, students have already been introduced to biological aspects related to plant nutrition such as the general structure of the plant, plant cells, different food groups (carbohydrates, proteins and fats), biochemical processes in plants and chemical reactions. The Year 10 textbook (pp. 126-128) presents plant nutrition using the following elements (summed up and translated by the researcher, and reviewed by two supervisors and two biology teachers): - Plants make their own food without being dependent upon any organic resources. This food-making means the synthesis of organic compounds from inorganic components. - In the presence of light and other requirements, water drawn from the soil and carbon dioxide absorbed from the air, plants make food inside the chloroplast, which is located in the leaf cells. - Plants need other elements in the form of minerals. - The chemical equation for photosynthesis is: $6\ H_2O + 6\ CO_2 \rightarrow 6\ O_2 + C_6H_{12}O_6$ - Photosynthesis is completed through two phases, light and dark reactions (details of this aspect constitute about 50% of the content). - Food is exported from the leaves to all other parts of the plant.
***Students**:* profile, age and expectations	Descriptions provided in this section are based on the researcher's own experience and observations, and only apply to boys' schools. Schools are single-sex throughout the country. The word "students" refers only to “boys” whenever mentioned in the Saudi context including this sequence. Students are aged 15-16 in Year 10, which is the first year of secondary education (middle and secondary education is taught in separate schools). Students are usually equally distributed amongst classes with regard to age, nationality and ability. Students rarely work in groups or do practical work in the class or the science laboratories. Their role in the class is to listen to the teacher and take notes. It is expected that students will find it difficult to shift to the new teaching style and activities adopted in this sequence. They might require extensive guidance and monitoring from teachers while completing the activities.
Teachers: features of the teachers’ expertise and expectations	All high school biology teachers are specialised in biology, educated to at least BA level in Botany, Zoology or Microbiology. Some may also pursue an additional pre-service year of educational training that covers courses in educational psychology, educational assessment and biology instruction. This includes a pilot teaching section of one semester under the supervision of their university tutors.

	Biology is usually taught in the classroom with no additional equipment or facilities beyond a normal white board. Although teachers are trained to do practical work they rarely do so as the laboratories are mainly prioritised for physics and chemistry tuition. The majority of the teachers are neither familiar with contemporary pedagogies nor are they aware of some aspects of the content presented in this sequence. Biology lessons usually start by questioning students for 5-10 minutes on the content of a previous lesson, and then the teacher writes the title of the new topic on the board or may initiate a question as an entry point. The rest of the lesson is built around a lecturing teaching style where the teacher introduces the ideas presented in the textbook. During teaching, students may ask for additional clarification, although this is quite unusual. Very often students copy down what the teacher writes on the board, while some teachers may dictate the key ideas or refer to them in the textbook to be underlined. Notes taken in the lessons and/or textbooks are the main source that students rely on when preparing for exams.
***Institutional constraints**:* class size, facilities and assessment	Teachers are officially required to follow the content presented in the textbook. Plant nutrition, including photosynthesis, is expected to be introduced over two lessons in the third week of the 2nd semester. Class sizes vary from 25 to 40 students. As most biology teaching takes place in the classroom, practical work is not expected. Assessment of students' knowledge is conducted twice, during and at the end of the semester, using direct questions which are mainly fact-recall oriented. The purpose of assessments is to determine whether students pass to the next year.

Part 2: Conceptual analysis of the content to determine the key ideas to be taught

Based on the reviewed literature and previous teaching schemes (Roth and Anderson, 1987; Hind et al., n.d.) it appears that the ideas presented in the textbook fall short of the aspects that should be covered to help students develop a proper understand of plant nutrition. These are the main features of the textbook content related to plant nutrition:

- An emphasis on subject knowledge, without taking students' existing ideas into consideration;
- Discussing the source of plant food while ignoring the source of biomass;
- Providing misleading sentences about the roles of soil and minerals in photosynthesis. For example, in the Grade 11 textbook (p.25); *"Notice: photosynthesis is really an amazing process because with little soil, water and light a small seed can result in a big plant which can be as long as tens of meters*". Also in the 10th Grade textbook (p.119): "*plants take in carbon dioxide from the air and absorb water and minerals from the soil to synthesise organic substances which constitute its food*".
- Details of ideas related to chloroplast structure and light/dark reactions, which are, on the one hand not fundamental to understanding photosynthesis at this age, and might, on the other hand, disturb students grasping the essence of the topic.

To this end, the researcher decided to refine the textbook content with the view of only focusing on the key ideas necessary to understand photosynthesis and exclude other inferior concepts. The resulting key ideas have been developed from the textbook and previous schemes (Oldham et al., 1985; Roth and Anderson, 1987; Hind et al., n.d.), which are presented in the first section of the next part.

Part 3: Specification of the content aims for the teaching and expected learning outcomes

This part presents content goals for the teaching sequence by analysing learning demands for plant nutrition.

Curriculum content [partly taken from the textbook, and augmented by other sources (see above)]	*Evidence about students' likely starting points (Driver et al., 1994a; Wood-Robinson, 1992; Wandersee, 1983)*	*Learning demands*	*Teaching goals*	*Expected learning outcomes*
Photosynthesis, as an explanation of plant nutrition and increase of biomass, is a complex topic thus its details need to be minimised (Eisen and Stavy, 1988) as much as possible to achieve the essence of the topic, at this age. Therefore, the content will concentrate on the macroscopic level of photosynthesis that enables students to explain plant food and biomass. Enabling students to develop these explanations requires the teacher to address some underpinning pre-requisites (Simpson and Arnold, 1982a) that are fundamental to the subject. The content will revolve around the following: – ***Photosynthesis***: carbon dioxide combines with water using light energy, which is trapped by chloroplast, in order to produce glucose as a main product, and oxygen, as	*Conceptual and ontological starting points:* – **Nature of food**: students think of food as material that organisms eat or take in to the body, regardless of the energy-provision requirement. – **Source of plant food**: Students believe that plants obtain their food from the environment. Although they might refer to making food internally, they still believe that water, minerals, fertilizers and light are food too. Also, students retain a model of plant food similar to that of the animal feeding model. – **The nature of photosynthesis and what it is for**: students usually struggle to appreciate that combining gas and liquid (carbon dioxide and water) can result in a solid (glucose, cellulose and woods). In addition, students might	*Conceptual and ontological learning demands:* – Reconsider what food is, to include food as the chemical substance that serves in respiration to liberate the energy needed for chemical processes. – Recognise that carbon dioxide does have mass and can contribute to making food and building plant material. – Understand that it is plausible that plants make food (sugar) by combining gas (carbon dioxide) with liquid (water) in the presence of light;	– *To establish energy supply as a criterion to determine whether a certain substance is food*. This will help students to distinguish food from other substances that plants obtain from the environment and they will therefore be able to start questioning whether soil, water and minerals are food for the plant. – *To introduce a simple model of photosynthesis:* plants have the capability to independently produce their own food by combining carbon dioxide with water. – *To highlight the implausibility of the scientific explanation:* by highlighting the underlying conceptual barriers that stand in the way of acceptance of the scientific explanation. These underlying barriers are: • How can a weightless gas (carbon dioxide) contribute to the formation of other substances? • How can combining a gas (carbon dioxide) with a liquid (water) form a solid (sugar)? • How can combining simple molecules like carbon dioxide and water form a complex compound like glucose? – *To address the implausibility of the scientific explanation by demonstrating that:* • Carbon dioxide molecules do have mass	At the end of the teaching sequence students should be able to: – *Identify that:* • Plants make their own food via photosynthesis from inorganic components, carbon dioxide and water. • Plants use energy from sunlight to power the reaction between carbon dioxide and water. • The products of photosynthesis are glucose and oxygen. – *Explain what plant food is and how it is obtained:* Plants make (or produce) their own food (or glucose, starch, carbohydrate) from the raw materials available in the environment (carbon dioxide and water) through a process called photosynthesis. – *Explain how photosynthesis*

a by-product. Photosynthesis takes place in chloroplasts that are located in leaves. It is described at a molecular level by the equation: $6H_2O + 6CO_2 \rightarrow 6\ O_2 + C_6H_{12}O_6$ – ***Plants exploit glucose in two ways:*** • As a source for energy: glucose is used as fuel in respiration from which energy is liberated to carry out biochemical functions. • To assimilate plant biomass: some of the glucose is converted into other complex chemicals such as cellulose, proteins and fats, which make up the plant biomass, with the addition of some minerals absorbed from the soil.	confuse photosynthesis with respiration. Others may focus on the analogy that plants work as filters to clean up the environment, so they see photosynthesis as primarily an oxygen making process rather than a food making process. – **Plant biomass**: even though students may explain the source of plant food by photosynthesis, it is rather difficult for them to accept that plan biomass could also be explained by the photosynthesis model. They often refer to soil and water as sources of plant biomass.	– Accept that photosynthesis is the only scientific explanation for the sources of plant food and extra biomass.	• Gas and liquid can be converted into solid • Simple molecules (carbon dioxide and water) can combine to produce a complex compound (sugar). – *To develop a simple explanation by adding other aspects of the photosynthetic process :* • Plants make their own food in photosynthesis from inorganic substances (carbon dioxide and water). • Plants use energy from sunlight to power the reaction between carbon dioxide and water. • The main product of photosynthesis is sugar, which is regarded as plant food. • Oxygen is released as a by-product. • Photosynthesis takes place in chloroplasts which are located mainly in the leaves. – *To use the scientific explanation to explain the source of biomass and food:* • Make students' concept of biomass formation explicit, • Introduce the fact that glucose can combine to produce carbohydrates, fats and proteins; • To revisit the basic structure of the plant cell to show its composition, and how glucose contributes to these chemicals; • To emphasize that all creatures need energy to carry out biochemical processes. This energy is liberated in respiration from glucose. The photosynthesized glucose is the only organic substance that plants have. – *To support practicing the scientific explanation in a different context.*	*explains plant biomass:* The extra biomass comes from the food (or glucose, starch, carbohydrate) that plants make (or produce, form, obtain) through photosynthesis, with small proportions of minerals absorbed from the soil

Part 4: Specification of pedagogic strategies and sequencing of content

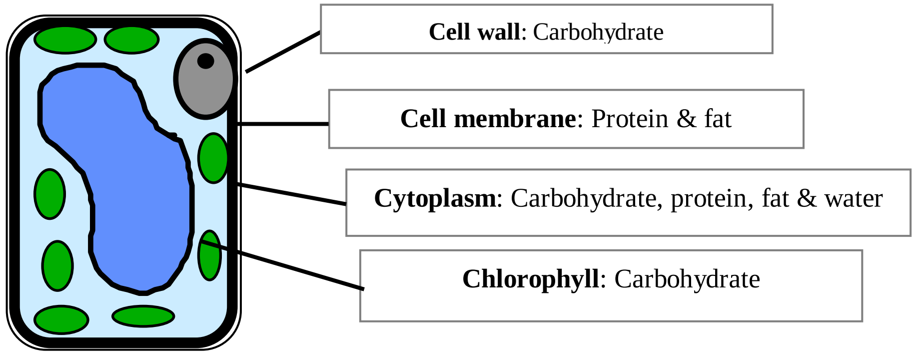
This part presents an overview of the design decisions concerning sequencing the content and pedagogic strategies employed for supporting students' learning at a fine grain size

Aspect of the teaching sequence to be designed	*Explaining the changes in teaching*	*Rationale and justification*
Overall structure of the teaching intervention (large grain size)	1. *Staging the scientific story*. Starting from exploring and then challenging students' ideas, the teacher guides them to a simple explanation of the source of plant food. 2. *Supporting student internalisation*. The teacher helps students to recognise the reasons for the implausibility of photosynthesis, and addresses these issues. 3. *Staging the scientific story*. The teacher and students use photosynthesis as an explanation for plant food and extra biomass. 4. *Handing-over responsibility to the students*. Students are challenged to use learnt information in contexts that differ from the learning context.	• *Perspectives on teaching, learning and stages of classroom communication* The overall structure of the teaching sequence adopts Leach and Scott's (2002) approach to designing teaching. This is based on social constructivist perspectives where the teacher leads classroom interaction towards the construction of knowledge in the classroom. They suggest planning the teaching through three stages, not necessarily sequential. Firstly, staging the scientific story through activities led by the teacher to make the scientific view available in the social plane. Secondly, the teacher works closely with students to support them in making personal sense of the scientific view which will involve checking understanding, challenging students' ideas and giving feedback. Finally, the teacher plans and provides both assisted and unassisted opportunities for students to make use of the scientific knowledge in contexts that might differ from the original ones. As the teaching purposes are different in these three stages, the teacher is supposed to use different classes of talk (Mortimer and Scott, 2003). The teacher might start with a dialogic talk to explore students' starting points (How do plants get food? How can we define food?) to make them aware of their views, then he might turn to non-interactive/authoritative talk to present the scientific point of view (plants make their own food from inorganic substances), and he might use again a dialogic talk to support students' use of what they have learnt (why soil, minerals and water cannot be regarded as plant food). • *Choices of content and its sequence* It is important to answer the following question here: "How much detail should the sequence cover?" If we acknowledge that photosynthesis is a complex topic (Waheed and Lucas, 1992), what can a designer do to simplify it, and, yet, keep it scientifically acceptable? Referring back to the teaching objectives, the core of this sequence is to promote students' understandings of the nature of plant food, how plants make their food, and the source of extra biomass. To this end, ideas related to micro level processes (light/dark reactions) might seem unnecessary towards achieving the teaching goals. In addition, the literature reveals that students often confuse photosynthesis with respiration. Therefore, it seems that it will be more sensible to separate the two topics altogether, except for briefly mentioning the role of glucose in plant cells. Moreover, a gradual addition of details is advanced in this sequence. First, only carbon dioxide and water will be introduced as reactants and glucose as product. Other aspects will be postponed to prevent developing misunderstandings. For example, the introduction of light is postponed to prevent developing the common misunderstanding that light is a reagent equivalent to carbon dioxide and water. In addition, introducing oxygen is delayed to prevent it from being seen as the key product of photosynthesis. With regard to sequencing the design, Posner and Strike (1976) suggested principles for sequencing the content, some of

		which are relevant here. First, the learning is most likely to occur if we start with the "logical-prerequisites". Therefore, It seems that starting with students' conceptualization of food is a primary step before moving to introduce photosynthesis. Students will be ready to look for another source of plant food if they first realize that inorganic substances are not food for plants. In addition, appreciating that carbon dioxide has mass and contributes to the food making process is a pre-requisite concept that needs to be available (Simpson and Arnold, 1982a). Another relevant sequence principle is to move from the easiest (or the most likely to be understood) to the difficult. To this end, the problem of biomass is less difficult than using glucose to serve in respiration to liberate energy (Driver et al., 1994a). Therefore, it might be useful to build students' understanding of biomass before addressing plant food. • *An overview of the teaching flow* - As mentioned above, students come to the class with views that hinder them from accepting the plausibility of photosynthesis. Starting from the concept of food, the sequence focuses students' attention on energy supply as a criterion to call something food. - To make the scientific explanation easier to accept, it will be presented through simple pictorial form (Carbon dioxide + Water → Sugar). In addition, because some students view photosynthesis as merely a gaseous exchange process, discussion about oxygen will be postponed. - Once photosynthesis has been suggested to explain the source of plant food the implausibility of the explanation will be highlighted to make students aware of the problematic aspects. That is, how can a simple weightless gas (carbon dioxide) combine with a mere liquid (water) to form a complex molecule (glucose)? These issues are then tackled in series of activities. - Before using photosynthesis to explain the source of extra biomass, the basic structure of plant cells should be revisited, and then the concept of how glucose can combine with small proportions of minerals taken from soil to constitute most of the plant cell parts should be introduced. - An explanation of plant food through photosynthesis is developed by persuading students that creatures need energy for metabolic functions, energy can only be liberated from glucose, and plants can only obtain glucose from photosynthesis. - The research also documents (Anderson and Smith, 1987) that even after formal teaching of photosynthesis, students find it hard to accept that only photosynthesis can explain plant food and extra biomass. Rather, they turn back to use their original ideas and sometimes use these alongside photosynthesis. Therefore, the intent at the end of the sequence is to use photosynthesis to reason why water, minerals and soil cannot be food for plants.

Sequencing of teaching goals from section 2, and selection of pedagogic strategies (large and fine grain size)	1. Conducting a formative assessment of the "concept of food" in order to establish the energy supply criterion.	1. Defining food based on the energy supply criterion is a pre-requisite to prepare students to recognise why inorganic substances taken in from the environment cannot be considered to be plant food. Although the sequence is related to plants, discussing food in relation to humans might be more sensible as it will be easy for students to start with something more familiar to them. To help students recognise that not all required substances provide energy, although they are essential, the teacher draws an analogy to the things needed for a car while only petrol provides energy to keep the car moving. 🗣 Communicative approach: interactive/dialogic to answer the question "Why do we need food?", and non-interactive/dialogic to review expressed ideas, and finally non-interactive/authoritative talk to establish the energy criterion.
	2. Probing students' spontaneous ideas about the nature of plant food and how it is obtained.	2. The purpose of this formative assessment is, on the one hand, to make students aware of their ideas and, on the other, to start building on them. Students will be questioned about the ways animals and plants obtain food, and the kinds of food they obtain. Although animals' food is not related to the topic, including animals might help students to make comparisons and recognise differences between plant and animal feeding. As documented in the literature, it is expected that students regard soil, water, minerals, fertilisers and light as plant food. Moreover, they might see roots as the entrance point of food, analogical to the mouth in humans and animals. As students are likely to have previously come across the term "photosynthesis" they might include photosynthesis alongside other kinds of food. 🗣 The communicative approach will be interactive/dialogic that probes ideas about plant food, clarifies meanings and, sometimes, challenges students' ideas based on the energy supply criterion.
	3. Challenging misunderstandings about the nature of plant food.	3. Challenging students' ideas of plant food by setting a conflict to the ordinary observation of the sweetness found in fruit. The challenge lies in the fact that fruit contain a sweet taste whereas soil, water and minerals in fact are not sweet. So, where does the sweet come from? Then, there is a bridge to suggest that there is another source that gives this sweet taste which is not in the listed ideas. 🗣 The communicative approach will be interactive/dialogic group discussions, and then interactive/dialogic between the teacher and groups' representatives.
	4. Introducing a simple explanation of the source of sweetness, and then transferring this explanation to the source of plant food.	4. In trying to resolve the previous conflict, students are then introduced to a simple pictorial form of photosynthesis that would explain the sweetness found in fruit. The basic argument is built for the source of sweetness; the case will be made later to explain that plants use this process too to produce food. 🗣 The communicative approach will be non-interactive/authoritative talk to introduce the simple explanation and non-interactive/dialogic to portray the scene to compare the two sources of plant food: inorganic substances or glucose.
	5. Making the implausibility of the simple explanation explicit.	5. Although some spontaneous ideas related to plant food may be refuted by the sweet source conflict, the alternative simple explanation is only introduced as a hypothesis which needs to be developed in two phases. The first phase involves helping students to recognise the concepts that make photosynthesis implausible, which include the concept that carbon dioxide has no mass so cannot contribute to form other substances, and that matter is a fixed entity that cannot be cycled. Students' views of mass and conservation of matter are critical pre-requisites here (Simpson & Arnold, 1982a) in order to

		appreciate the plausibility of the scientific explanation. As it is most unlikely that students will independently identify these problematic aspects, they will be led to identify; (1) how can a weightless gas (carbon dioxide) contribute to produce sugar, (2) how can a gas and liquid be converted into solid, and how can simple substances combine to produce a complex one. 🗣 Through interactive/dialogic talk the teacher leads students to recognise the problematic aspects, and the teacher re-asserts these issues through non-interactive/dialogic talk.
	6. Addressing the causes of implausibility through teacher-led demonstrations.	6. The aim of the teacher-led demonstration is to enable students to appreciate the plausibility of the scientific explanation by resolving the aforementioned problems. Firstly, to demonstrate that carbon dioxide does have mass. Secondly, to see that gas and liquid can form a solid to prove that matter can be converted into different forms. Yet, it is rather difficult to make a demonstration of how carbon dioxide and water can produce glucose. Therefore, building a model of glucose might help students to see how atoms of carbon dioxide and water can be re-arranged to form glucose. 🗣 The teacher uses interactive/authoritative talk to make a demonstration to resolve the problematic issues.
	7. Developing the simple explanation by adding sunlight to power the chemical reaction.	7. The scientific explanation was intended to be introduced with as few details as possible to ease its acceptance. Another reason to postpone introducing sunlight is that students tend to consider light as a reactant rather than a source of energy (Wood-Robinson, 1991). So, if it is introduced separately from carbon dioxide and water, they might treat it as a source of power. Sunlight is fundamental in the process of food making and, in fact; the process was partly named after it. The role of sunlight will be introduced through a simple demonstration to show that glucose cannot be formed without a source of energy. 🗣 The teacher uses interactive/authoritative talk to make a demonstration to illustrate the role of sunlight.
	8. To further develop the simple model by adding oxygen as a by-product.	8. There is evidence that students consider photosynthesis to be an oxygen producing process and they often confuse photosynthesis with respiration (Wandersee, 1983; Driver et al., 1994a). Therefore, postponing adding oxygen to the photosynthetic process will reduce the role of oxygen in students' eyes. It should be asserted here that glucose is the main intended product of photosynthesis, while oxygen is only produced as a by-product, and some even describe it as "wasteful" product. 🗣 Through interactive/dialogic talk students find out about the other products, and then through non-interactive/authoritative talk the teacher asserts that oxygen is only a by-product.
	9. Consolidating what has been presented so far, and making the explanation more plausible by locating the process in the leaf, and converting glucose into starch.	9. Students have been introduced to the structure of plants prior to this year which will help to locate photosynthesis in the most appropriate of plan parts, that is, the leaves because these contain chloroplasts that trap light and can bring together water and carbon dioxide. The teacher then introduces the fact that if the leaves are examined we will not find a trace of glucose. Introducing this fact is favoured over a practical investigation due to the lack of laboratory-work in the Saudi schools. The teacher then demonstrates, based on the different levels of solubility of glucose and starch, the reason that food is stored as a more stable molecule, which is starch. 🗣 Students try to decide through interactive/dialogic talk the most appropriate part to locate photosynthesis, and then the

<table>
<tr><td></td><td></td><td>teacher reviews their conclusions through interactive/dialogic talk. The teacher then introduces glucose into the conversation through non-interactive/authoritative talk.</td></tr>
<tr><td></td><td>10. Explaining that biomass comes mainly from glucose produced in photosynthesis.</td><td>10. Firstly, students' ideas concerning the source of biomass should be made explicit before introducing where the extra biomass comes from. Then there is a need to introduce some facts about the structure of the plant cell and the chemicals that comprise the cell. As these facts cannot be discovered or investigated at this age and in this context, they will be presented to students through two steps:


a. Students already know the basic structure of the plant cell. However, they need to appreciate how glucose contributes to building the plant cell through introducing the concepts that:
- The cell wall is cellulose which is a type of carbohydrate.
- The cell membrane is made of protein and fat, which are produced from glucose
- The cytoplasm consists of carbohydrates, proteins, fats and water
- Plastids contain chlorophyll that is produced originally from glucose.

b. Students already know that there are different types of food, carbohydrates, fats and protein and the differences between them. It should be stressed that glucose, which is produced through photosynthesis, contributes to the majority of different chemicals that make up the cell. In addition, this is the time to focus on the minerals which are often considered to be plant food (Wandersee, 1983).
🗣 The teacher introduces glucose into the conversation and cell structure through non-interactive/authoritative talk.</td></tr>
<tr><td></td><td>11. Explaining how glucose serves as a fuel for respiration.</td><td>11. Like the last step, students cannot discover by themselves that glucose serves as fuel in respiration from which energy is liberated. This will be introduced through two steps. Firstly, the teacher introduces the fact that all creatures need energy to carry out biochemical processes. Secondly, energy is only liberated in respiration from glucose. Then, relating this to the case of plants, photosynthesised glucose is the only substance that plants have that can be used in respiration. Therefore, soil, water, minerals and light cannot serve as fuels for respiration.</td></tr>
</table>

	12. Practicing the scientific explanation by revisiting ideas concerning the nature of plant food.	12. At this point students should know that food is produced by plants through photosynthesis, and plant biomass is formed from the surplus glucose. However, it has been documented in the literature that students continue, even after formal teaching, to consider inorganic substances to be a source of food and biomass, (Smith and Anderson, 1987), and some of them refer to photosynthesis simultaneously with other inorganic substances (Wood-Robinson, 1992). The purpose of this final phase is to stress again the scientific explanation to account for sources of food and biomass by revisiting the old ideas of plant food and justifying why they are wrong in the scientific view. 🗣 Through non-interactive/authoritative talk the teacher revisits the old ideas concerning the nature of plant food, and then through interactive/dialogic talk students are encouraged to practice using the scientific explanation when accounting for the source of plant food.
Teachers' Guide	Develop a Teacher's Guide to help the teacher understand and perform the sequence as planned.	Providing a detailed teacher's guide seems inevitable in an instructional materials-based context. Both teachers and students are dependent upon such materials, whether to plan teaching or to study for examinations. In addition, this must be provided in a written form which is easy to produce due to limited resources and is more teacher-friendly than alternative forms (e.g. media). The guide has the following features: • Introduction: this introduces the purpose of the sequence which is to help students understand photosynthesis by targeting their spontaneous ideas using a variety of strategies. • How to use this sequence: this section illustrates roles to be performed whether by the teacher or students, with specific icons alongside the guide: – Teacher's role: to explore students' ideas, introduce the scientific view and support students' learning. – Students' role: in terms of groupwork individual tasks. • The sequence and its activities are highly structured to improve consistency of teaching. For example: – Teaching scenarios are provided to describe the tuition step by step. – Student learning is enhanced by activities and structured worksheets. • As students normally write down teacher's notes in every lesson, this need has been met by providing prepared summaries of key ideas for teachers to give to students at the end of each lesson. • Two appendices are provided at the end of the teaching to develop teachers' understanding with regard to the communicative approach and students' common misunderstandings of photosynthesis (used in introductory sessions). • Powerpoint presentations to help the teachers perform the sequence as planned. • Based on the teachers' profile presented in section 1, it seems that introductory sessions are needed to introduce the teachers to the sequence and its associated pedagogies. It is also expected that both the content and pedagogies will be challenging for the teachers and they will need support in different forms such as quick individual meetings to discuss any concerns raised.

Appendix B: Using the Task analysis tool to break down the key ideas

Key Ideas	***Components embedded in the key idea***		***Familiarity***	***Related students' ideas***	***Decisions in terms of the content***
Carbon dioxide combines with water using light energy, which is trapped by the chloroplast, to produce glucose as a main product and oxygen as a by-product. Photosynthesis takes place in chloroplasts that are located in the leaves.	**Chemical reaction**	Reactions can take place in plants	Unclear	Confusion about whether this occurs in plants	Emphasise that chemical reactions (photosynthesis) take place in plants at the cellular level Address the concept that the atoms in carbon dioxide and water are broken down and re-arranged to form glucose
		Atoms of molecules can be broken down and re-arranged to form new molecules	Encountered	Unaware or only acknowledged to occur in a chemical rather than a biological context	
		Any matter can be converted into different matter regardless of its state (gas, liquid, solid)	Encountered	Matter and matter cycling mostly attributed to solid particles	
	Carbon Dioxide	Has mass and can contribute to making other substances	Encountered	Gas is weightless and cannot contribute to form other things	Address the concept that carbon dioxide does have mass and can contribute to form complex compounds
		Absorbed from air through stomata	Encountered	Nothing relevant	
		Consists of atoms (carbon and oxygen) and can be broken down to its atoms	Encountered	Only aware of the atoms from which it is made	
	Water	Absorbed from the soil through the root	Encountered	Some may think that leaves take water in	Introduce that water is sucked up through the roots and transported through the stems to the leaves
		Can be transported through stems (xylem) to the leaves	Encountered	Nothing relevant	
		Consists of atoms (hydrogen and oxygen) and can be broken down	Encountered	Only aware of the atoms from which it is made	
	Light energy	Trapped by chloroplasts, which are mostly located in the leaves	Encountered	Chloroplasts are mostly associated with giving green colour	Emphasise that light is trapped by chloroplasts and used as an energy source (rather than a reagent) to
		Light rather than heat is trapped by	Implicit	Students confuse light with heat	

Key Ideas	*Components embedded in the key idea*		*Familiarity*	*Related students' ideas*	*Decisions in terms of the content*
		chloroplasts	Encountered	Light is directly beneficial as food, or for health and living	power the reaction
		Light energy can be converted into chemical energy	Encountered	May be acknowledged in physical sciences rather than biology	
	Glucose	A simple organic molecule is a carbohydrate	Encountered	Nothing relevant	Introduce the nature of glucose and why it converts into starch
		Glucose is a soluble substance so it's transported as sucrose and stored as starch	Encountered	Nothing relevant	
	Oxygen	Released out through stomata	Encountered	Nothing relevant	Emphasise that oxygen is produced as a by-product
		Produced as a by-product	Implicit	The main product of photosynthesis	
	Photosynthesis	A biochemical process that occurs in green plants to produce glucose	Superficial	Regarded as plant's respiration, or the main aim is to produce oxygen	Emphasise that photosynthesis is a food-making process
Glucose is used as a fuel in respiration from which energy is liberated to carry out biochemical functions.	**Respiration**	All organisms respire to liberate energy needed for biochemical processes	Implicitly Encountered	A synonym for breathing, so it's only a gas exchange process	Emphasise that some of the photosynthesised glucose is used in respiration. Do not go further with respiration to maintain the clarity of the essence of photosynthesis.
		Plants do respire during day and night	Encountered	Plants don't breathe, or they only breathe at night, or breathe in carbon dioxide rather than oxygen	
		While both plants and animals need glucose for respiration they obtain it differently	Implicitly Encountered	Lack of awareness of cellular respiration or why oxygen is needed	
	Need for energy	Energy is needed for metabolic process	Implicitly Encountered	Food is mostly associated with growth rather than energy	Emphasise that all creatures need energy to carry out biochemical processes
				Lack of awareness of energy transfer at a plant metabolic level, energy can be obtained directly from the sun	

Key Ideas	*Components embedded in the key idea*		*Familiarity*	*Related students' ideas*	*Decisions in terms of the content*
				Energy is liberated in digestion rather than respiration	
	Food	Plants need food like other organisms	Encountered	Any absorbed substance	Establish a definition of food as a substance that serves to liberate energy in respiration
		Food is needed to liberate energy in respiration	Implicitly Encountered	Any absorbed substance that is edible or digestible	
		Glucose is the only organic substance that animals and plants use in respiration	Implicitly Encountered	Food keeps organisms healthy and alive	
	Plant food	Photosynthesised glucose is the only food that plants use	Implicitly Encountered	Soil, water, minerals and fertilisers are plant food	Emphasise that glucose is the only food for plants, and justify why inorganic substances are not food
				Both glucose and inorganic substances are food for plants	
	Biochemical processes	The processes that occur in the micro level of the cell, and need energy to process	Encountered	Aware of the biochemical processes but not the energy requirement	Introduce the concept that many chemical processes occur at the cellular level
Some of the glucose is converted into other complex chemicals such as cellulose, proteins and fats, which make up the plant biomass, together with some minerals absorbed from the soil	**Biomass**	Plants are made up of cells, cells are made up of tiny structures, these structures are made up of chemicals	Encountered	Awareness that cells are the basic units and consist of tiny structures, and this is the end of the story	Introduce the structure of plant cells, and the chemicals of which they are comprised
		Chemicals that plant cells are made of come mainly from glucose that can combine to form cellulose and fats, and from proteins formed from glucose and nitrogen absorbed from the soil	New	Nothing relevant	Introduce the concept of how much glucose is invested in these chemicals. Introduce the concept that glucose can combine to form other compounds
	Minerals	Only small proportions of nutrients are absorbed from the soil to contribute to the chemicals of which plants are made	Implicitly Encountered	Minerals absorbed from the soil are used to build up plant biomass	Emphasise that only small amounts of minerals are used in the chemicals of which the cell is made

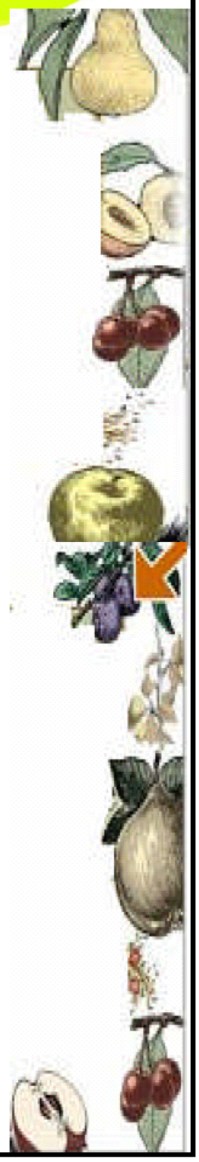
Appendix C: Translated Samples from the Arabic Worked Example

Sample **1** : The source of sweet found in fruits

Where does sugar come from?

In a friends gathering, Ahmed host his friend with apples, bananas and grapes. As usual Saleh asks, where does this sweet taste come from? All laugh and said it is simple! Ali suggests, from soil. Ahmed, No, it comes from water. Adnan, I suppose it comes from organic fertilisers. Saleh, but all these are not sweet, and fruits are too sweet. All say, Yes that's right.

So, could you help them to find out" Where does sugar come from?"



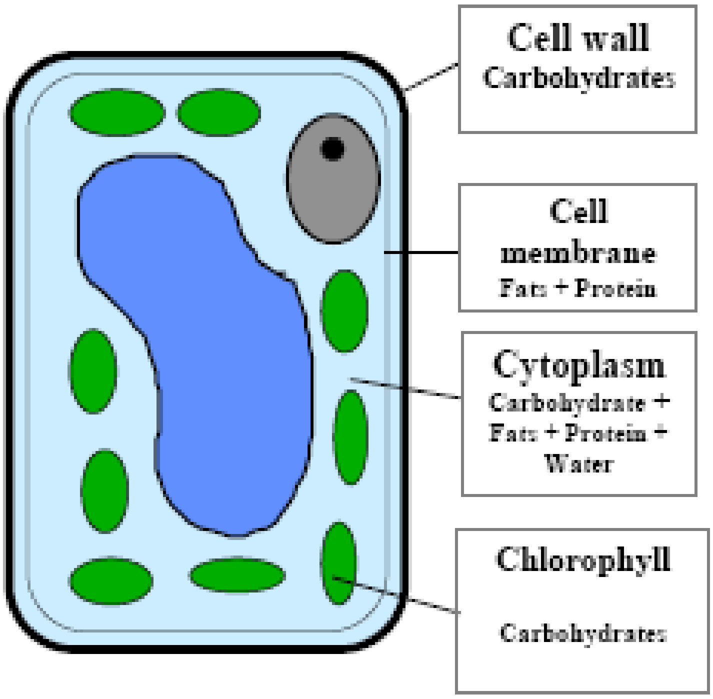
Sample 2: A quiz of testing glucose in the leaves.

Which food plants have inside the leaves?

- From what Ahmad learnt in biology is that plants photosynthesize to produce glucose, which is plant food. Ahmad wants to check if there is really glucose inside the leaves. So he did the following experiment;
    - Picked some fresh green leaves from one of the trees at mid-day.
    - Mashed the leaves to extract a solution that contains the photosynthesis product, and filtered the solution out.
    - Added to drops of Benedict solution to test whether there is glucose (if there is glucose the Benedict solution turns to red)
    - Ahmad was surpised that Benedict solution didn't change to red!!!
- What do you think the problem? Tick one of the followings;
    a) Photosynthesis does not produce glucose
    b) He should picked leaves in the night
    c) He should look for something else rather than glucose
    d) Another reason is: ……………………………………………………………
- The reason for my choice is:

Sample 3: Facts sheet about chemicals the plant is made if

The Chemicals that plant cell is made of



Chemicals that plan cell is made of:

Name	Composed of	Source
Carbohydrates	Chains of glucose	Photosynthesis
Protein	Glucose	Photosynthesis
	Nitrogen	*Soil*
Fats	Glucose	Photosynthesis
Chlorophyll	Glucose	Photosynthesis
	Magnesium	*Soil*

Appendix D: Samples from video descriptions

Teacher: **T1** **Lesson: 1**

Item	Code	Time	Description
The teacher discusses with the whole class: Why do we need food, and things that can be called food?	F-Implemented P-Implemented Replaced Ignored	**6.04**	The teacher raised the question "What do we need food for?" He added that "…we've learnt before that all living things feed". Then through whole class discussion he called for responses from students which were: for producing energy, growth, be alive, repair damaged tissues and carrying out biological functions. Then he moved to the second question "What are the things that can be called food?" Students' responses were: things that can be used for the aforementioned purposes, anything the body benefits from. He finally stressed that all living thing need food, there are different types of food, but to call something "food" it should supply energy. Then he went on to present the fuel analogy.
Setting group discussion of the source of food for animals and plants	F-Implemented P-Implemented Replaced Ignored	**13.5**	The teacher explained the activity and asked students to work in groups, he moved between groups to clarify the task if needed. Students seemed to be working collectively and one of each group wrote down their ideas. Then the groups presented their ideas regarding the sources of plant food, which were: plants are autotrophic, through photosynthesis and roots, plants absorb things, obtain food from soil, minerals and water.
The teacher starts discussing students' ideas showing their limitations, and stressing the energy-supply criterion to determine the nature of food.	F-Implemented P-Implemented Replaced Ignored	**10.07**	It seemed that students' focus turned towards ways of obtaining food rather than the nature or kinds of food, so the teacher asked "If we say that plants absorb food through roots, what kind of food do they get?" He explicitly asked about water, soil, minerals, and fertilizers. Then stressed the criterion that "…only things that provide energy can be called food". He went further to examine water, minerals, fertilizers and sunlight based on this criterion.
Setting a conflict by asking students to explain the source of sweetness found in fruit.	F-Implemented P-Implemented Replaced Ignored	**11.35**	The teacher asked students to taste grapes and follow the activity dialogue to find out where the sweetness comes from. Through group discussions, students ascribed the sweetness to glucose which is produced by photosynthesis. It seems that most groups' responses agreed on photosynthesis.
The teacher focuses on the idea that a reaction happens inside the plant that can produce sweetness or sugar	F-Implemented P-Implemented Replaced Ignored	**1.45**	Following the discussion that emerged from the last activity, the teacher presented a simple possible source for sugar, which is combining water with carbon dioxide. Students seemed ready to accept this possible source, so no contradictions were raised.
The teacher makes a link to the next lesson to check plausibility, and then sums up what has been presented.	F-Implemented P-Implemented Replaced Ignored	**0.34**	The teacher closed the discussion and stated that they will examine the plausibility of this simple reaction in the next lesson.
		43.10 mins	

Teacher: T2 Lesson: 1

Item	Enactment	Time	Descriptions
The teacher discusses with the whole class: Why do we need food, and what things can be called food?	**F-Implemented** P-Implemented Replaced Ignored	**6.16**	The teacher started by raising the question: Why do we need food? Through whole class discussion he obtained students' ideas and wrote them on the board: produce energy, growth, be alive, repair damaged cells. Then he discussed with the whole class substances that can be called food. Students' responses were: milk, anything needed for growth, vegetables, fruit, meat and legumes. One of the students added: food comprises what is needed for producing energy and growth, then students started to comment on this. The teacher didn't sum up or comment on students' responses, and presented the fuel analogy.
Group discussion of the source of food for animals and plants	F-Implemented **P-Implemented** Replaced Ignored	**9.28** *And again* **6.06**	The teacher explained the activity task and asked students to work in groups, then moved between groups to clarify if necessary. Students seemed to be working collectively and one of them wrote down their ideas. At the end of the activity and before presenting ideas, he collected the activity sheets, but I asked him to return them. However, he didn't give students the chance to present their ideas as he moved to the next activity; the source of sweetness. Then I reminded him to do the activity. The groups presented their ideas which were: photosynthesis, respiration, glucose, air, water, minerals, fertilisers, CO2, sunlight and soil. One of the group said there are two ways: food produced through photosynthesis and water and minerals from soil. He didn't sum up the ideas or use the board.
The teacher discusses students' ideas stressing energy supply as a determinant of the nature of food.	F-Implemented P-Implemented Replaced **Ignored**	**0.13**	The teacher mentioned that the idea will be discussed in the next lesson saying "We will find out in the next lesson".
Setting a conflict by asking students to explain the source of sweetness found in fruit.	F-Implemented **P-Implemented** Replaced Ignored	**9.17**	The teacher asked students if they found grapes sweet. Then he followed the dialogue presented in the activity sheet. He was planning to use a whole class discussion, but I reminded him to do it through groups. Students' responses were glucose and photosynthesis. He didn't sum up or write on the board. He said "We will find out in the next lesson".
The teacher focuses on the idea that a reaction happens inside the plant that can produce sweetness or sugar	F-Implemented P-Implemented Replaced **Ignored**	**0.15**	The teacher presented a simple model of what happens inside plants and mentioned that this will be discussed in the next lesson.
The teacher makes a link to the next lesson to check the plausibility, and then sums up what has been presented.	F-Implemented P-Implemented Replaced **Ignored**		
		31.7 mins	

Teacher: T3 **Lesson: 1**

Item	Enactment	Time	Descriptions
The teacher discusses with the whole class: Why do we need food, and substances that can be called food?	**F-Implemented** P-Implemented Replaced Ignored	**7.77**	The teacher asked students to quickly discuss the two questions in groups, and asked them to present their ideas. Then he asked one of the students to sum up the presented ideas which were: we need food for energy, growth, carrying out biological functions. Examples of food were: carbohydrates, minerals, vitamins, proteins, fat, water and sunlight. Also he encouraged students to comment on or reject these ideas. One of them rejected sunlight as food and distinguished between food and things needed for life and health. Then he introduced the “fuel analogy”.
Setting group discussion of the source of food for animals and plants	**F-Implemented** P-Implemented Replaced Ignored	**8.9**	The teacher explained the activity and asked students to work in groups. He moved between groups to clarify if necessary, students seemed to be working collectively and one in each group wrote down their ideas. Then the groups presented their ideas which were: water, sunlight, soil, CO2, photosynthesis, minerals, oxygen at night and carbon dioxide at day, fertilizers. The teacher summed up students' ideas on the board.
The teacher discusses students' ideas stressing energy supply as a determinant of the nature of food.	**F-Implemented** P-Implemented Replaced Ignored	**5.05**	The teacher went back to "Why we need food" highlighting that food is needed for energy. He followed the students’ ideas one by one, examining them based on energy supply. Most of the talk was non-interactive-authoritative. The teacher concluded this part and moved on to the next activity.
Making students think of photosynthesis through finding out the source of sweetness in grapes, and starting a discussion about possible sources.	F-Implemented **P-Implemented** Replaced Ignored	**6.17**	The teacher asked students to taste grapes and follow the activity dialogue to find out where the sweetness comes from. Through whole class discussion students ascribed the sweetness to: water, minerals, reactions inside the plant that utilize water, minerals etc. He then asked students to agree or disagree with the last idea. Then students started to comment on the reaction idea and some mentioned photosynthesis.
The teacher focuses on the idea that a reaction happens inside the plant that can produce sweetness or sugar	**F-Implemented** P-Implemented Replaced Ignored	**5.45**	Following the discussion that emerged from the last activity, the teacher presented a simple possible source for sugar, which is combining water with carbon dioxide. He asked students to raise their hands if they agree or disagree and justify their choice. Students focused on agreement rather than rejection and started to talk about photosynthesis. Some students suggested adding soil alongside carbon dioxide and water.
The teacher makes a link to the next lesson to check plausibility, and then sums up what has been presented.	**F-Implemented** P-Implemented Replaced Ignored	**6.69**	The teacher closed up the discussion and stated that they will investigate the plausibility of the simple model in the next lesson. He also summarized what has been presented, the need for food, employing energy creation to say that something is food, he stressed that food is something that provides energy, this excludes water, minerals, soil and fertilizers from being food for plants.
		40.48 mins	

Teacher: T4 Lesson: 1

Item	Enactment	Time	Descriptions
The teacher discusses with the whole class: Why do we need food, and substances that can be called food?	**F-Implemented** P-Implemented Replaced Ignored	**11.20**	The teacher raised the question "Why do we need food?" and called for responses through a whole-class discussion. While receiving responses he wrote them on the board. Students' responses were: energy, growth, reproduction, be alive, carrying out biological functions, produce heat, repair damaged tissues. He kept students' responses related to his intended answers by rejecting or rephrasing them. At the end he summed up students' ideas. Then he moved to the things that we can call food. Through a whole class discussion students' responses were: minerals, carbohydrates, vitamins, proteins, vegetables, fruit, water, fates and oxygen. At the end he summed up their ideas. He stressed that carbohydrates, proteins and fats are the only things that can be called food, using the fuel analogy. He sometimes went further with points that aren't closely related to the discussion (e.g. explaining red cells, defining biological processes, tissues)
Setting Group discussion of the source of food for animals and plants	**F-Implemented** P-Implemented Replaced Ignored	**10.03**	The teacher explained the activity task and asked students to work in groups, he moved between groups to clarify if necessary. Students seemed to be working collectively and one of them wrote down their ideas. The students' ideas were: water, sunlight, soil, photosynthesis, air, minerals, oxygen, carbon dioxide, fertilizers. The teacher summed up students' ideas on the board.
The teacher discusses students' ideas stressing energy supply as a determinant of the nature of food.	F-Implemented **P-Implemented** Replaced Ignored	**8.09**	Then the teacher went back to the question of "Why do we need food?" telling students a story of a man in the desert with only water, would he survive or not, and why. Then he went further, asking if we put a plant in the dark but we provide water, would it survive. Although he stressed the energy creation, he didn't link to students' ideas and said we will talk about this in the next lesson".
Making students think of photosynthesis through finding out the source of sweetness in grapes, and starting a discussion about possible sources.	**F-Implemented** P-Implemented Replaced Ignored	**9.07**	The teacher asked the students to taste grapes and follow the activity dialogue to find out where the sweetness comes from. Through group discussions students ascribed the sweetness to: a plant has the ability to convert inorganic substances into organic substances like sugar, carbohydrates, water and sunlight, cellulose, water soil and fertilizers. He summed up the students' ideas and then asked specifically if water, minerals and fertilizers are sources of sweetness. He asked students if they agree or disagree and then moved on to present a possible source which is that reactions occur inside the plant.
The teacher focuses on the idea that a reaction happens inside the plant that can produce sweetness or sugar	F-Implemented **P-Implemented** Replaced Ignored	**1.25**	The teacher simply presented that plants can combine water with carbon dioxide to produce sugar. He added that we will discuss this possible source in the next lesson.
The teacher makes a link to the next lesson to check the plausibility, and then sums up what has been presented.	F-Implemented P-Implemented Replaced **Ignored**	**0.20**	The teacher only summed up what had been presented in the lesson.
		40.24 mins	

Appendix E: An activity for defining food

Food that provides energy

Compare between the four products below in terms of energy supply, and which one can be considered as food and why.

Serving Size: 1 bottle • 1/2 L	
Amount Per Serving	
Calories 0	Calories from Fat 0
	% DV
Total Fat 0g	0%
Saturated Fat 0g	0%
Trans Fat 0g	
Cholesterol 0mg	0%
Sodium 0mg	0%
Total Carbohydrate 0g	0%
Dietary Fiber 0g	0%
Sugars 0g	
NET Carbs 0	
Protein 0g	0%
Vitamin A 0% •	Vitamin C 0%
Calcium 0% •	Iron 0%

Nutrition Facts	
Serving Size 1/4 tsp (1.5g)	
Servings Per Container 7560	
Amount Per Serving	
Calories 0	
	% Daily Value*
Total Fat 0g	**0%**
Sodium 590mg	**25%**
Total Carbohydrate 0g	**0%**
Protein 0g	
*Percent Daily Values are based on a 2,000 calorie diet.	

Supplement Facts		
Serving Size 3/8 cup (3.2 fl. oz./95mL)		
Servings Per Container 10		
Amount		**% Daily Value***
Calories	40	
Total Carbohydrate	10 g	3%
Dietary Fiber	1 g	4%
Sugars	8 g	
Vitamin A	5,000 IU	100%
Vitamin C (as ascorbic acid)	60 mg	100%
Vitamin D (as cholecalciferol)	400 IU	100%
Vitamin E	30 IU	100%
Vitamin K	80 mcg	100%
Thiamin	1.5 mcg	100%
Niacin	20 mg	100%
Vitamin B6	2 mg	100%
Folate	400 mcg	100%
Vitamin B12	6 mcg	100%

Nutrition Facts	
Serving Size	3 Cookies (29g)
Servings Per Container	About 13
Amount Per Serving	
Calories 140	Calories from Fat 50
	% Daily Value*
Total Fat 6g	**9%**
Saturated Fat 1.5g	**8%**
Trans Fat 2g	
Cholesterol 0mg	**0%**
Sodium 140mg	**6%**
Total Carbohydrate 21g	**7%**
Dietary Fiber 0g	**0%**
Sugars 11g	
Protein 1g	
Vitamin A 0% • Vitamin C	0%
Calcium 0% • Iron	2%