The
University
Of
Sheffield.

ENHANCED ROCK WEATHERING SUPPLY CHAIN LIFECYCLE SUSTAINABILITY

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Sheffield University Management School

December 2020

Supervisors:
Prof Lenny Koh
Prof David Beerling

PhD Candidate: Eunice Pokuaa Oppon BSc (Hons), MSc
Registration Number: 160240995

“The future can be predicted to the extent that we are involved in making it happen”
(Gramsci, 1971)

Declaration

This thesis submitted for examination for the award of PhD is the author's original work. It is declared that the work as a whole or portions of it and has not been submitted elsewhere for this or any other award.

The thesis was conducted and written in accordance with the University of Sheffield's ethics and regulation for postgraduate research.

The University has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Abstract

Climate change caused by anthropogenic greenhouse gas (GHG) has been widely reported as one of the negative human induced impacts with the scientific evidence suggesting that climate change presents overwhelming global risks to economies, the environment and livelihood and so it demands urgent global response in mitigation and adaptation. In view of this, there is growing research into potential CO_2 sequestration methods that can be implemented as climate mitigation strategies. One such option, which has been reported as a credible mechanism is Enhanced Rock Weathering (ERW); a form of global carbon sequestration which involves the spreading of crushed silicate rocks on lands to speed up the removal of atmospheric carbon dioxide. Despite the potential of ERW, there is limited understanding of the Triple Bottom Line (TBL) supply chain sustainability implications of ERW which encompasses economic, environmental, and social impacts and these remain an important but underexplored research area. Consequently, providing a robust theoretical base and developing a quantitative supply chain modelling framework for analysing and understanding the TBL implications of ERW have become timely and important.

To address the aforementioned issues, this research adopts a quantitative research approach based on the methodological principle of supply chain TBL (economic, environmental, and social) impact assessments to address the pertinent questions surrounding ERW sustainability. For the environmental quantitative analysis, environmentally extended input-output and process life cycle analyses are used separately for estimating impacts across a range of comprehensive and integrated indicators. The economic assessment of ERW is done by way of performing macro-level lifecycle costing of silicate production using economic input-output model. Social implications of the ERW process such as labour rights and human rights issues are assessed using a socially extended input-output method based on the social hotspot database (SHDB).

The research findings suggest that improvements in TBL sustainability associated with ERW implementation is dependent on improvements in environmental and social impacts. Based on a comparative lifecycle assessment, the study also highlights that embodied environmental impacts of basalt fertiliser is less when compared to industrial fertilisers and artificial silicate sources.

Dedication

To God Almighty for how far he has brought me.

To my family both in UK and Ghana. You have been my inspiration and motivation for my PhD journey.

Acknowledgement

I thank God Almighty for the wisdom and strength during my PhD journey. I would not have made it this far without His grace. Special thanks also to my supervisors, Prof Lenny Koh of Sheffield University Management School and Prof David Beerling of Animal and Plant Science Department for the excellent supervision, guidance and mentoring throughout my research. Special thanks to you Prof Lenny Koh for being a great source of encouragement and offering career guidance to me. You have pushed me to be the best I can be as an early career researcher. My thanks also go to the Leverhulme Centre for Climate Change Mitigation and the Grantham Centre for Sustainable Futures for funding my studies.

I also like to thank Dr Adolf Acquaye (Kent Business School), for his tremendous help on this PhD journey; right from the very start when you sent me the PhD advertisement and your continuous support to the very end; I am eternally grateful to you. To Dr Taofeeq Ibn-Mohammed (University of Warwick) and Dr Raphael Espinosa (University of Sheffield); both of you have been of tremendous help to me on this PhD journey with your continuous mentoring for valuable advice especially the time you would take to explain relevant methodologies to me; I am deeply grateful. I also thank the administrative staff of Sheffield Management School for their support.

A very special thanks and gratitude to my family here in UK especially my big sister, nephew, and niece; thank you for your love and support. To Aunty Vivian, I say God richly bless you for opening your home to me during my entire stay in Sheffield. Many thanks to my parents, Victor and Francesca Oppon and my siblings back in Ghana; for your encouragement, though miles away. To Dr Davina Osei; you have been a constant source of support and inspiration and I am so proud to call you my friend. To all my friends and loved ones, I say God bless you for your words of encouragement all through this journey; this success is equally yours as it is mine.

Table of Contents

List of Figures

Chapter 1:

Chapter 2:

Chapter 3:

Chapter 4:

Chapter 5:

Chapter 6:

Chapter 7:

Chapter 8:

Chapter 9:

Chapter 10:

List of Tables

Chapter 1:

Chapter 2:

Chapter 4:

Chapter 6:

Chapter 7:

Chapter 8:

Abbreviations and acronyms used in this thesis

AP-Acidification Potential

BECCS-Bioenergy with Carbon Capture and Storage

BRIC- Brazil, Russia, India, China

CCS-Carbon Capture and Storage

CDR-Carbon Dioxide Removal

CE- Circular economy

DAC-Direct Air Capture

EC Index- Economic index

EIA- Environmental impact assessment

EIO-Economic Input Output

EEIO-Environmentally Extended input-output

EP-Eutrophication Potential

ERW-Enhanced Rock Weathering

FAETP-Fresh Water Aquatic Ecotoxicity

FSETP- Fresh Water Sediment Ecotoxicity

GDP- Gross Domestic Product

GHG- Greenhouse gas

GOS- Gross Operating Surplus

GTAP-Global Trade Analysis Project

GWP-Global Warming Potential

HTP- Human Toxicity

IFA-International Fertilizer Association

IO- Input-Output

ISO-International Organisation for Standardisation

ILO International Labour Organisation

ITUC International Trade Union Confederation

KCL- Potassium Chloride

KOH-Potassium Hydroxide

LCA-Life cycle assessment

LCC- Life cycle costing

LCIA-Life Cycle Impact Assessment

LCI-Life Cycle Inventory analysis

LCSA-Lifecycle Sustainability Assessment

MAETP-Marine Water Ecotoxicity

MJ-Megajoules

MSETP-Marine Sediment Ecotoxicity

M&Q- Mining and Quarrying sector

NET- Negative Emission Technology

PPM-Parts per million

SCM- Supply chain management

SDG- Sustainable Development Goals

SETAC-Society for Environmental Toxicology and Chemistry

SHDB- Social Hotspot Database

SIO-Social Input Output

SRBV-Social Resource-Based View

SSP- Single Superphosphate

TAETP-Terrestrial Ecotoxicity

TBL- Triple Bottom Line

TSP- Triple Superphosphate

UK-United Kingdom

USA-United States of America

UNEP- United National Environment Programme

UPR-Unit process exchanges

UNICEF- United Nations Children Fund, originally known as United Nations Children Emergency Fund

WIOD-World Input-Output Database

Glossary of key terms and definitions used in this thesis

S/N	Term	Definition
1.	**Artificial silicates waste additive**	This refers to waste by-products (secondary waste sources) such as cement kiln dust, steel slag and coal ash that have been cited in the literature as possible alternatives for CO_2 sequestration through Enhanced rock weathering.
2.	**Carbon dioxide (CO_2) sequestration**	This is the process of reducing global warming by capturing atmospheric carbon dioxide and storing in mediums such as rock or the ocean floor for an extended time period.
3.	**Comminution**	This is usually a common term that refers to the crushing and grinding of rocks.
4.	**Direct impact**	Supply chain lifecycle impacts resulting from direct inputs of production. In the context of this study, the direct impact refers to all impacts within the direct sector (mining and quarrying) where crushed silicate/basalt are produced.
5.	**Domestic inputs**	These are the production inputs that are sourced locally, that is from sectors within national boundaries.
6.	**Economic Sustainability Index**	The economic sustainability index (EC index) is a combined weighted value of all the economic impact categories (GDP, GOS, imports, employee compensation, and working hours). It indicates the overall economic sustainability performance of countries in producing silicates for ERW.
7.	**Emerging economies**	In the study, they are used interchangeable to refer to BRIC countries, that is Brazil, Russia, India, and China.
8.	**Enhanced Rock Weathering**	Enhanced Rock Weathering, is a geoengineering technology that enhances the earth's natural way of

		safely removing atmospheric carbon dioxide through large scale mining, crushing, and spreading of silicate rocks mainly on cropland.
9.	**Environmental Impact Intensity**	Environmental impact intensity refers to the impact per unit of output produced derived by dividing total sector environmental output (example GHG emissions) by the total output produced in that sector.
10.	**Environmentally Extended Input Output**	This is a type of LCA method based on the input-output framework where environmental impacts such as emissions have been incorporated in the analysis.
11.	**Environmental Sustainability Index**	The environmental sustainability index (EN index) is a combined weighted value of all the environmental impact categories (energy use, GWP, material use, acidification potential, and eutrophication potential) measured. It indicates the overall environmental sustainability performance of countries in producing silicates for ERW.
12.	**Greenhouse Gases**	Greenhouse gases refer to gases such as carbon dioxide, nitrous oxide and methane which when emitted into the atmosphere, raises the heat temperature of the earth planet.
13.	**Gross Domestic Product (GDP)**	GDP is an indicator of a country's output of goods and services within a specific time and depicts how the economy is faring.
14.	**Gross Operating Surplus (GOS)**	GOS is an indicator of the capital that economic sectors within a country have and use for expenses including tax payment and repayment of debt to creditors.
15.	**Imported inputs**	These are the production inputs for a product sourced externally from sectors in other countries
16.	**Indirect impact**	Supply chain lifecycle impacts resulting from indirect inputs. These relate to other production inputs purchased not by the product sector under

		consideration but indirectly through their reliance on other sectors.
17.	**Input-Output Framework**	The framework is underpinned by economic resource flow (products and services) recorded as monetary transactions, usually in US dollars or other national currencies depending on the source of data. The I-O framework depicts transactions between sectors within an economy.
18.	**Intermediate consumption**	This represents the sector-to-sector transactions in an economy, including domestic and import consumption.
19.	**Integrated Resource-Based View (IRBV) theory**	In this study, a proposed integrated resource-based view (IRBV) is presented to capture the inter-linkages between firms and how this can lead to competitive advantage, that is TBL sustainability advantage.
20.	**Leontief Inverse Matrix**	Leontief inverse matrix also referred to as total direct requirement matrix, shows the direct and indirect input required per unit output in each sector.
21.	**Lifecycle Assessment**	Lifecycle assessment is an extensively used method for estimating the potential environmental impacts associated with a product or service.
22.	**Lifecycle Costing**	Life cycle costing is considered as an extension of the traditional LCA method but with a focus on supply chain economic impacts of products and processes.
23.	**Lifecycle Sustainability Assessment**	This usually refers to the use of Lifecycle assessment (LCA), lifecycle costing (LCC) and Social lifecycle assessment (SLCA) for measuring sustainability.
24.	**Lifecycle Sustainability Assessment index**	The lifecycle sustainability index score (LSCA index) for a country is an aggregated weighted value of all TBL impact index scores (economic, environmental, and social) measured. It indicates the overall social

		sustainability performance of countries in producing silicates for ERW.
25.	**Macro-level assessment**	This refers to any analysis that occurs at either sectoral, national, or regional levels.
26.	**Nature Resource-Based view theory**	Nature Resource-based view (NRBV) theory proposes that firms can achieve a competitive advantage based upon the firm's relationship to the natural environment. The NBRV theory is composed of three interconnected strategies: pollution prevention (minimise emissions and waste), product stewardship (minimise lifecycle cost of products), and sustainable development (minimise environmental burden of firm growth).
27.	**Process-based lifecycle assessment**	The measurement in physical terms of all the energy and material flow that goes into the manufacture of a product usually undertaken at the firm level.
28.	**Resource-based view theory**	The Resource-Based View (RBV) is used to explain how firms can achieve sustained competitive advantage with valuable, rare, imperfectly imitable and non-substitutable resources.
29.	**Social extension matrix**	In the SIO model, the social extension matrix refers to the sectoral direct risk working hours derived for a social indicator (forced labour, child labour, etc.) in a given sector. Data used in constructing the social extension matrix is obtained from the social hotspot database (SHDB)
30.	**Social Hotspot Database**	A database created by researchers at Harvard University and New Earth B Enterprise that provides comprehensive country and sector level data on social themes. Data is collected from publicly available and credible sources, including ILO, World bank, etc.

31.	**Social Input-Output**	This is a term used in the study that refers to a type of SLCA method based on the input-output framework where social risk impacts such as forced labour have been incorporated in the analysis.
32.	**Social Lifecycle assessment**	UNEP defines Social Lifecycle assessment as a social impact (potential impact) assessment techniques that aim to access the social and socio-economic impacts of products and their potential positive and negative impacts along their lifecycle
33.	**Social Resource-based view theory**	Social resource-based view (SRBV) is defined as an expansion of the RBV and NRBV theory to include social sustainability dimension where competitive advantage is achieved in the context of a firm's relationship to the society in addition to the natural environment (Tates and Bals., 2016).
33.	**Social risk impact**	This refers to the potential positive or adverse impact on stakeholders associated with a product's supply chain or lifecycle.
34.	**Social Risk Impact Index**	The social risk impact index (SR index) for a country is a combined weighted value of all social risk impact categories (Labour rights, health & safety, Human rights, community infrastructure, and socio-economic contribution) and indicates the overall social sustainability performance of countries in producing silicates for ERW.
35.	**Technology Matrix**	A matrix showing direct inputs required per unit sectoral output. It is also commonly referred to as the direct requirement matrix.
36.	**Triple Bottom Line impacts**	These are impacts relating to the economy, environment, and society.

CHAPTER 1: INTRODUCTION

1.1 Research Background

This thesis forms part of the first phase of a 10-year research grant awarded to the Leverhulme Centre for Climate Change Mitigation (LC3M) in 2016. The Centre which is led by Professor David Beerling is centred on developing evidence-based research for mitigating climate change and promoting food security, whilst conserving natural resources. This research is focused on Enhanced Rock Weathering as a safe and cheaper climate change mitigation strategy. Enhanced Rock Weathering (ERW) is a geoengineering technology, based on the principles of carbon sequestration, which works by enhancing the earth's natural way of safely removing atmospheric carbon dioxide and stabilizing global warming temperatures through natural reactions in the chemical breakdown of rocks (Taylor et al. 2016; Beerling et al. 2018). Research in the LC3M Centre is organised around four interdisciplinary central themes:

- Theme 1-Earth Systems Modelling.
- Theme 2- Fundamental Crop Weathering Science.
- Theme 3- Applied Weathering Science.
- Theme 4- Sustainability and Society.

This thesis falls under Theme 4-Sustainability and Society, which is tasked to assess the sustainability dimensions for ERW in addressing the real-world feasibility of the technique. The current study is specifically geared towards analysing and understanding the triple bottom line (TBL) impacts (environmental, social, and economic) of enhanced rock weathering from a lifecycle perspective. Research work in Theme 4 which is mainly focused on supply chain assessment of ERW has clearly defined roles and distinct aims and objectives outlined. In line with this structure, the current study presented in this thesis centres on the lifecycle sustainability assessment of ERW (that is triple-bottom-line impacts), and is primarily focused on ERW supply chain relating to production; mainly mining and comminution (crushing and grinding). Complementary work being carried by other researchers in Theme 4 extensively covers the additional ERW supply chain lifecycle stages particularly involving transportation and application of the crushed rocks based on novel spatial lifecycle assessment method and predictive modelling of ERW supply chain into the future. In addition, the ethical implications and public acceptance of ERW are also considered under Theme 4. This approach adopted by the LC3M Centre, therefore avoids duplication and redundancy of research work. Fig 1.1 shows the different research themes under LC3M Centre and where the current thesis study fits into.

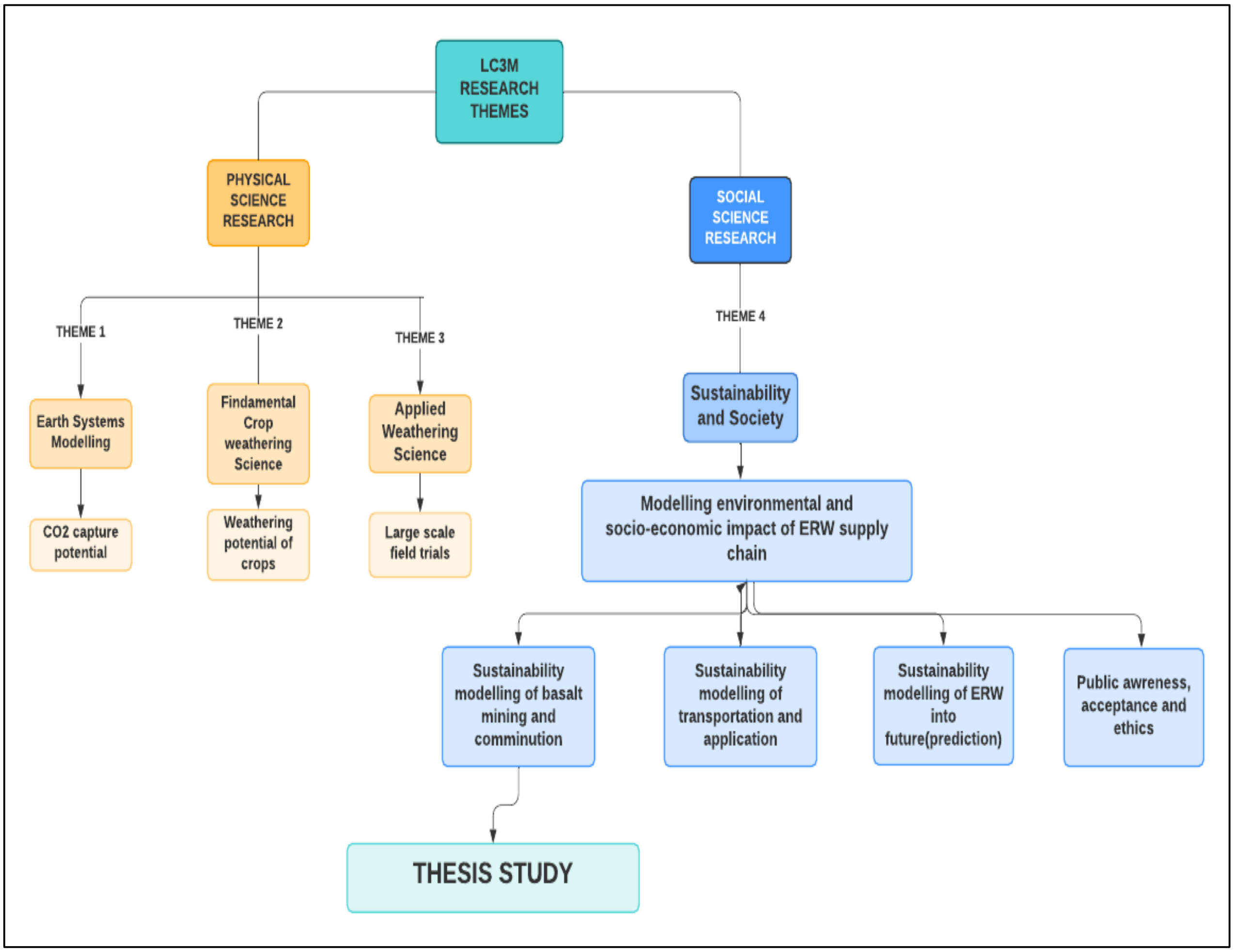


Fig 1.1 Thesis study and relationship with research themes under the Leverhulme Centre for Climate Change Mitigation (LC3M)

1.2 Research Motivation

Contemporary research has emphasized the increasing influence of the impacts of humans on the natural environment. Consequently, this has led to the crossing of certain biophysical threshold and planetary boundaries of the eco-system (Rockström et al. 2009). In fact, out of the nine planetary boundaries where potential human existence and development exist, four has been exceeded, including climate change. Within this context, climate change caused by anthropogenic greenhouse gas (GHG) emissions has been widely reported as one of such human-induced impacts with the scientific evidence suggesting that climate change presents overwhelming global risks to economies, the environment and livelihood and so it demands an urgent global response (Allison et al. 2009, Pall et al. 2011).

Under the Paris climate agreement, member countries agreed to work collectively in reducing global warming temperature to about 1.5 degrees Celsius if indeed any meaningful positive impact on climate change mitigation is to be achieved (Rogelj et al., 2016). Two main approaches are usually adopted on climate change mitigation. These are:

- Mitigation technologies focused on GHG avoidance or low carbon emissions.
- Mitigation technologies focused on GHG removal.

Table 1.1 Different technological approaches to Climate change mitigation with examples- Adapted from Smith et al. (2016) and IPCC (2014)

Technologies aimed at GHG avoidance or low carbon emission	Technologies aimed at GHG removal or carbon dioxide removal
Wind farm energy	Carbon Capture and Storage (CCS)
Biofuel	Bioenergy with Carbon Capture and storage (BECCS)
Hydro-electricity	Direct Air Capture (DAC)
Nuclear energy	Afforestation
Solar farm	Enhanced Rock Weathering

In terms of GHGs emissions prevention, research has focused mainly on renewable energy mix such as wind farm technology, solar panels, biofuels among others while gradually trying to face out the use of fossil fuels including coal, oil and natural gas (IPCC 2014). Although this strategy has been widely welcomed, there are concerns and unsolved questions on whether this approach should be the only strategy in tackling the climate change problem. For instance, what happens to the already emitted GHGs in the atmosphere since they remain trapped for long periods causing the continuous rise in atmospheric temperature? Furthermore, how realistic is the possibility of doing away with anthropogenic GHGs from fossil fuel-based activities such as electricity from coal power stations (Johnsson et al., 2019)? Even if this is possible, it might not be realized soon and in time to meet the global temperature target of 1.5-degree Celsius. This has called for research into the development of strategies that aims at capturing released GHGs because of currently unavoidable anthropogenic activities causing climate change (Sharifzadeh et al. 2019). Commonly described as carbon dioxide removal (CDR) strategies and in some case net-emissions technologies (NETs), these include carbon capture and storage (CCS), bioenergy with CCS(BECCS) and Direct Air Capture (DAC).

However, the Intergovernmental Panel on Climate Change (IPCC) in the published Fifth Assessment Report (IPCC 2014), emphasized that despite a growing number of climate change mitigation policies, there have been absolute decadal increases in anthropogenic greenhouse gas (GHG) emissions; the highest in human history occurring between 2000 and 2010. Further to this, it reported that without additional efforts to reduce GHG emissions beyond those in place today, emissions growth is expected to persist and it will be driven by increase in global population and economic activities (IPCC 2014). Consequently, to achieve the emission reductions necessary to forestall a continuing cycle of global warming, new and innovative climate change mitigation strategies are emerging. One such climate mitigation option is Enhanced Rock Weathering which can be described as a form of atmospheric CO_2 sequestration or removal technology and is one of the three policy approaches suggested by the Stern Review to reduce GHG emissions (Stern 2007).

Rock Weathering has been a long-established research field in the geological literature (Goldich 1938) but it is not until recently that it has been explored as a form of climate change mitigation strategy (House et al. 2007). The science of enhanced rock weathering (hereafter referred to as ERW) is based on carbon dioxide being sequestered from the atmosphere through the dissolution of silicate minerals in rocks. The principle for the ERW process is that carbon dioxide in the atmosphere dissolves in rainwater forming carbonic acid, which, once in contact with rocks, slowly dissolves them (Renforth 2012). The weathered by-products, which include carbon, are then transported by surface and groundwater runoff into the oceans, which act as a sink for the trapped carbon (Taylor et al., 2016). It can therefore be argued that the technological process of ERW is very much in sync with Article 2 of the United Nations Framework Convention on Climate Change (Protocol 1997), which seeks to promote climate mitigation human interventions through the enhancement of the sinks of GHG emissions. In the case of the ERW process, the ocean ultimately serves as a sink for carbon sequestration. Indeed, in a study published in Nature Climate Change, Beaulieu et al. (2012) stressed the potential role that weathering might play in the evolution of the global carbon cycle over the next centuries.

The 'weathering', or breaking down, of rocks, is a hugely important but very slow part of the carbon cycle under atmospheric conditions. As such, to accelerate this process within the context of using ERW as a climate change mitigation strategy, the weathering process will need to be artificially enhanced. This may involve industrial-scale mining, grinding, transporting, and spreading of crushed silicate rocks over land or in the sea to speed up the carbon sequestration process (Moosdorf et al., 2014). The science behind this has been hailed as credible (Cressey 2014) with reported estimates suggesting that 5 Gigatonnes of crushed olivine rocks on beaches annually can offset 30% of global CO_2 emissions; assuming 1990 levels of emissions (Hangx and Spiers 2009). There are several studies on the potential of ERW as a climate change mitigation strategy. One study in the UK estimates a theoretical carbon dioxide capture potential of 430 billion tonnes from silicate rock resources in the country (Renforth et al. 2011). A study by Taylor et al. (2016) also suggests that idealised scenarios of enhanced weathering on a global scale can potentially result in 30-330 ppm atmospheric CO_2 by 2100.

An additional reason why ERW is gaining prominence as a viable CDR technology is a fact that its implementation requires already available structures compared to other technologies such as DAC and CCS which involves the setting up of entirely new infrastructure solely for its purpose. In the case of ERW, quarry industries and mines are already a massive part of the primary aggregates sector in most countries, and therefore the sourcing of silicate rocks will be relatively less challenging. It is reported that in the UK, for instance, 47 million tonnes of igneous rock is mined yearly (Renforth et al. 2011) and therefore represents excellent potential for use in ERW.

Another reason why ERW compares more favourable to other CDR techniques is the potential impact it can have on agricultural crop farming, particularly in terms of promoting food security (Beerling et al., 2018). Rocks that can be potentially used for ERW purposes such as basalt rock is known to contain some traces of macronutrients for soil amendment and subsequently boosting crop yield (Kantola et al. 2017). In pot trials study conducted in Mauritius as far back as the 1960s, it was found that by using basalt alongside conventional N-P-K fertilisers, crop yields increased by 29% compared to trials without basalt addition (D'Hotman and Villiers 1961). Since the spreading of crushed rock grains on croplands is also not a new phenomenon, implementation of ERW fits perfectly into this farm practice. In addition to its carbon dioxide removal potential and positive impact on crop yield, ERW also has added co-benefits of reducing ocean acidification (Taylor et al., 2016). All the above benefits make the ERW technique a very desirable climate change mitigation strategy.

1.3 Research Problem and Knowledge Gaps

While the underlying science and co-benefits for the rock weathering process are well understood, there are limited studies on the effectiveness or feasibility of the ERW strategy from a sustainability point of view. The potential unknown consequences, including environmental impacts of the ERW process, social acceptability and cost implications of ERW supply chain remains under-researched (Taylor et al. 2016). In particular, for environmental sustainability, it has been reported that lifecycle stages of critical processes and inputs can affect the overall environmental impacts and carbon hotspots of product supply chains (Acquaye et al. 2011, Barthel et al. 2015). Moosdorf et al., (2009) also assert that the overall efficiency of CO_2 sequestration due to ERW depends on the amount of carbon dioxide produced during key lifecycle stages such as mining, grinding and transportation of the crushed rocks and therefore emphasised that these processes must be considered carefully to determine the net environmental benefits of ERW.

Further to this, assuming that the broader environmental impact is acceptable, questions surrounding scalability, scenario modelling, the logistics of transporting the rocks across countries and regions (given the ores are deposited in particular countries) and other factors such as social acceptability, supply chain risk and ethical dimensions remain unresolved. Most existing research, as discussed in the literature review chapter, focuses on ERW's 'functional' efficiency and largely ignore the societal implications (including humanity dimension), which are difficult to predict and measure. These specific supply chain issues, therefore, remain relevant research gaps that need to be filled if indeed the credible potential of ERW can be translated into a feasible climate change mitigation option.

Aside its primary role in CO_2 removal upon weathering, the advocate of silicate rocks such as basalt for ERW purposes has been cited in the literature as a viable alternative to industrial fertilisers specifically, Phosphorus (P) and Potassium (K) fertilisers which are also rock-based (Garcia et al. 2020; Beerling et al. 2018). In addition, ongoing research at the LC3M Centre in theme 1-3 as outlined in Sections 1.1 is focused on exploring the nutrient release from basalt and impact on crop yield (refer to Fig 1.1). However, what is missing from the literature on these studies on basalt as a rock fertiliser is that, there is a limited understanding of how it compares with the current system of use of industrial fertilisers. This is particularly an important research gap to fill as it can determine the extent to which ERW with basalt is adopted by crop farmers. The wide-scale adoption of the ERW technique as a climate change mitigation strategy may depend to some extent on the compatibility of the ERW technique with already existing practices.

Lastly, there are other sources of silicates which have been cited in the literature as possible alternatives for ERW purposes. These secondary waste materials (coal ash, steel slag and cement kiln dust) have gained much attention as their use for ERW fits into circular economy agenda (Dora et al, 2016; Genovese et al, 2015) where waste is converted to a resource (Renforth 2012, Pan et al. 2017, Pullin et al. 2019). However, what is missing in the discourse on the use of these artificial silicates as they are commonly termed is that, their environmental sustainability has not been assessed.

Consequently, gaining insight into these supply chain issues and its implication across the triple bottom line through the lenses of the sustainable supply chain, would contribute to resolving these research gaps and provide the basis for a holistic understanding of the issues and consequently, to formulating and theorising new lifecycle thinking for ERW supply chain.

From the above discussion on research problems, associated with ERW, the main research gabs identified in the study is summarised below:

1. **Knowledge Gap 1**: **Lack of understanding on the lifecycle sustainability (economic, environmental and social) impacts associated with of ERW.**

2. **Knowledge Gap 2: Limited understanding of environmental sustainability impacts between basalt and industrial fertilisers.**

3. **Knowledge Gap 3: Limited environmental sustainability insight into different silicate material for ERW, that is basalt (natural silicate) and artificial silicates.**

1.4 Research Aims and Objectives

The overarching aim of the research is to analyse the triple bottom line supply chain impacts for ERW. Specifically, the research objectives in the study aimed at addressing the research gabs outlined above are as follows:

i. **Research Objective 1**: **To carry out a lifecycle sustainability assessment (economic, environmental and social) of ERW.**

ii. **Research Objective 2: To access the environmental profile of basalt and industrial phosphorus(P) and potassium (K)-based fertilisers.**

iii. **Research Objective 3: To analyse environmentally sustainable supply chain life cycle for ERW, based on a comparison between, natural silicates (basalt rock) and artificial silicates (coal ash, cement kiln, dust, and steel slag).**

1.5 General research methodology

To address ERW supply chain sustainability issues, models were developed using existing sustainability modelling techniques. This is mainly based on the principles of Lifecycle Assessment (LCA). The LCA methodology has mainly been used to identify and quantify the environmental impacts of products and business activities on the natural environment throughout its lifecycle from resource extraction, production, use and re-use, disposal phases (Govindan et al. 2014, Hellweg and i Canals 2014). Given the range of contemporary local and global sustainable development needs and challenges, sustainability goes beyond environmental issues on which traditional LCA studies have focused. This is because environmental systems do not operate in isolation since there are dynamic interactions between the environment, economic and social activities (Eskandarpour et al. 2015).

For a significant global climate change mitigation option such as artificially accelerating ERW processes, it is expected that environmental considerations be balanced with social responsibility and improved economic performance. Integrating these multiple criteria indicators of environmental, social, and economic factors within a consistent modelling framework has, therefore become timely and relevant. It is however widely acknowledged that whilst integrating the Triple Bottom Line goals of environmental, social and economic sustainability indicators is considered best practice (Epstein and Buhovac 2014), it has also been reported to be a major research challenge (Malik et al. 2014, Ahi and Searcy 2015). From a methodological viewpoint, limited research has been conducted, which examines an optimum way to adequately consolidate TBL into a usable framework to measure the sustainability of ERW supply chain life cycle. Pieragostini et al. (2012) describe the integration of multiple sustainability criteria with LCA methodology as an ambitious challenge, although it can result in the development of robust decision support models.

Based on a review of literature, it has been established that there is no standard or widely accepted method for the measurement of TBL sustainability impacts. (Slaper, 2011). Some studies employ the use of integrated sustainability assessment which involves estimating an overall and aggregated measure for the three pillars of sustainability. Examples of studies adopting the integrated approach to sustainability measurements include Kucukvar and Tatari, (2014), Onat et al. (2014), Halog and Manik (2011), Wiedman and Lenzen, (2018) and Foran et al. (2005). Proponents for integrated sustainability assessment are of the view that integrating or aggregating sustainability impacts makes it relatively much easier for stakeholders to make more holistic decisions (Slaper, 2011). Contrary to integrated sustainability assessment, other researchers prefer to conduct separate sustainability analysis based on each of the TBL goals. Examples of such studies include Traverso et al. 2018; Kloepffer, 2008; Wang and Lin 2007. Advocates for stand-alone sustainability assessment hold the view that modelling individual TBL goals (economic, environmental, and social) provides more in-depth insight into sustainability concerns (Kloepffer, 2008). Both approaches (integrated and individual assessments) to measuring sustainability has benefits, and therefore in this study, the two approaches are used where first a separate evaluation of ERW's production supply chain is carried out and subsequently this is followed by an integration of the results through the use of indices.

For the current work, the LCA, Life cycle costing (LCC) and social lifecycle assessment (SLCA) methods are respectively used to analyse the environmental, economic and social impact of ERW in different supply chain scenarios. There are three well-known LCA methods used for environmental impact assessments. The process-based LCA and the environmentally extended input-output (EEIO) form the LCA based methodologies. These two models can be integrated to form the hybrid LCA method (Finnveden et al. 2009). In this study, environmental sustainability analysis of ERW supply chain is based on the two base methods; the process-based method and the EEIO method as they respectively provide a bottom-up approach with enhanced accuracy (the process LCA) and a top-down approach with extended system boundary (EEIO method). The economic assessment of ERW is done by way of performing macro-level life cycle costing of silicate production using economic input-output modelling.

With regards to social sustainability assessment, there is no widely accepted and standardised methodology for social lifecycle assessment. However, emerging work on SLCA began in 2011 by UNEP through the publication of the "Guidelines for social lifecycle assessment and Methodological sheets" (Benoît et al. 2010, Benoît-Norris et al. 2011). However, the guidelines do not include specific methodologies for conducting social life cycle analysis. Following the publication of the UNEP Guidelines, there has also been the development of a comprehensive database known as the Social hotspot database (SHDB) that provides country and sector level data on potential social risk impacts across important social themes including labour rights, human rights and health and safety (Norris et al. 2013). Based on the SHDB, this study advances the economic input-output framework to include social risk impacts by developing a social input-output method for assessing the production of silicates for ERW. A detailed discussion of all the methods used for each of the sustainability pillars in the study is covered extensively in both the methodology and empirical chapters of the thesis.

1.6 Research outputs

It is envisaged that this research makes significant contribution to existing knowledge on assessing supply chain life cycle sustainability, climate change policy and sustainability impact on specific sectors within the economy. Important research outputs in terms of research publications and contribution to knowledge as well as research grants that has been delivered through this study are also highlighted.

1.6.1 Potential Research Publications

The empirical chapters of the research study have been organised into a format fit for peer-reviewed journals in line with the requirements for an alternative thesis. One paper has been published, and five key research papers for potential journal publications have been produced from the research, which will potentially contribute, to Sheffield University Management School's REF2024 or future submission. The papers and journals for submission are detailed below:

i. Paper 1 **(Published)** based on the EEIO methodology used in this research: Oppon et al. (2018). "Modelling multi-regional ecological exchanges: The case of UK and Africa". ***Ecological Economics***, 147, 422-435.

ii. Paper 2 based on Chapter 4 and 5: "**Macro-level economic and environmental impact assessment of enhanced rock weathering using input-output analysis"** This paper is to be submitted to *European Journal of Operational Research; 4* ABS Listed journal*.

iii. Paper 3 based on Chapter 6: "**Estimating social sustainability of supply chains using a social input-output method; a case study of the risk and socio-economic impact of enhanced weathering"** The paper presents a novel methodology, (social input-output method) for assessing the social impact of supply chains. The target journal for the paper submission is *Business and Society journal; athree3* ABS Listed journal.*

iv. Paper 4 based on Chapter 7: "**Integrated lifecycle sustainability index for enhanced rock weathering using Triple bottom line input-output analysis".** The target journal for the paper submission is *Global Environmental Management which is a four a 4* ABS Listed journal.*

v. Paper 5 based on Chapter 8: "**Comparative lifecycle assessment indicates low environmental footprint of basalt rock dust relative to industrial fertiliser"**. The paper present analysis and results of a detailed comparative lifecycle assessment analysis of embodied supply chain impacts of basalt rock dust fertiliser (a potential rock for use in enhanced weathering), compared with five widely used industrial P and K fertilisers. This paper is at the revised and resubmit stage for *Nature Communication Journal*.

vi. Paper 6 based on Chapter 9: "**Environmental impact of enhanced weathering; Natural Basalt versus Artificial silicate waste additive"** The paper presents and compares results for the sustainability of enhanced weathering supply chain based on the use of basalt and artificial silicate waste such as cement kiln dust, steel slag and coal ash. The target journal for the paper submission is *Journal of Environmental Management; 3* ABS Listed journal*.

1.6.2 Summary Contribution to Knowledge and theory

A summary of contributions to knowledge resulting from this PhD research are listed below. These are further expanded in the conclusion chapter

a. New understanding for ERW supply chain through novel methodological developments:

b. Solidifying the Triple Bottom Line supply chain understanding of ERW to support and complement the science of developing ERW as a truly credible and feasible climate change mitigation option.

c. Theorising new lifecycle thinking for ERW supply chain based on the application of an extension of Resource-based view (RBV) theory to include TBL sustainability as a competitive advantage.

1.6.3 Research Grant Award

Based on the Triple bottom line method used in this study, the author wrote a research proposal and has received a Global Challenges Research Fund (GCRF) award om Agri-Food Innovation. The research topic is Triple Bottom line analysis of agri-food circular economy in Sub-Saharan Africa.

1.7 Thesis Structure

This thesis follows the alternative format style. The alternative format thesis is a thesis format that has both traditional thesis sections in addition to journal style sections. The beginning three chapters follow the traditional thesis structure while the empirical studies are presented in article format, and the last chapter concludes the study highlighting future work. Figure 1.2 shows an overview of the chapters in this thesis and a summary of the issues discussed in each chapter.

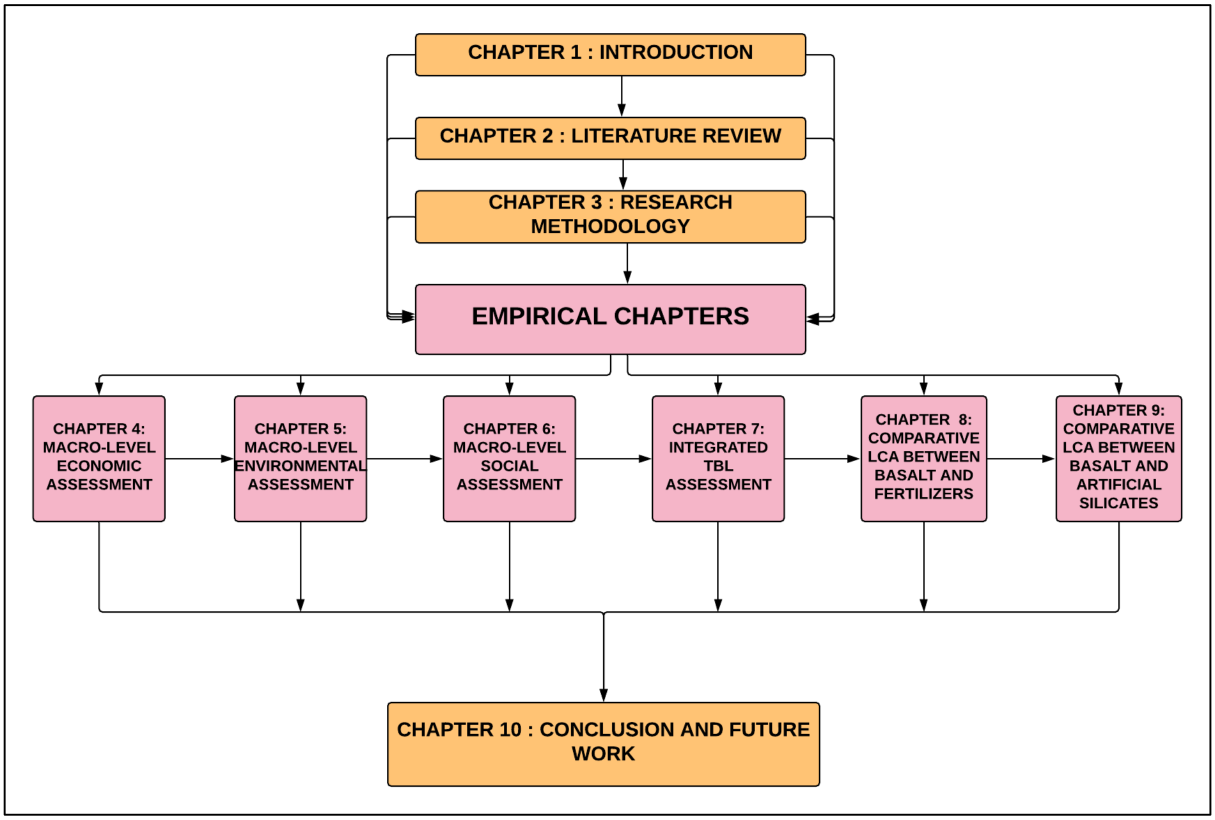


Fig 1.2 Thesis Structure and Organisation

This thesis follows the alternative format style. The alternative format thesis is a thesis format that has both traditional thesis sections in addition to journal style sections. The beginning three chapters follow the traditional thesis structure while the empirical studies are presented in article format, and the last chapter concludes the study highlighting future work. Figure 1.2 shows an overview of the chapters in this thesis and a summary of the issues discussed in each chapter.

Chapter 1 provides an introduction of the project background, outlines research motivation, aims and objectives, the general methodology used in the study and contribution to knowledge. The second chapter, which is the literature section of the thesis, is presented in two parts. In the first part, a comprehensive review on ERW and its underlying science, its role in agriculture and lifecycle supply chain processes involved is presented and discussed, highlighting the research gaps identified. The second part of the literature review focuses on supply chain sustainability, including measurement and modelling techniques. In Chapter 3, the research methodology employed in the study is presented, which covers research design and approach, philosophies, and theoretical underpinnings of the study.

The empirical sections are divided into six studies in line with the research objectives. In line with Research Objective 1, Chapter 4, 5 and 6 presents analysis and results of individual TBL macro-level sustainability assessment (economic, environmental, and social) associated with the production of silicates (basalt) for ERW. This is subsequently followed by Chapter 7, which presents analysis and results of an integration of the results from Chapter 4 (economic), Chapter 5 (environmental) and Chapter 6 (social). This is followed by the last two empirical chapters; Chapters 8 and 9. Chapter 8 is based on a comparative lifecycle assessment between basalt and industrial fertilisers in line with Research Objective 2. In Chapter 9, comparative lifecycle assessment between basalt as natural silicate and artificial waste silicates are presented in line with Research Objective 3. The last chapter presents the conclusion of the study, outlining the key findings, policy implications, limitations, and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Chapter Overview

The literature review section provides a contextual background of the research topic by exploring the relevant extant literature in order to highlight existing knowledge, identify critical research gaps that are potentially addressed by the empirical chapters. In addition, it justifies that the thesis makes valuable knowledge contribution. A comprehensive narrative literature review method is presented in this section which highlights an overview of the research topic and relevant research areas. The literature review is divided into two main sections. The rational and choice for adopting this two-prong approach in reviewing the extant literature are influenced mainly by the interdisciplinary nature of the study.

The first section covers a review of literature on enhanced weathering mainly from the natural science research field. This part of the review presents and discusses studies on the potential of enhanced weathering as a climate change strategy and its underlying science that leads to atmospheric carbon dioxide removal. Also highlighted are the lifecycle processes involved in ERW, which relates explicitly to silicate rock extraction, comminution, transportation, and the application of silicate rocks. The section also expands on the co-benefits of enhanced weathering, specifically in the area of agricultural croplands which falls within the scope of research on ERW.

To further understand the sustainability of ERW supply chain life cycle, which is an emerging research direction, the second section of the literature review focuses on supply chain management from social science research field with a specific focus on supply chain sustainability. Most of the existing studies on ERW are grounded from the environmental science field, and limited research can be found that is grounded from the supply chain field. To address this, sustainable supply chain is used as an analytical lens. The second section, therefore, presents a review of supply chain management (SCM) literature with a specific focus on the subject area of sustainable supply chain, triple bottom line concept and lifecycle sustainability assessment.

2.2 Method used in Literature Review

Figure 2.1 shows a summary of the literature review process employed in this study.

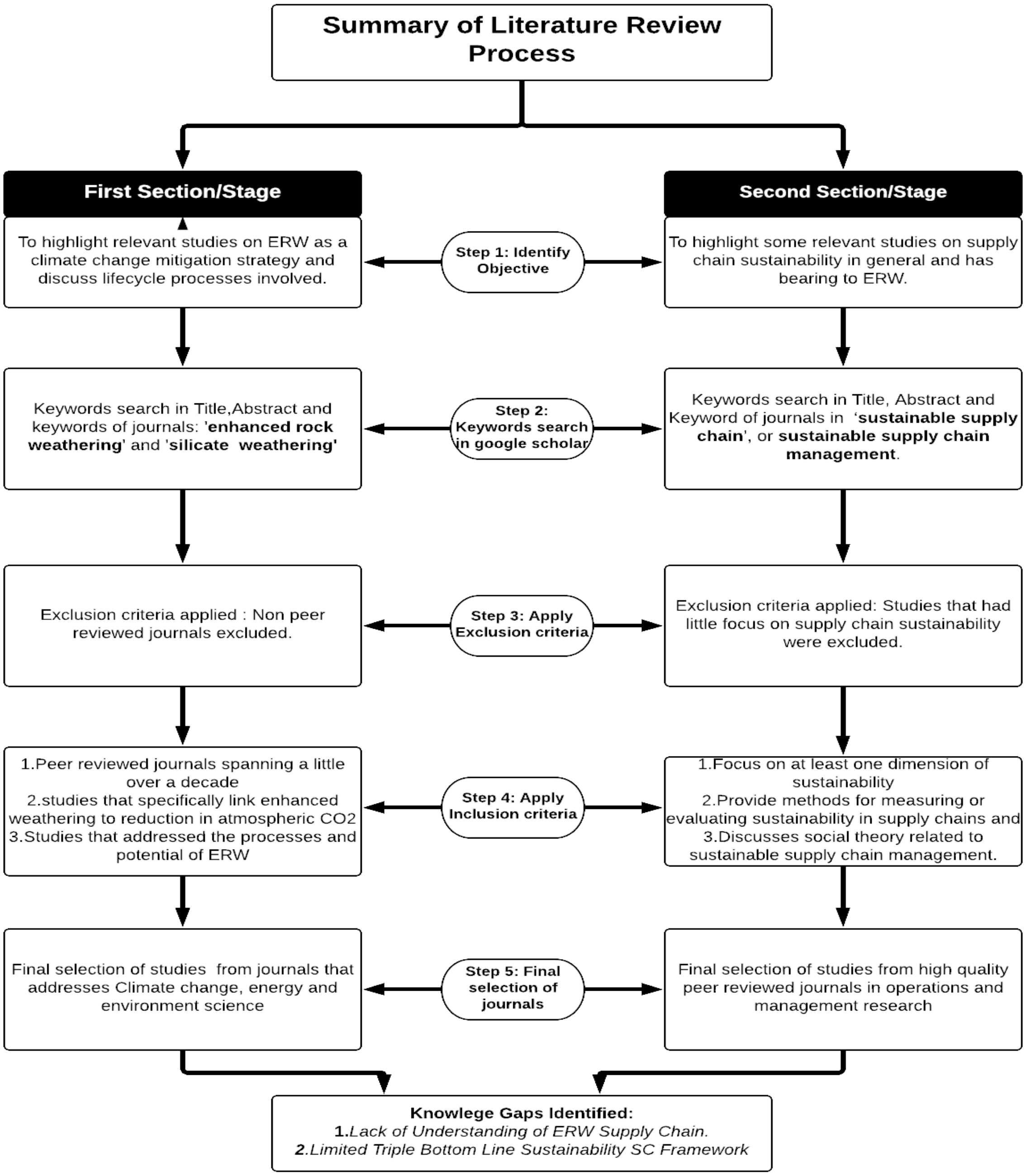


Figure 2.1: Summary of literature review process employed in this study

In the first section, the focus of the review is on literature that addresses "enhanced rock weathering" as a technology for reducing atmospheric CO_2 levels. An alternate term in the research literature is "silicate weathering" or simply "enhanced weathering". These keywords were used in the google scholar search engine, which generated a vast number of results. From the extensive search results generated, an exclusion criterion was used to reduce the number of studies to a manageable quantity that can be reviewed, bearing in mind the limited time resource in conducting this study. Studies that touched on enhanced weathering or silicate weathering but not as the primary research topic in the study were excluded. Also, all non-peer-reviewed journal papers were excluded. To further reduce the number of studies, an inclusion criterion was used to select relevant journals:

i. Peer-reviewed journals spanning a little over a decade.
ii. Studies that specifically link enhanced weathering to a reduction in atmospheric $CO_{2.}$
iii. Studies that addressed the processes and potential of ERW.

Some studies in the pure sciences field were included mainly to gain an understanding of the underlying science of chemical weathering in rocks, as these are not usually published in social science or management journals. Final selection of studies reviewed was from journals that address Climate change, energy, and environmental science such as Nature Climate change, Energy Environment, Environmental Science and Technology, International Journal of Greenhouse Gas control among others. In most cases, a representative publication was selected from those authors who have published numerous papers and reports on the subject. Table 1 shows the publications on ERW in chronological order over the past decade, that is from 2010 to 2020.

Table 2.1: Highlights of some key references on ERW over the past decade

Author(s)	Article Title
(Power et al. 2020)	Prospects for CO2 mineralisation and enhanced weathering of ultramafic mine tailings from the Baptiste nickel deposit in British Columbia, Canada.
(Lefebvre et al. 2019)	Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil.
(Strefler et al. 2018)	Potential and costs of carbon dioxide removal by enhanced weathering of rocks
(Kantola et al. (2017)	Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering.
(Taylor et al., 2016)	Enhanced weathering strategies for stabilising climate and averting ocean acidification.
(Strefler et al. 2015)	Enhanced weathering and BECCS-are carbon dioxide removal technologies complements or substitutes
(Moosdorf et al. 2014)	Carbon dioxide efficiency of terrestrial enhanced weathering."
(Hartmann et al. 2013)	Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification
(Renforth 2012)	The potential of enhanced weathering in the UK
(Schuiling and Wilson 2011)	Enhanced silicate weathering is not limited by silicic acid saturation
(Köhler et al. 2010)	Geoengineering potential of artificially enhanced silicate weathering of olivine.

A similar approach, as used in the first section of the literature review on ERW, is used in the second section, which covers mainly supply chain management (SCM) studies. The literature on SCM tends to be informed by the management discipline, and strongly linked with the operations management domain specifically. It will be out of scope in the context of this research to review all articles in the vast and general areas of sustainable supply chain management which typically concentrate on the classical areas of manufacturing or services. The main objective of this section of the literature was to show relevant review that has a bearing on the current study of ERW and highlight relevant studies and gaps in the literature concerning sustainable supply chain. The review process started by searching Title, Abstract and Keyword of journals in Google Scholar that contained the keywords' sustainable supply chain', or 'sustainable supply chain management'. For a distribution across a broader range of relevant studies and to minimise the risk of reliability, peer-reviewed articles published in operations and management journals were selected such as *International Journal of Operations & Production Management, Supply Chain Management – An International Journal, Journal of Operations Management, Production and Operations Management, International Journal of Production Research, and The Journal of Supply Chain Management* (formerly International Journal of Purchasing and Materials Management*).* The following inclusion criteria were used to select relevant studies:

i. Studies that focus on at least one dimension of sustainability (environment, economic or social)
ii. Studies that provide methods for measuring or evaluating sustainability in supply chains.
iii. Studies that had little focus on supply chain sustainability were excluded.

Part 1 of Literature Review

2.3 Enhanced Rock Weathering as a Climate Mitigation Technology

There is growing research into the potential CO_2 sequestration methods that can be implemented as climate mitigation strategies. Among these include Direct Air Capture (DAR), Carbon Capture and Storage (CCS) and more recently Bio-Energy with CCS (BECCS) which involves the capturing of CO_2 emissions at the point of sources such as power stations and coal mines and then storing it in aquifers and old gas mines (Gibbins and Chalmers 2008, Vergragt, Markusson et al. 2011). However, some concerns have been raised on the environmental and social risks associated with some of these strategies in particular CCS due to its potential long-term carbon leakages (Shackley, McLachlan et al. 2004, Blackford, Stahl et al. 2014). The challenge, therefore, is to come up with relatively safer and permanent methods of removing carbon dioxide from the atmosphere.

Enhanced rock weathering has received attention as a promising solution in safely and cheaply removing tons of CO_2 (Lackner 2003, Schuiling and Krijgsman 2006). The role of rocks in the global carbon cycle has been highlighted as far back as the early nineties, showing that there is a correlation between weathering of silicate minerals in rocks and the reduction of atmospheric CO_2 (Brady 1991). The principle of the enhanced rock weathering process is that carbon dioxide in the atmosphere dissolves in rainwater forming carbonic acid, which, once in contact with ground silicate rocks, slowly dissolves them. This dissolved carbon and other weathering products are then transported by run-off water and rivers into the oceans, which act as a sink for the trapped carbon (Moosdorf et al., 2014).

The science behind this has been hailed as credible (Cressey, 2014), with reported estimates suggesting that 5 Gigatonnes of crushed olivine rocks on beaches annually can offset 30% of global CO_2 emissions; assuming 1990 levels of emissions (Hangx and Spiers 2009). In a more recent paper, Taylor et al. (2016) project that enhanced weathering could lead to an estimated 30-300ppm reduction in atmospheric CO_2 by 2100. In the UK, silicate rocks have been estimated to have a potential CO_2 capture of 430 billion tonnes (Renforth,2012).

The weathering of silicates minerals remains an essential process in regulating atmospheric CO_2 levels (Brady, 1991). Silicate minerals occur widely in nature and are found in globally abundant rocks such as basalts. There exists a wide variety of different silicate minerals which combine silicon and oxygen with calcium, magnesium, potassium and many other elements. One of such silicate minerals is olivine, which in particular is cited in the literature as a good source for CO_2 sequestration since it is relatively the fastest weathering silicate mineral (Schuiling and De Boer 2010). The weathering of these silicate minerals found in rocks leads to the formation of carbonate minerals such as limestones where trapped carbon is stored for long periods (Lackner et al. 1995).

The process begins when carbonic acid (H_2CO_3), a product of carbon dioxide (CO_2) and water (H_2O), upon contact with silicate materials such as magnesium or calcium silicate, reacts and converts CO_2 into bicarbonate solution($HCO3^-$) and magnesium ions (Mg^{2+}) or calcium ions (Ca^{2+}). These weathering products (bicarbonate ions, magnesium or calcium ions) are washed off by groundwater and finally end up in the ocean where they precipitate to form carbonates such as limestones where carbons are held for relatively long periods (Moosdorf et al., 2014). According to Beaulieu et al. (2012) the trapped CO_2 in the carbonates can stay for at least a few thousand years. In essence, the ocean acts as a natural sink for the trapped carbon (Bachu 2000). The process also results in increased alkalinity, which consequently reduces ocean acidification (Kheshgi 1995).

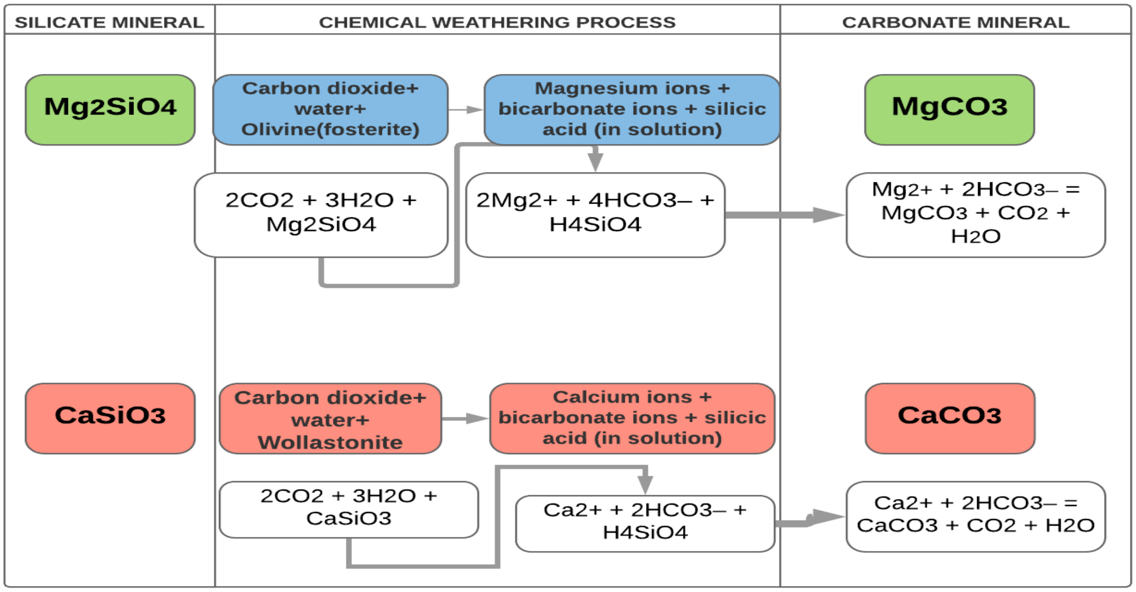


Figure 2.2: Illustration of chemical reactions in silicate weathering leading to CO_2 sequestration

Figure 2.2 illustrates the chemical reactions in the silicate mineral weathering process using the magnesium-end member of olivine known as fosterite (Mg_2SiO_4) and calcium silicate ($CaSiO_3$), which naturally occurs as the mineral wollastonite. The chemical reaction of rainwater (carbonic acid) and the rocks produces bicarbonate ion and magnesium ion (in the case of fosterite) and calcium ions (in the case of the wollastonite). The dissolved weathered products (magnesium, calcium and bicarbonate ions) travel in groundwater to the rivers and ultimately end up in the sea, where they are precipitated as magnesium and calcium carbonate respectively. CO_2 is stored in these carbonate minerals for long periods. The precipitation of silicate-weathered products to form carbonates is what leads to the actual CO_2 sequestration in the entire enhanced weathering process (Taylor et al., 2016; Moosdorf et al., 2014; Renforth et al. 2009).

The enhanced weathering process differs from similar CO_2 sequestration techniques such as *mineral carbonation*, which involves injection and storage of CO_2 into suitable silicate rocks (Matter and Kelemen 2009). Although with mineral carbonation, the underlying CO_2

sequestration from the chemical reactions with the rocks is similar to what happens in enhanced weathering, the mineral carbonation method and the modes of application has been tagged as rather expensive and seemingly complicated (Schuiling 2013). In the case of enhanced weathering, the trapping of atmospheric CO_2 is only a facilitation of the natural global carbon cycle process by consciously mining, crushing and transporting crushed silicates to be applied on target lands after which the actual weathering and subsequent CO_2 sequestration process take place as earlier described.

2.*4* Supply chain lifecycle processes of Enhanced Rock Weathering

Relying solely on the natural process of rock weathering (as explained in previous section 2.2) which leads to CO_2 sequestration will be inefficient especially in comparison to the rate of growing global annual increase in CO_2 levels (Cressey 2014). To achieve a significant drawdown in atmospheric CO_2, it would require the enhancement of this natural process by a conscious effort to mine, crush, transport and spread these rocks in relevant areas to speed up the CO_2 sequestration process. This process of mining, comminution (crushing and grinding), transportation and application of silicate rock debris to target areas forms the critical supply chain lifecycle of enhanced rock weathering (Moosdorf et al, 2014; Renforth et al. 2012; Hangx and Spiers, 2009). This section discusses a review of the literature associated with each of the lifecycle processes.

2.4.1 ERW supply chain stage 1: Silicate rock selection and extraction

Implementation of enhanced weathering may require an upscaling of current rates of rock extraction. For instance, in the UK where 47 Mt of igneous rocks are mined annually, Renforth (2012) estimates that a significant expansion of current annual production to 125Mt needs to be extracted to achieve substantial drawdown of emissions by 50 $MtCO_2$. Such expansion will have an economical cost and environmental impacts as well as socio-economic impacts. However, the magnitude of the triple bottom line impacts (economic, environmental and social) of such expansion remains unknown (Moosdorf et al., 2014, Renforth, 2012).

To reduce extraction cost and minimise environmental impact, existing or abandoned mines of silicate-rich rocks could be used. For example, massive weathering from olivine-rich mining wastes found in mine dumps in Australia captured 11% of the mine's annual emissions (Wilson et al. 2014). Again, the availability of already existing large mines in a country would imply there is no need to clear forest land to set up a mine which would also mean less ecological damage and infrastructure investment (Schuiling and Tickell 2010). Knowing the enormous environmental and toxicological impact from mining (Azcue 2012), it is within the scope of this research to explore various scenario modelling to understand the net effect from ERW using virgin silicate rocks or recycled silicates to further understand the optimum combination of rock types and supplies.

2.4.2 ERW supply chain stage 2: Comminution

Stage 2 in the ERW supply chain is to industrially crush and grind the extracted rock, which is referred to as comminution. The typical flow of the comminution process usually involves a series of primary, secondary, and tertiary crushing and then final grinding to desired grain sizes (Renforth, 2012). The comminution process is usually very energy-intensive; thus, the size of the rock grains is of importance as it determines the energy input and the weathering rate output when applied to designated areas (Hangx and Spiers 2009). The smaller the grain size, the higher the energy input in the comminution process, but the more efficient is the weathering rate.

A review of extant literature shows that different studies report different grain sizes. Still, mostly a significant number of the studies state grain sizes of 100μm whose energy input depends mainly on the grinding surface areas (Moosdorf et al., 2014). Large grain sizes such as 300μm are considered as less effective in CO_2 sequestration especially for weathering in sea temperatures of 15–25 °C. Kohler et al. (2010) report that small fine grain size of olivine (10μm) have high dissolution rate usually within 1 to 2 years and these require energy input of 180kWh t^{-1} (Hangx and Spiers 2009). Schuiling and Krijgsman (2006) also state that with olivine grains size of about 100 microns in diameter, weathering rate would be 10 to 20 microns per year in the tropical climates. Clearly, these studies have collectively shown that there is a trade-off between grain size and energy input for an optimum weathering rate; and these will depend on silicate types, application areas and climate conditions.

Highest emissions and energy cost are usually associated with the comminution stage. According to Moosdorf et al. (2014), these emissions may reduce the carbon dioxide efficiency of enhanced weathering, which is calculated by subtracting CO_2 emissions from the potential carbon capture of the rock. In their study, comminution generated emissions between 0.074-0.229 tCO_2 for a global suitable rock volume area of 760,000km^2. In the case of the UK, Renforth (2012) also estimates emissions from comminution to be between 0.0040-0.1264tCO_2. Since the final destination of the crushed and ground rocks where the weathering process takes place are usually on agricultural soils, Priyono and Gilkes (2008) in their study advocate for high energy milling as more effective in improving silicate rocks as fertilisers. In the UK, energy cost could be as high £40.7 per tonne of rock crushed and ground (Renforth, 2012). Schuiling and Tickell (2010) report that the use of fragmented and powdered rock deposits (such as volcanic ash) would significantly reduce or eliminate cost and energy requirements for milling.

2.4.3 ERW supply chain stage 3: Distribution and transportation of silicates

The crushed silicate rocks will have to be transported to target areas where they will be applied for the actual weathering and CO_2 sequestration process to take place. Infrastructure such as strong transport networks could significantly reduce the overall cost of the enhanced weathering process. Feasibility of ERW requires a cost-effective, low-impact way to transport crushed rocks and make ERW efficient and effective. Global implementation of enhanced weathering implies a likely situation where silicates are extracted in one region but are spread in another area. As an example, ultramafic rocks which are most abundant in the west coast of Norway can be extracted but then transported to countries which are typically within 3000km sea freight distance such as UK, Germany, Belgium and Spain for use in enhanced weathering (Renforth, 2012). In Europe, typical transport distance is estimated to be approximately 1000km (Hangx and Spiers, 2009).

A combination of different modes of transport can be used, which includes roads, rails and sea freight, each of which has different associated emissions intensity and cost. Kohler et al. (2010) found that transportation could potentially lead to 2.4%, 1.6% and 11% decrease in a net efficiency of EW per 1000km of transport for inland and coastal ships, freight trains, and trucks respectively. Trucks could be used to transport crushed silicates to the point of use, but Schuiling and Tickell (2010) maintain that this mode of transport is seen as more expensive and may lead to a more significant loss in net efficiency. Application in areas where silicates rocks are in abundance reduces transport cost. Schuiling and Tickell (2010) suggest that transport distance between mines and the point of use should be less than 300km. Distribution and transportation of silicates will play a key role in determining how best to ensure the supply of the right quantity, the right type and right size of rocks to the application areas.

Table 2.2 summarises the global geographical areas with silicate resources and the implications for global rock movement. This summary presented in Table 2.2 is an extension and interpretation of the work of Moosdorf et al. (2014) by focusing on the potential extrapolation of the secondary data provided by the aforementioned authors concerning developing a large scale ERW supply chain.

Table 2.2 – Silicate locations and relocation considerations

Silicate Location	Application Area (proximity-wise)	Potential Transportation Mode	Key Concerns
West Coast of N. America and Canada	Continental and Central America	Rail or Intermodal (Rail + Short Sea Shipping)	Extraction and processing price, Carbon Caps, Overall mining social stigma.
East Coast of N. America and Canada	Continental and Central America	Rail or Intermodal (Rail + Short Sea Shipping)	Extraction and processing price, Carbon Caps, Overall mining social stigma.
East Coast and Central S. America	Central and Eastern parts of South America	Rail or Intermodal (Rail + Short Sea Shipping)	The potential need for FDI, various governance models involved and interest groups.
North Europe	Central and Southern Europe	Rail	Extraction and processing price, Carbon Caps, Overall mining social stigma.
Central + South Europe	Central and Southern Europe	Rail	Extraction and processing price, Carbon Caps, Overall mining social stigma.
South + East Africa	Central and East Africa	Rail	The potential need for FDI, various governance models, involved and interest groups, poor transportation infrastructure.
All Russia + Asia	South Russia, South and East Asia.	Rail or Intermodal (Rail + Short Sea Shipping)	The potential need for FDI, various governance models involved and interest groups, Carbon caps.

In more specific terms, Table 2.2 shows an ideal situation of proximity-based assignment of silicate rocks to the areas of application. However, considering factors such as financial incentives, regulatory pressure, rocks supply, processing and transportation infrastructure need and so on, it is reasonable to assume that such rock may need to be moved between continents facilitated by global transportation routes (maritime primarily) in order to transport the silicates from the source of extraction to the application areas.

2.4.4 ERW supply chain stage 4: Application of silicate grains

Stage 4 of the ERW supply chain is the application process of spreading the silicate rock grains on specific target areas mostly farmlands and coastal regions (Schuiling and De Boer, 2010; Hangx and Spiers, 2009). Hangx and Spiers (2009), however, concluded that large scale coastal spreading of olivine is not a viable method of CO_2 sequestration. The application of silicates on agricultural farmlands is cited as more effective (Hartmann et al., 2013). Schuiling and Krijgsman (2010) proposed that the grains could be spread simultaneously alongside fertiliser machinery application on farmlands or as slurries mixed with pesticides.

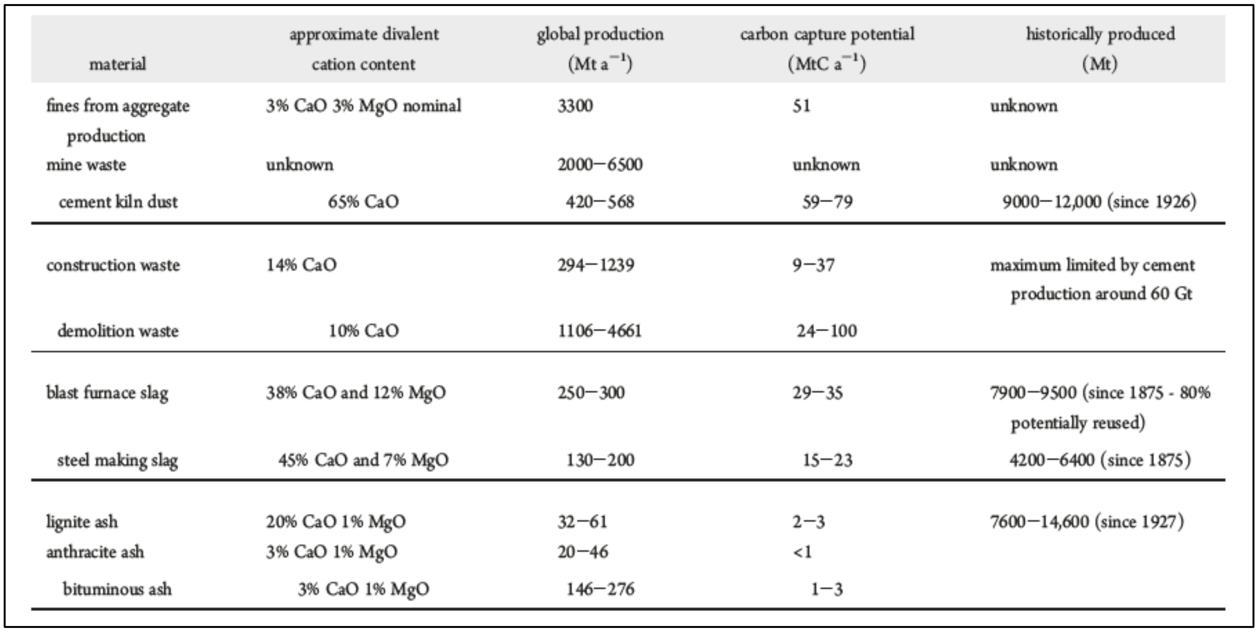
An important factor worth considering in the assessment of suitable application areas for enhanced weathering is favourable weathering climate regions. In terms of the right climate, the humid tropical regions are considered most efficient as studies prove that such sites experience relatively high humidity, which facilitates weathering (Macias and Chesworth 1992). According to Taylor et al. (2016), a third of tropical land-use for enhanced weathering purposes is ideal to result in a significant drop in atmospheric CO_2. The same conclusion was made by Köhler et al. (2010). They showed that by spreading fine olivine powder over land areas in the humid tropical regions, up to 1 Petagram of carbon could be potentially sequestered annually if olivine is distributed as fine powder over land areas of the humid tropics.

Spreading ground silicate rocks in humid regions, therefore, is essential for ensuring both food security and CO_2 sequestration. This does not mean, however, that enhanced weathering is impossible in temperate climates, but only that the rate of weathering will be slower. In a few instances outside the tropical zone, conditions may also be favourable to allow for massive olivine exploitations. According to Schuiling and Krijgsman (2006), one of such areas outside the tropics is Oman, which has the largest ophiolite zone in the world and a long coastline along the Indian Ocean. Basalt, which is preferred to olivine, is also located in other temperate regions and these present great potentials for ERW in these countries.

2.5 Circular economy potential of ERW

The sources of silicates do not necessarily have to come from newly extracted rock deposits. Instead, some authors argue that such silicates can be re-used from existing waste resulted from mining/construction sectors (Renforth et al., 2011). For example, a share of 20% of aggregate materials processed for construction purposes cannot be used (due to crushing inefficiencies). In rare cases, this percentage is repurposed (Lowndes and Jeffrey 2009). On a global scale, such unexploited source of silicates can become a useful primary resource for ERW, especially in the context of circular economy and resource efficiency. Even more, the core benefits of adopting this approach reside in the availability of the waste in proximity to the intended application areas. Examples of such wastes are summarised by Renforth et al. (2011) in Table 2.3.

Table 2.3: Industry wastes and their CO2 sequestration potential Source: (Renforth et al. 2011)



material	approximate divalent cation content	global production (Mt a^{-1})	carbon capture potential (MtC a^{-1})	historically produced (Mt)
fines from aggregate production	3% CaO 3% MgO nominal	3300	51	unknown
mine waste	unknown	2000−6500	unknown	unknown
cement kiln dust	65% CaO	420−568	59−79	9000−12,000 (since 1926)
construction waste	14% CaO	294−1239	9−37	maximum limited by cement production around 60 Gt
demolition waste	10% CaO	1106−4661	24−100	
blast furnace slag	38% CaO and 12% MgO	250−300	29−35	7900−9500 (since 1875 - 80% potentially reused)
steel making slag	45% CaO and 7% MgO	130−200	15−23	4200−6400 (since 1875)
lignite ash	20% CaO 1% MgO	32−61	2−3	7600−14,600 (since 1927)
anthracite ash	3% CaO 1% MgO	20−46	<1	
bituminous ash	3% CaO 1% MgO	146−276	1−3	

The study by Renforth (2011) highlights the core artificial silicate waste or by-products that can be used for ERW purposes. According to his study, the UK produces approximately 86 Mt of silicate material annually as a by-product of cement manufacturing, construction and demolition waste, iron and steel processing and coal combustion. However, the impacts of the use of these artificial silicates have not been estimated. To this end, a potentially relevant research question for ERW would reside in the investigation of whether silicate wastes from industrial by-products would be more sustainable than using virgin rocks.

2.6 Enhanced weathering with crops

The growing attention given to enhanced weathering as a climate mitigation strategy partly relates to the collateral benefits associated with the process in addition to its CO_2 sequestration potential. Many studies on enhanced weathering have identified such co-benefits to include improvement in soils, forests, agriculture croplands and reduction in ocean acidity (Beerling et al. 2018; Taylor et al., 2016; Renforth et al. 2009). Combining enhanced weathering with the growing of crops by spreading silicates on soils as fertiliser presents enormous benefits for both food security and climate change mitigation (Kantola et al., 2017).

In addition, evidence also suggests that rock weathering is facilitated by the growth of plants through the process of converting soil carbon into bicarbonate solution (HCO_3^-) that ultimately is washed off together with dissolved Ca^{2+} or Mg^{2+} into the ocean and so the carbon is trapped in Ca-Mg carbonate minerals (Kantola et al., 2017). The organic acid produced by plants weathers the rock, releasing the nutrients and dissolving its silica content (Hinsinger, Barros et al. 2001). The role of crops in enhanced weathering can therefore be viewed in a two-way dimension. Firstly, plants through the conversion of soil carbon into HCO^- accelerate the weathering process, and secondly the weathering process facilitates the release of nutrients from the rock into the soil.

There are increasing demands on agriculture to provide sustainable food security and particularly in developing countries in sub-Saharan Africa where an acute food shortage has been forecasted over the coming years. The FAO estimated that in the year 2000 on the average, 50kg of plant nutrient was depleted in Sub-Saharan Africa. Therefore without a system to replenish, many of these countries will not be able to support future food consumption rates (Roy et al. 2006). According to Sanchez (2002), for every hectare of land cultivated in Africa, there is a 22kg loss of Nitrogen (N), 2.5kg Phosphorus (P) loss and 15kg loss of Potassium (K), which represents $4billion worth of fertiliser. Annual nutrient depletion loss in Sub-Saharan Africa is calculated as 4.4 million tonnes of N loss, 500,000 tonnes P loss and 3 million tonnes of K (Van Straaten 2006). Fertile soils and adequate nutrient supply for crops have, therefore become crucial for sustainable high production (Roy et al., 2006).

Crushed rocks can be used as soil fertilisers, which is not an entirely new practice in agriculture (Van Straaten, 2006). A typical example is an application of calcium carbonate ($CaCO_3$) to alter soil ph and release nutrients, generally referred to as liming. However, this method has the side effect of emitting CO_2 as the carbonates weather and therefore the application of basaltic rocks is an alternative for agricultural liming (Schuiling and Krijgsman, 2006; Priyono and Gilkes, 2004). Whereas the application of lime decreases soil pH, enhanced weathering by basalt application raises soil pH as well as the availability of plant nutrients. Basalt contains Ca and Mg, phosphate and potassium, as well as small quantities of micronutrients (Dessert et al. 2003) and these nutrients, are released to replenish the soil and crops. Application of rocks as fertilisers is seen as a cost-effective method for sustainable farming of crops such as corn, and sugar cane that can reduce the use of expensive chemical fertilisers (Theodoro and Leonardos 2006).

Aside from the benefit of soil nutrient release, enhanced weathering with crops will also have impacts on climate change mitigation. Deployment of basalt with a rock composition of 10% CaO and 10% MgO on an annual production of 70Mha of maize and soya beans in the USA for example, implies a theoretical maximum CO_2 capture of 0.2–1.1 Gt CO_2 (Kantola et al., 2017). By implication, it makes sense to spread the ground silicates on agricultural croplands in order to reap the benefits of both increased nutrients to crops and accelerated weathering rate to aid in CO_2 sequestration. If farmers experience direct benefits from silicate spreading, they will be more prone to collaborate (Schuiling and Krijgsman, 2006).

However, large-scale farming with silicate rocks presents challenges, and therefore there is a need for extensive research to develop a global sustainable supply chain for large scale enhanced weathering. The environmental, economic, and social implications of ERW must be measured to ensure the sustainability of the method. For example, high-energy milling has been cited as improving the effectiveness of silicate rock fertilisers (Priyono and Gilkes, 2008), this will ultimately have some environmental impacts associated with the high-energy use, and these impacts need to be measured.

2.7 Understanding the capacity of farms to spread silicates

The actual process of spreading silicates (i.e. basalt) on agricultural lands would require a mobile basalt storage recipient with rotating discs that randomly spread the particles on the cultivated land surface. Renforth (2012) suggest an energy requirement for rock dust application is approximately 21 kWh t^{-1} for 2.5 t ha $^{-1}$. Thus, these findings strengthen the argument of applying basalt rocks (or other silicate rocks) as core fertilisers in crops while providing a direct contribution to CO_2 sequestration through ERW.

Edwards, Lim et al. (2017) provide one of the most recent advancements in the field of farm capacity utilisation in terms of spreading silicates (and more specifically basalt). The authors focus on warm tropical climates with higher weathering rates and discuss the application of basalt on an area of 680 million hectares of tropical agricultural lands and tree plantations to reduce CO_2. In their analysis, they discovered that large and medium scale businesses (crop production) have the necessary infrastructure to spread basalt and fertilisers for their crops. In contrast, small ones face substantial barriers (Jason and Clay 2004). However, examples provided by Sanchez (2002) and Van Straaten (2002) showed how small African farms had used indigenous rock phosphates to boost soil productivity and produce better yields – thus there are incentives for the proliferation of basalt spreading in a similar context. However, research shows that even such smaller level farms are currently modernising and adhering to technologies and infrastructures that will enable ERW (Van Vliet et al. 2012).

Together with such modernisation, Edwards et al. (2017) argue that the expansion of the land-use for crop production in tropical areas is expanding very fast, however, in many cases this is done via deforestation, which causes a domino effect with biological and environmental issues. This can be highly mitigated via ERW in the sense that if the existing crops are being exposed to basalt, the localised production yield will be higher and there will be no need to expand at a high pace to other lands (Hertel et al. 2014). On the other hand, Edwards et a. (2016) summarise the critical potential pitfalls of spreading basalt rocks in tropical farms namely; increased emissions for grinding and extraction; yield quality; unknown biosphere impacts; reduced water quality and the requirement of new mine creation.

Furthermore, Smith et al. (2016) review and compare the effectiveness of various negative emission technologies (NETs) and argue that ERW has lower land-use intensity requirements (<0.01 ha t−1 sequestered yr−1) than other methods (i.e. BECCS) as well as water-resource use (1.5 m^3 water per tonne sequestered). Thus, in case of ERW as a NET, farm capacity of spreading silicate rocks for CO_2 sequestration and soil neutralisation is substantially eased as compared to the use of other technologies.

However, the key drawback of ERW as reported by Smith et al. (2016) resides in the high-energy intensity (which is not directly related to the deployment/farm/crop side – being rather related to the extraction, comminution and transportation of the rocks). The core challenge of farms in terms of silicate spreading to support ERW resides in the cost-benefit analysis of the entire process (in terms of initial investment, which will be gradually absorbed). It is of high importance to develop balanced and financially viable supply chain models that will minimise the cost of ERW.

2.8 Fertiliser usage and the role of basalt

One relevant research related to ERW is the extent to which farms (globally) rely on the use of basalt as a key fertiliser. Boosting agricultural soil with nutrients is vital to maintain a healthy ecosystem. With growing population to 10 billion and global food production/trade accelerated, crop-fields around the globe have been subjected to agricultural production intensification (Potter et al. 2010) which has significantly reduced soils' nutrient levels. These unsustainable operations cannot continue in its current form, and research is required to compare how ERW can provide a more sustainable option than current agricultural practices (Garcia et al.,2020).

As a response, crushed basalt and other ultramafic rocks have an important and well-documented use for agricultural purposes as natural fertilisers to boost the productivity of crops (Watkin 1999, Gillman et al. 2002, Shamshuddin et al. 2011, Bjørseth 2016). Their application to large agricultural areas is seen as a critical success factor of CO_2 sequestration under the framework of ERW (Taylor et al., 2016). Following this trend, some studies including Moosdorf et al. (2014); Schopka et al. (2011); Dessert et al. (2003) argue that ultramafic rocks such as basalt should be the most suitable ones for terrestrial weathering and this aspect becomes highly relevant to farmlands and crops culture which require pH adjustments and soil acidity amelioration.

Using such silicate rocks as a natural fertiliser has excellent potential in the substitution of highly toxic and environmentally damaging fertilisers such as ammonium nitrate. Ideally, crushed silicate rocks mixed with agricultural nutrients and enhancers will make the overall crop area more productive and will improve the local biosphere (Schuiling & Krijgsman, 2006), though, as Smith et al. (2016) mentioned, to directly assist CO_2 reduction of 1 Gt Ceq yr−1, a land surface of 10Mha is required.

The work of Potter et al. (2010) focuses on the mapping of global scale application of N nutrients for soil performance-boosting using global fertiliser databases and the results

(Figure 2.3) show that most N application intensive areas are precisely the areas where ERW could be implemented most favourably. Instead of fostering the chemical production of N composites, ERW via basalt rocks could substitute the need for N application, as the outcome of basalt application on soils will mitigate the N depletion rate (Kantola et al., 2016). In this research, this will be extended to examine the impact on P and K in addition to N.

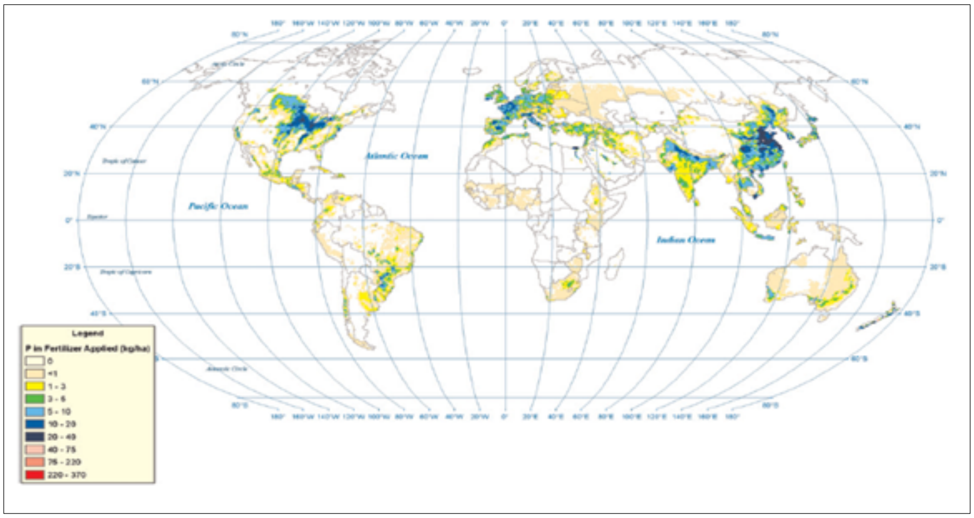


Figure 2.3: Global mapping of N nutrient application on crop areas (Potter et al., 2010)

2.9 Factors to consider for ERW success

i. Suitability of Silicate Rocks

Selection of suitable silicate rocks is key to the success of enhanced rock weathering. To ensure CO_2 removal efficiency in ERW, Moosdorf et al. (2014), states that the choice of source rocks could potentially contribute to how much CO_2 can be removed through the ERW process. Usually, rocks belonging to the ultramafic group; rocks with low silica content have relatively high carbon capture potential compared to that of the mafic group; rocks with high silica content (Renforth, 2012). Ultramafic rocks such as dunite have carbon capture of $\sim 0.8tCO_2^{-1}$ compared to mafic rocks such as basalt which mostly have carbon capture potential of $\sim 0.3tCO_2{}^{-1}$ (Renforth, 2012).

However, globally ultramafic rocks are of limited quantity than mafic rock formations. Taylor et al. (2016) estimated the mining capacity of global dunite (ultramafic rock) resources to be approximately 560 Petagrams while global basalt (mafic rock) resources are between 13-15 million petagrams. In the UK, out of the 430 billion tonnes of potential carbon capture of rocks, only 25.4 billion tonnes are attributed to ultramafic rocks.

ii. *Availability of Silicate Rocks*

Closely linked to rock suitability is the availability of the silicate rocks. To ensure the CO_2 efficiency of enhanced weathering (Moosdorf et al. 2014), large amounts of silicate rocks must be used if there is to be any significant drawdown in global CO_2 levels. This means that not only should the chosen geographic land have suitable rock types for enhanced RW, but also, more importantly, these rocks should be in abundance. Limited rock availability in a particular area would mean relatively high-enhanced weathering cost compared to other regions with abundance of silicate rocks. Mining in areas where silicates rocks are in abundance reduces transport cost. Schuiling and Tickell (2010) suggest that transport distance between mines and point of use be less than 300km.

Unlike carbon capture and storage, where CO_2 is sequestered from point sources such as coal-fired plants and power stations, Schuiling and Tickell (2010) argue that CO_2 can be captured anywhere in the world irrespective of location or origin. Therefore, with enhanced weathering carbon sequestration from point sources of either pure CO_2 or dilute sources do not really matter. Furthermore, climate change is a global environmental problem hence reducing CO_2 levels in an area different from the origin still leads to a global reduction in CO_2 that is the main aim of climate mitigation solution.

Schuiling and Tickell (2010), in their research, provided a comprehensive list of suitable geographic areas where olivine deposits, in particular, are abundant. They cited countries such as India, Brazil, China, Indonesia and Canada as having large olivine deposits that could be exploited and used in enhanced weathering. According to their research, Brazil and India have their large olivine deposits overlaid with nickel and chromite laterite crust, which are already being mined. Therefore, with the mining infrastructure already in place, they suggest that these same mines can be used to remove this overlay in order to reach the olivine deposits. India is also reported to have large dunite deposits in the Chittadurga greenstone belts in South India and the Chalk Hills near Salem (Mani et al. 2008).

iii. Climatic Conditions

Another important factor worth considering in the geographic land assessment of suitable areas for enhanced RW is favourable weathering climate regions. In terms of a suitable climate, the humid tropical regions are considered most efficient as research suggests that such regions experience relatively high humidity, which facilitates weathering (Macias and Chesworth 1992, Stallard 1998).

Taylor et al. (2015) also assert that a third of tropical land-use for enhanced weathering purposes is ideal to result in a significant drop in atmospheric CO_2. The same conclusion was made by Köhler et al. (2010) who according to their results showed that by spreading fine olivine powder over land areas in the humid tropical regions, up to 1 petagram of carbon could be potentially sequestered annually. Mined and ground silicate rocks should be spread at humid tropics where weathering rates are highest due to the high temperature. As explained earlier, this does not mean that weathering is impossible in temperate climates, but only that the rate of weathering will be slower.

iv. Prospects for Co-Benefits

The growing attention given to enhanced weathering as a climate mitigation strategy is partly owed to the co-benefits associated with the process in addition to its CO_2 sequestration ability. Many studies on enhanced weathering have identified such co-benefits to include improvement in soils, forests, agriculture and reduction in ocean acidity (Taylor et al.,2015, Renforth et al. 2015, Renforth et al. 2009). Mineral components of the rocks such as magnesium, which could improve, soil nutrients as rocks breakdown (White and Brantley

1995). This point is crucial and must be emphasised if farm and landowners are to collaborate in offering their land for the spreading of the crushed silicate rocks. If farmers, foresters or fishermen experience direct benefits from silicate spreading, they will be more prone to collaborate (Schuiling and Tickell, 2010).

Also, according to Schuiling and Tickell (2010), some dunites contain sub-economical contents of chromite, nickel or platinum minerals and therefore by mining them for olivine, it may become economical to recover these by-products as well. This also holds for kimberlites, the host rock of diamonds, where marginal diamond grades may become economical if the rock is mined and crushed to spread kimberlite (Schuiling and Tickell, 2010).

v. *Availability of related Infrastructure*

Land for the economic viability of enhanced weathering could also be assessed on the level of infrastructure in an area. Infrastructure such as transport networks could significantly reduce the overall cost of the enhanced weathering process. In cases like Guinea, Schuiling and Tickell, (2010) report that the country's inland rail transport offers a good possibility, as two railroads for bauxite transport from the interior pass close by the possible location for a future olivine mine. They suggest that the empty trains can carry loads of olivine inland on their return from the port at the tip of the peninsula. Again, the availability of already existing large mines in a country would imply there is no need to clear forestland to set up a mine, which would also mean less ecological damage and infrastructure investment.

2.10 Cost considerations in ERW implementation

This section reviews estimates of the potential cost associated with the implementation of Enhanced Rock Weathering. According to Schuiling and Tickell (2010), except in cases where the required silicate-rich rock is already available in crushed form on mine dumps, the application of enhanced weathering implies mining and milling of solid rock from a large open-pit mine. They estimate the total annual cost of CO_2 sequestration by enhanced weathering to be 250 billion US$/year worldwide, assuming that was the only method to sequester all man-made CO_2 emissions. Even with this amount, they maintain that enhanced weathering would still be a favourable choice compared to other CO_2 sequestration methods.

Schuiling and Tickell (2010) report that crushed olivine in bulk from a small mine in Greenland costs €23 per ton in the port of Rotterdam. According to their research, it is expected that the cost of silicate rocks will drop below €15 per ton for large mines in low-wage countries and limited transport distances between application sites and mine. The cost per ton of CO_2 will then be around €10 per ton, as one metric ton of olivine captures 1.25 tons of CO_2. This compares very favourably against the cost of CO_2 capture by CCS, which is 60 to 90 € / ton. In terms of transport cost, they suggest that a maximum limit of 300km around the mine would lower the cost considerably.

Another issue worth considering is the state in which these rocks are found. If they are already semi-crushed, then it will relatively cost less in terms of mining and milling. For example, ore deposits of popularly mined minerals such as nickel, magnesite, chromite, and sometimes diamond happen to be rich in olivine. Therefore, it most likely several tons of these rocks will be in crush form mine residue (Schuiling and Tickell, 2010). Schuiling and Tickell, (2010) report that the use of already fragmented and powdered rock deposits in powder form (such as volcanic ash deposits) would significantly reduce or eliminate cost and energy requirements for milling, lowering costs and energy input. To reduce extraction cost, existing or abandoned mines of silicate-rich rocks could be used. For example, massive weathering from olivine-rich mining wastes found in mine dumps in Canada has captured at least 82,000 tons of CO_2 in less than 20 years rapid (Wilson, Dipple et al. 2009). This also holds for kimberlites, the host rock of diamonds, where marginal diamond grades may become economical if the rock is mined and crushed to spread kimberlite (Schuiling and Tickell, 2010). According to Schuiling and Tickell, 2010 some silicate source rocks contain sub-economical contents of chromite, nickel or platinum minerals and therefore by mining them for olivine, it may become economical to recover these by-products as well.

Part 2 of Literature Review

2.11 Supply Chain Sustainability and Triple Bottom Line

The term sustainability in management literature is used broadly to describe an integration of economic, environmental and social responsibilities of organizations (Carter and Rogers 2008). There are several definitions of the term, but fundamentally these include at least the environmental and economic aspect. The common definition of sustainability is given by Bruntland (1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their needs." Sustainability can be implemented from both a micro-economic and macro-economic viewpoint, although more applications of the former are implemented in management and operations field (Carter and Rogers, 2008). According to Maloni and Brown (2006) the application of sustainability in assessing supply chains was not until the late 1980s. Despite the three-dimension feature of sustainability, a review of the management literature shows that most conceptualization of the term has taken a one-dimensional view usually with a focus on environmental sustainability (Vachon and Klassen 2006, Abbasi and Nilsson 2012, Cucchiella, Koh et al. 2012) with just a few studies recognising the socio-economic dimension (Jennings and Zandbergen 1995, Starik and Rands 1995, Svensson and Wagner 2015, Wilson 2015).

One concept that runs through the supply chain sustainability literature is the Triple Bottom Line (TBL) approach, which is described by Willard (2012) as providing a new sustainability advantage from a three-dimension view. First coined by Elkington (1998) the TBL concept is an accounting framework that differs from traditional models by integrating the three sustainability pillars (economic, environmental and social). In the past, the bottom line of firms in a strategic management sense was to make financial gains. However, as the pressure by customers, shareholders and regulators began to rise, firms started broadening their bottom line to go beyond economic gains and include the other equally important core aims namely environmental and social (Govindan et al. 2013).

The basic premise of TBL reporting is to measure sustainability based on what is commonly referred to as the three Ps that is profits, planet and people relating to economic, environmental and social impacts respectively (Slaper and Hall 2011). Before the introduction of TBL by Elkington (1998) and the three Ps, measuring how sustainable a firm remained a challenge as there were no criteria for measuring sustainability. With the introduction of the TBL approach, firms can be evaluated based on their impacts on the economy, environment and society. It is worthy to note, however, that pursuing a TBL approach does not undermine the importance of economic sustainability (Willard, 2012). Advocates of TBL strategy assert that the approach to engage in environmentally and socially responsible behaviours must be seen as complementary to achieving sustainable financial gains in the long term (Willard 2012, Savitz 2013). According to Carter and Rogers (2008), adoption of this approach can help organisations achieve competitive advantage over firms that are still stuck with the bottom line of financial profits. Aside the benefit of competitive advantage that a TBL approach offers, in recent times it is becoming increasingly essential to towing this line as the pressure and requirements for sustainability reporting by regulation and legislation continues to mount (Govindan et al.,2013). It is no longer a mere choice but a necessity for both firms and governments to stay on top of their game.

Measurement of TBL, however, is challenging, as there is currently no standard unit of measure for the three pillars of sustainability (Singh et al. 2009). Several studies have suggested the use of a TBL framework for measuring sustainable supply chain (Wiedmann and Lenzen 2008, Kucukvar et al. 2014, Onat, Kucukvar et al. 2014). Govindan et al. (2013), in their research, developed a framework for measuring sustainability in the mining and minerals industry. In their framework, they listed indicators that cut across all TBL factors. For economic sustainability indicators, contribution to GDP, operation cost, capital investment was among some of the indicators considered crucial. Environmental indicators included GHG emissions, energy use, ecotoxicity, resource use. For the social indicators, employment creation, health and safety, human rights and labour were listed as being vital to the sustainability of the mining and minerals industry.

However, of the three sustainability indicators, economic and environmental indicators are the most developed making it easily measurable. Social indicators such as human rights will be challenging to measure in quantifying terms but excluding such impacts will lead to incomplete sustainability assessment (Willard, 2012, Wiedmann and Lenzen, 2007). A review of the literature reveals that there are no TBL frameworks for ERW. Nevertheless, knowledge from studies that have used TBL frameworks (Onat et al. 2014, Fredline et al, Foran et al. 2005, Wang and Lin 2007, Nikolaou et al. 2013) can apply to some extent in measuring TBL impact of ERW supply chain although some of the sustainability indicators and methods may have to be adapted.

In addition to the individual sustainability TBL indicators, integrated or composite TBL indicators also present a holistic measure of sustainability performance for more understandable and easy decision making instead of using disaggregated TBL indicators (Singh et al. 2009, Zhou et al. 2012). These are usually a combination of two or all dimensions of TBL. However, this method is not without limitations as eliminating the common unit TBL measurement problem can be very challenging (Mayer 2008). However, a review of the literature shows quite a number of studies that have attempted to provide such composite sustainability indicators (Mori and Christodoulou 2012, Koh et al. 2016). The Integrated Resource Efficiency index (IRE index), a composite indicator developed by Koh et al. (2016) provides a measure of sustainability across all three pillars by extending the Human Sustainability Development Index (HSDI) and informed by Integrated Resource Efficiency View (IREV). Most of these integrated indicators, however, are usually used in accessing country's sustainability and not necessarily a strategy such as ERW (Koh et al., 2016; López et al. 2007, Siche et al. 2008).

Although the review of the literature is void of research that uses the TBL approach explicitly on enhanced weathering, the principle of this approach is still very much applicable to evaluating the sustainability of ERW supply chain. As stated previously, current research on ERW has focused mainly on evaluating the financial cost of the implementation and the positive environmental potential of reducing atmospheric CO_2 (Moosdorf et al., 2014, Renforth, 2012, Hangx and Spiers, 2009). Mere mention is usually made at the conclusion segment of these studies on the need for social impacts and environmental feasibility to be researched without it being done.

The importance of adopting a TBL approach cannot be overemphasised. Suppliers and actors within the ERW supply chain will largely affect the sustainability of the ERW supply chain. A recent study by Sarkis and Dhavale (2015) stated that the selection of suppliers within in a firm's supply chain based on the TBL impacts of these suppliers is more sustainable than the traditional approaches, which focused on selecting suppliers based on low cost they present to the firm operations. For instance, the selection of quarry firm who will most likely be the suppliers of basalt rock dust should not be determined by price only. Giovindan et al (2013), in their research, showed that the sustainability performance of supply chains is influenced by supplier selection based on their TBL impacts.

2.12 Lifecycle Sustainability Assessment

Supply chain impact assessment of supply chains needs to be carried out from a holistic lifecycle approach where impacts across all three TBL sustainability indicators will be analysed. The lifecycle approach to measuring TBL impacts will ensure that negative impacts are not merely passed on to other parts of the supply chain. The lifecycle thinking provides a bird's eye view of a firms supply chain depending on the level of assessment being carried out (global or local) and enables assessors to identify the hotspot.

To do this, a Life Cycle Sustainability Analysis (LCSA) approach is seen as an appropriate method (Kloepffer 2008, Swarr et al. 2011, Zamagni 2012). Life Cycle Sustainability

Assessment (LCSA) uses distinct analyses for each of the three pillars of sustainability: environment, economic and social impacts. It encompasses the use of Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) (Halog and Manik 2011). Swarr et al. (2011) describe the process in simple equation terms as LCSA=LCA+LCC+SLCA.

Whilst contemporary research is ongoing on the role of enhanced weathering as a climate change mitigation strategy, there is currently no existing study that specifically assesses ERW supply chain impact from a Life Cycle Sustainability approach. Most of the studies on ERW reviewed had a limited scope since they addressed one pillar of sustainability (Moosdorf et al., 2014; Schuiling and Tickell, 2010; Schuiling and Krijgsman, 2006). However, to understand the implications in terms of long-term environmental, social and economic impacts, the use of LCSA is needed (Finkbeiner, Schau et al. 2010). The following section discusses each method under LSCA and how they apply to the enhanced weathering supply chain.

2.12.1 Environmental Lifecycle Assessment

The Lifecycle Assessment (LCA) is a widely accepted method used in estimating the environmental impacts of products and processes (Guinee 2002). In terms of Lifecycle Sustainability Assessment, environmental impacts are much more easily standardised and quantified using the LCA method than social and socio-economic (Finkbeiner et al 2010, Heijungs et al. 2010). To ensure environmental sustainability, it is vital to know first, the environmental impacts of a product or process. These environmental impacts occur along the different supply chain life cycle stages of a product or process (Acquaye et al., 2011). LCA has mainly been used to identify and quantify the environmental impacts of products and business activities on the natural environment throughout their lifecycle from resource extraction, production, use and re-use, disposal phases (Govindan et al. 2014; Hellweg and Canals 2014).

There are three main types of LCA namely the Process LCA, the Input-Output LCA and Hybrid LCA (Suh and Nakamura 2007, Finnveden, Hauschild et al. 2009, Guinee, Heijungs et al. 2011). Process LCA is used to evaluate the environmental impacts of the downstream production activities within a firm's supply chain (Suh and Nakamura, 2007). It requires a system boundary to be clearly defined within which the environmental impacts are estimated and therefore raises reliability issues associated with the truncation of environmental impacts indirectly related to the product or service (Lenzen 2000, de Haes, Heijungs et al. 2004). This implies that upstream environmental impacts of a supply chain are not included in the analysis and therefore, does not give an accurate picture of a product's environmental footprint (Acquaye et al., 2011). The Input-output LCA method, on the other hand, can estimate upstream environmental impacts in supply chains. To capture indirect impacts and broader environmental impacts, the Hybrid LCA is used as it integrates process LCA and input-output methodology (Suh and Nakamura 2007).

A global EW supply chain could imply that raw materials could be extracted and crushed in one country and then transported and applied in another country as was carried out in Moosdorf et al. study (2014). Therefore, in reality, it is most likely a network of firms will carry out the lifecycle processes of ERW that are mining, comminution, transportation and application across different industries and even countries. The more extensive the network of partners along the supply chain, the more environmental impacts that are potentially generated. Therefore, these impacts along the supply chain need to be estimated. In such a case, a lifecycle assessment based on multi-regional input-output (MRIO) model can capture the knock-on environmental impacts of EW on related industries on both local and global levels (Acquaye et al. 2011, Oppon et al. 2018).

A review of the literature shows some few scattered studies on environmental impacts. Ten et al. (2012) in their research, for example, investigates the impact of olivine weathering on soil and plant nutrient uptake. Moosdorf et al. (2014) also estimate the environmental impact of ultramafic rocks in terms of the associated lifecycle CO_2 emissions. Although these are crucial environmental impact measures, it provides a narrow assessment for silicate rock types since they are based on only one environmental impact and in addition they are not carried out as a comparative study which would allow for practical trade-off analysis between alternatives. A more efficient basis for assessment and comparison of different materials will require the estimate of multiple environmental impacts before generalisations on environmental sustainability can be made (Ibn-Mohammed et al. 2016).

Life Cycle Analysis on enhanced weathering to ascertain its environmental viability remains an unexplored research area. Consequently, providing a robust theoretical base and developing a quantitative LCA framework for analysing and understanding the environmental implications of ERW has become timely and essential. Environmental impacts associated with the use of mine tailings, for instance, will differ from the extraction of silicate rocks from active mines and these impacts are addressed in the current study on ERW supply chain.

2.12.2 Lifecycle Cost Assessment (LCC)

In addition to assessing the environmental impacts of ERW supply chain, another critical issue is the economic cost associated with its life cycle. Decoupling economic analysis from environmental impacts can limit proper decision making and policies (Acquaye et al., 2011). Integrating economic impact analysis into the traditional LCA is commonly referred to as Life Cycle Costing (LCC) (Norris 2001, Rebitzer et al. 2003). LCC is considered as an extension of the traditional LCA method but with a focus on supply chain economic impacts of products and processes (Gauthier 2005). The LCC method can provide a cost breakdown; identify cost drivers as well as areas where cost reduction efforts are likely to be most effective in the implementation of ERW (Xu et al. 2006).

Limited literature exists on the application of Life Cycle Cost analysis to enhanced rock weathering. A basic search in google scholar shows that there is no specific study on Life cycle economic analysis of Enhanced rock weathering. Schuiling and Tickell, 2010 in their research were able to provide some cost-benefit analysis on ERW. Overall, few studies have attempted to do an economic analysis of ERW. These studies, such as Moosdorf (2014), Renforth (2012), Hangx and Spiers, (2009), among other things, have failed to estimate the indirect economic impacts of enhanced weathering. They, therefore, have not fully quantified the life cycle costing of ERW.

The economic assessment of ERW therefore remains a relevant research gap if indeed the already credible potential of enhanced RW can be translated into a feasible climate change mitigation option. The LCC method can be used to outline and estimate the potential direct and indirect economic cost associated with ERW and serve as a benchmarking analysis to assist in decision making alongside other CO_2 mitigation strategies. This research aims to address this gap by employing the use of LCC based on economic input-output model (Leontief, 1986).

2.12.3 Social Life Cycle Assessment(S-LCA)

UNEP defines Social Lifecycle Assessment (S-LCA) as a "social impact (and potential impact) assessment technique that aims to access the social and socio-economic impacts of products and their potential positive and negative impacts along their lifecycle"(Andrews et al., 2009). One common assertion that runs through the literature on SLCA is that it serves as a decision support tool aimed at either comparing or improving the social performance of products. SLCA can be used to measure either real or potential impacts (Macombe et al. 2013) which includes both negative and positive impacts. The latter category of impacts (positive) is seldom discussed in the literature, but it is important to note that impacts are not necessarily negative but could be positive. An example of positive impacts, for instance, could be the absence of child labour (Jørgensen et al., 2008; Ciroth and Franze 2011).

Compared to LCA and LCC, the S-LCA method is relatively new with no standardised method of applications (Jørgensen et al. 2008). Some studies have attempted to provide some general guidelines and social impact indicators to the S-LCA methodology (Dreyer et al. 2006, Andrews 2009, Muthu 2014). (Petti et al. 2014, Petti et al. 2018) conducted a systematic review where they reviewed 35 SLCA case studies from 2009 to 2015. According to their review, 56% of case studies were on a product, 41% on a service and only 3% on a process. Dominant studies of SLCA focus on sectors with environmental impact as well, reinforcing the fact that the SLCA method was born from the need for an extension of environmental impact assessment. Due to data availability and concentration of authors in the region, the geographical area where most SLCA studies are conducted is in Europe despite the region having relatively low social risk compared to other. Zamagni et al. (2011) proposes SLCA be conducted without a functional unit. Especially in the case of solely qualitative indicators. Umair et al., 2015 states that the impacts cannot be related to a functional unit. Some studies did not specify the functional unit (Manik et al. 2013).

Moosdorf et al. (2014) highlighted the need for research on the social acceptability and mechanisms of governance for enhanced weathering. Stakeholders, including workers, local government, community all play a vital role in the successful operation of enhanced rock weathering and will most likely be affected one way or another by its implementation. Taylor et al. (2016) also recommended the need for research into the social impacts of enhanced weathering since these are a crucial part of the TBL sustainability factors. According to (Muthu 2014) the social impact assessment is no longer an option but a necessity. However, studies on ERW excludes this social dimension of its implementation. Undoubtedly, there is a need for evidence-based research into the impacts of ERW on society. The current work, therefore, employs the use of a proposed Social Life Cycle Assessment method in assessing the potential supply chain impacts of ERW from a social sustainability perspective, highlighting the pros and societal implications of ERW on all direct and indirect stakeholders across its supply chain.

2.13 Theoretical lenses

A review of literature on ERW supply chain reveals almost no theoretical scope on sustainable ERW implementation through the lens of management theories. Sarkis et al. (2011), however, provides an overview of a number of organisational and management theories that are applicable in assessing sustainable supply chains. These according to their study include the resource-based view theory, stakeholder theory, resource dependency theory, ecological modernisation and complexity theory which have been broadly introduced and applied in operations and supply chain management literature (Sarkis et al. 2011).

- The resource-based view theory is used to explain how firms can achieve a competitive advantage with valuable, rare, imperfectly imitable and non-substitutable resources (Barney, 1991). The theory stipulates that firms can gain a competitive advantage that is, efficiency and effectiveness by harnessing their resources which include capabilities, assets, information and even unique processes and knowledge (Barney, 1991).

- Stakeholder Theory: Freeman (1984) defines a stakeholder as "any group or individual who can affect or is affected by the achievement of an organisation's objectives". Stakeholder theory suggests that the activities of a firm can lead to third party impacts (externalities) on stakeholders. The affected stakeholders, therefore, may put pressure on the firm to reduce these externalities when negative or to increase in the case of a positive externality. Although further development and applications of the stakeholder theory exist in the literature (Delmas, 2001; Mitchell et al., 1997), the underlying principle of the theory is that both internal and external groups can influence firms' practices.

- Resource dependence theory (RDT) suggests that individual partner firms achieve long-term benefits and high-performance gains within a supply chain correlating and depending on each other's resources (Sarkis et al., 2011). According to the theory, a firm's resource can be input to other firms and vice versa, thus requiring some sort of interdependency between firms within a supply chain (Hillman et al., 2009). The hypothesis of the RDT, therefore, is that firms are not entirely self-sufficient thus reliance on other firms are crucial for their survival (Heide, 1994) as well as for sustainable development (Ulrich and Barney, 1984). The literature also shows the relationship between the resource dependency theory and stakeholder theory (Gollagher et al., 2010). Success in implementing sustainable supply chain management, therefore requires the efficient interdependency of supply chain members.

- Ecological modernisation theory (EMT) which stems from sociology theory, suggests that innovation and technological advancement, in other words, "modernity" gives rise to industrial development and environmental protection (Huber, 2000). In a study using ecological modernisation as an explanatory theory, Huber (2008b) showed how technological, environmental innovation (TEI) is achieved mostly from the upstream supply chain other than the downstream thus highlighting the crucial role of suppliers in a supply chain.

- The complexity theory proposes that the environmental factors (customers, suppliers, government regulations, etc.) in a system within which a firm operates are diverse and heterogeneous and interactions between these factors can determine the performance outcome of the firm. Firms must be able to learn and adapt to these complex interactions within the supply chain environmental factors (Starkis et al., 2011). In the same way, it is expected that such complexities will increase in achieving supply chain sustainability as the economic, environmental, and social impacts are considered along an extensive supply chain involving large quantity of parties (Bai and Sarkis, 2010a).

Although each theory presents a unique perspective, they are also complementary as far as achieving sustainable supply chains is concerned (Halldorsson, Kotzab et al. 2007). This work adopts the resource-based view theory as the theoretical lens for the study. The following sections discuss the resource-based view (RBV) theory and how it is extended and applied to the current research on ERW supply chain sustainability.

2.13.1 Resource-Based View theory

The Resource-Based View (RBV) is used to explain how firms can achieve sustained competitive advantage with valuable, rare, imperfectly imitable and non-substitutable resources (Wernerfelt 1984). Resources are valuable when they either help firms reduce cost or increase differentiation, thereby increasing value to customers. Resource are rare if they are viewed as not widely obtainable by rivals; therefore, if a resource is easily accessible, then it cannot be considered as rare and therefore can be a source of competitive advantage. Inimitable resources are costly or difficult to imitate and thus, cannot be easily implemented by others. An example of an inimitable resource is the technological know-how of a firm which can be difficult to imitate, by other firms within the same industry. Non-substitutable resources are difficult and costly to replace with other available resources.

The RBV theory stipulates that firms can achieve a competitive advantage, that is efficiency and effectiveness by harnessing their resources which include capabilities, assets, information and even unique processes and knowledge (Barney and Clark 2007). Previous studies, particularly in strategic management literature, have explored the importance of firms in adopting a resource-based perspective by identifying both tangible and intangible resources (Carter and Rogers,2008) that can help increase their supply chain operational performance (Rungtusanatham et al. 2003, Wu et al. 2006). Tangible resources refer to resources that have a physical presence including land, buildings, equipment and capital. Tangible resources, however, confer a short-term competitive advantage in that these can be easily bought in an open market, so once a 'competitor' can acquire this, there is no more competitive advantage. Intangible resources, on the other hand, include resources such as skills, technical knowledge, know-how processes, and these have long term competitive advantage.

In addition, to the above characteristics, the resources must satisfy the conditions or assumptions of being both heterogeneous and immobile (Barney and Clark, 2007). Heterogeneous assumption means that resources differ among firms and therefore even though firms may belong to the same industry, they internally differ in terms of resources or capabilities which give rise to one having a competitive advantage over another. Immobility assumption suggests that a firm's resources cannot be easily moved to another in the short term which means the firm can gain a competitive advantage as competitors cannot quickly replicate these resources or capabilities.

Rungtusanatham et al. (2003) in their study applied RBV in developing a framework that proves that supply chain linkages which they defined as a 'firm's linkages with entities in its supply chain' is a resource that can help firms maximize their operational performance. Wu et al. (2006), also in their study, draws on the RBV theory to show that information technology can serve as a resource that can give firms a completive advantage. These studies and many others employ the use of RBV from a firm-level perspective.

2.13.2 Natural Resource-Based View Theory

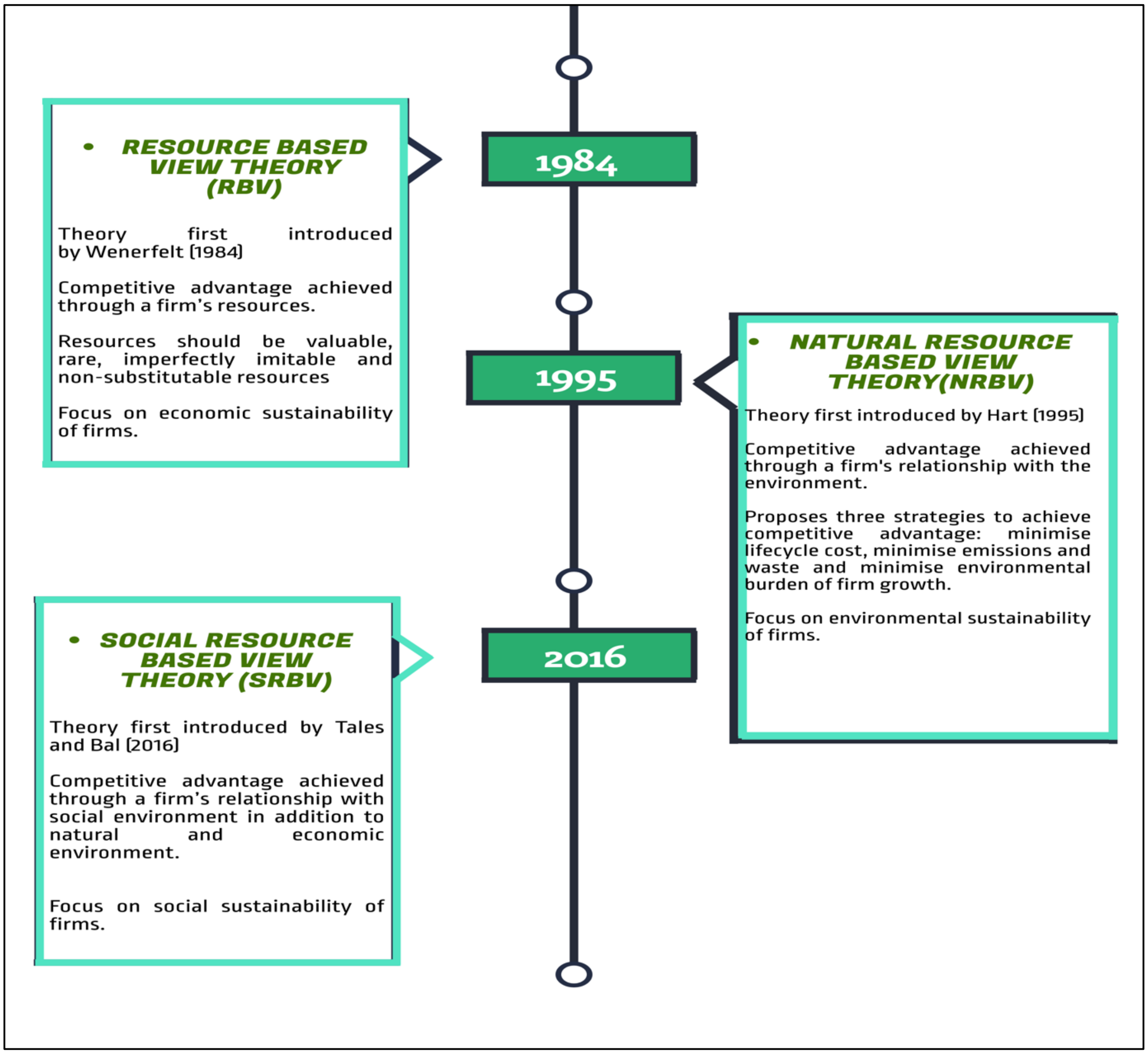
The RBV theory discussed above fails to consider the constraints that the natural environment poses in a firm achieving competitive advantage (Hart 1995, Kraaijenbrink et al. 2010). In addressing the limitation of the RBV theory, Hart (1995) extended the theory to include natural resource environment referred to as the Natural Resource-Based View (NRBV). The NBRV theory proposes that firms can achieve a competitive advantage based upon the firm's relationship to the natural environment. The NBRV theory is composed of three interconnected strategies: pollution prevention (minimise emissions and waste), product stewardship (minimise lifecycle cost of products), and sustainable development (minimise environmental burden of firm growth).

However, over a decade later, Hart and Dowell (2011) in their review of the NBRV theory application found that most empirical research that has applied the theory focused more on the strategy of pollution prevention to increase firm's performance while less attention has been directed on the other two propositions of the theory, that is, product stewardship and sustainable development. Examples of such studies include the works of De Stefano et al. (2016) and Chan (2005) on the automobile industry and foreign-invested enterprises in China, respectively. A review of these studies shows that the application of NRBV theory by firms is mostly driven by the potential financial gains that can be obtained from environmental performance, especially pollution prevention. No attention is, however, given to a firm's relationship with society.

2.13.3 Social Resource-Based view (SRBV)

Despite the NRBV being an improved version of RBV, its application in some of these research studies shows the limitation of the NRBV theory in failing to inculcate the social pillar of sustainability. In measuring the TBL impacts of ERW, the underlying theory of the methodologies employed must be one that encompasses all three pillars of sustainability. The three strategies of the NRBV as developed by Hart (1995) all focus on environmental sustainability but does not include the social sustainability dimension. Expanding the NRBV theory to include social impacts will provide a holistic sustainability view.

Expansion of the RBV and NRBV theory to include social dimension is first introduced by Tates and Bals (2016). Their study work proposes the social resource-based view(SRBV) which is defined as an expansion of the RBV and NRBV theory to include social sustainability dimension where competitive advantage is achieved in the context of a firm's relationship to the society in addition to the natural environment. Tates and Bals (2016) extension of RBV theory to SRBV is based on these three expansions; expanding range of variables by adding social capabilities, extending the stakeholder interest to include environment, economy and society and linking social capabilities and shared TBL value creation. The social sustainability dimension addresses social themes such as human wellbeing and safety, poverty, employment, social justice and equity and community involvement. One critique of the SRBV theory is that demonstrations of the application of the theory have mainly been focused on the organisational and micro-level.



Theory first introduced by Wenerfelt (1984)

Competitive advantage achieved through a firm's resources.

Resources should be valuable, rare, imperfectly imitable and non-substitutable resources

Focus on economic sustainability of firms.

Theory first introduced by Hart (1995)

Competitive advantage achieved through a firm's relationship with the environment.

Proposes three strategies to achieve competitive advantage: minimise lifecycle cost, minimise emissions and waste and minimise environmental burden of firm growth.

Focus on environmental sustainability of firms.

Theory first introduced by Tales and Bal (2016)

Competitive advantage achieved through a firm's relationship with social environment in addition to natural and economic environment.

Focus on social sustainability of firms.

Fig 2.4 Overview of Resource-based view, Natural Resource-based view and Social Resource-based view theories

2.13.4 Integrated Resource-based View (IRBV)

The RBV, NRBV and SRBV theory discussed above, mostly look at a firm-level competitive advantage without considering the inter-linkages and inter-reliance between firms. To produce, firms rely on one another, and therefore these linkages may also affect the ability of a firm to achieve competitive advantage. Such an outlook requires that competitive advantage is viewed from a supply chain level and not just the firm level. Competitive advantage at the firm level, which is what the RBV, NRBV and SRBV theory entails looks at internal resources of a firm. However, equally important are the resources from the supply chain level, which may be external to a firm but due to the inter-linkages among firms are equally important. Competitive advantage must also be viewed from an integrated manner such that the competitive advantage is not explained as firms achieving just economic, environmental or social competitive advantage but as an overall integrated TBL competitive advantage. A firm may have an economic competitive advantage but not an environmental or social competitive advantage. These trade-offs can only be highlighted if the idea of firms' inter-linkages is considered.

The current study is set up as a comparative analysis studies to identify, measure and compare countries. In order to provide insight into how countries will perform in terms of TBL sustainability impacts, a theory on competitive advantage may be appropriate in this instance. One such theory that speaks on competitive advantage is the resource based view (RBV) theory discussed in previous section. Using the RBV theory as a theoretical base, the study seeks to explain why there are differences in TBL sustainability performance among countries in production of silicates for ERW. The limitations of the RBV is that it fails to consider the competitive advantage of firms based on environmental and social resources or capabilities. Another limitation is that the RBV theory does not consider how integrated firms are which reflects the inter-connections that exist between firms in producing to meet demand. Therefore, how the TBL impacts are managed in the inter-linked firms at the supply chain level can explain why a country has a competitive advantage and thus potentially perform better than another country in ERW.

In this study, a proposed integrated resource-based view (IRBV) is presented to capture the inter-linkages between firms and how this can lead to competitive advantage in the context of the TBL sustainability of ERW supply chain from a macro-level perspective. In the proposed IRBV theory, countries can be compared with firms and the competitive advantage considered here is the TBL sustainability advantage such that a country that can combine economic, environmental and social performance/capabilities effectively and efficiently would have a competitive advantage. The IRBV theory can therefore be used to explain differences in country performances which depends on supply chain inter-linkages among firms within a country. The underlying assumption of IRBV theory is that countries can implore the use of valuable, rare, inimitable and non-substitutable resources to achieve a competitive advantage that is a TBL sustainability comparative advantage. Comparative advantage implies countries can meet demand or produce at a low cost to economy, environment and society than other economies.

2.14 Research Gaps and Questions

Literature review is vital in assessing the current knowledge and identifying areas where research questions can be developed in addressing any research gaps. In line with the literature review, two primary research gaps are identified:

- **Research Gap 1: Lack of understanding on the lifecycle sustainability (economic, environmental and social) impacts associated with of ERW:** Conspicuously missing from the literature on ERW is a lack of understanding of the potential TBL impacts associated with ERW supply chain. Although the science behind the ERW has been well documented and explained in the literature (section 2.3), the TBL sustainability of the supply chain processes involved (section 2.4) has not been researched on. The cost considerations of producing crushed silicate rocks for ERW (section 2.10) excludes the likely environmental and social cost associated with the technique, especially from a macro-level perspective.

- **Research Gap 2: Limited understanding of environmental sustainability impacts between basalt versus industrial fertilisers; basalt versus and artificial silicates** Although ERW has been closely aligned with agricultural practices such as the use of rocks as fertilisers (section 2.6-2.8) and the repurposing and recycling of waste silicates which fits into the circular economy agenda (section 2.5), there is a lack of understanding on the associated environmental sustainability associated with these practices in comparison to ERW with rocks, particularly basalt. The wide-scale adoption of the ERW technique as a climate change mitigation strategy may depend to an extent on the compatibility of the ERW technique with these already existing practices. Therefore, there is a need to research into how these practices compare with ERW in terms of environmental sustainability

In line with the research gaps identified, research questions are formulated which provides clarity on the scope of the study that is conducted. (Williams 2007). The research questions are as follows:

- **Research Question 1:** The success of any climate change mitigation strategy, including ERW, will depend on the wide adoption of the strategy by several countries globally especially from regions known to be high contributors to global emissions. The question, however, is that **what are the potential macro-level TBL impacts associated with large-scale basalt production in selected top GHG emitting countries?** Research Question 1 is further divided into four sub-questions, that is RQ1a (macro-level economic impacts), RQ1b (macro-level environmental impacts), RQ1c (macro-level social impacts) and RQ1d (integrated sustainability impacts).
- **Research Question 2:** A consensus that runs through the ERW literature is how the strategy aligns with accepted agricultural crop practices specifically concerning the application of silicate rocks, including basalt as fertiliser. Although this assertion appears to be widely accepted in the literature, **how does ERW with basalt compare with current conventional and industrial fertilisers in terms of an environmental footprint?**

- **Research Question 3**: The literature shows that ERW can be implemented based on the use of natural silicates mined or the use of artificial silicates which are by-products of other production systems. In line with this, **how environmentally sustainable is the use of artificial silicates versus natural silicates?**

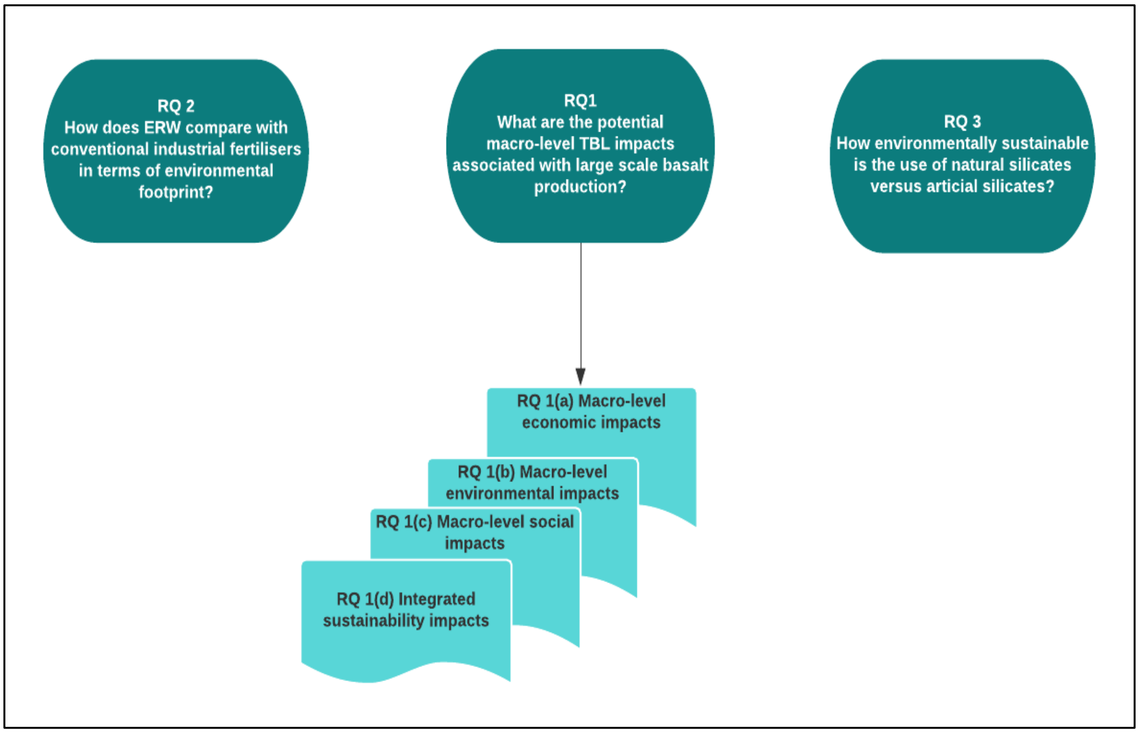


Fig 2.5 Overview of research questions

2.15 Chapter Summary

The literature review section has highlighted relevant studies on ERW from both the natural science field and social science. For the natural science, studies on ERW as a climate change mitigation strategy and its role in agriculture were discussed whilst from the social science angle, studies with relevance to sustainable supply chain management were discussed. This approach is essential due to the interdisciplinary nature of the thesis topic. Based on the identified gaps in the literature and subsequent research questions, the next chapter, Research Methodology will explore and discuss how these are addressed in the analysis chapters.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

In line with achieving the set objectives (outlined in chapter 1; section 1.5) and in answering the research questions (outlined in Chapter 2; section 2.13), it is vital first to develop and follow a well-chosen and justifiable research strategy and methodological process. Research is conducted based on some assumptions on the researcher's perception and understanding of the world (Trochim and Donnelly 2001). The assumptions are usually guided by the research focus area or scope (McCusker and Gunaydin 2015) and the theme under investigation (Remenyi et al. 1998, Sukamolson 2007). In addressing the research questions, frameworks employed must also be guided through perspectives of research philosophies (Kumar 2019).

In the subsequent sections of this chapter, a discussion of the research philosophy that underlines the methodological framework of the study is presented in addition to the research strategy employed. It is impossible to exhaustively discuss all the research methodological themes because of the broad and interdisciplinary nature of the research topic, especially given the wide range of diverse views from various researchers. In view of this, the chapter focuses on the aspects of methodological framework that is unique and relatable to the current research.

3.2 Research philosophy and paradigms

Research philosophy reflects how a researcher views knowledge source (Holden and Lynch, 2004). This section discusses the different philosophical stands in research and the chosen research philosophy that specifically applies to this study. The research philosophy selected justifies the choice of research design, research approach and data collection in the study.

3.2.1 Ontology and Epistemology

In broad terms, research philosophy can be viewed from two perspectives, that is ontology and epistemology (Greene et al. 2008). The philosophical grounds that helps us understand what a researcher constitutes as knowledge (Crotty 1998) and how this knowledge is acquired legitimately is known as epistemology (Maynard 1994). Put differently, epistemology is concerned with the idea of how we know what we know and also establishes a link between the researcher and the knowledge acquired (Creswell and Creswell 2017).

Ontological position, on the other hand, reflects the researcher believes and interpretation about what constitutes a fact either from an objective or subjective point of view (Saunders, Lewis et al. 2003). Ontological objectivity is when the research is independent of the social phenomena being studied whereas, with ontological subjectivity, the researcher is involved and is therefore subject to individual's biases and feeling (Creswell and Creswell 2017, Tuli 2010). In this study, the researcher assumes an ontological objectivity position. This is because the study of ERW supply chain sustainability is independent of the researcher conducting the study and therefore any potential biases are significantly reduced.

3.2.2 Positivism, Interpretivism and Pragmatism

In this section, the different philosophical positions and their implications in research are discussed. Positivism and Interpretivism are two main popular types of philosophical positions in research. Positivism and Interpretivism can be described as being at opposite ends of the research philosophy paradigm with most studies falling broadly under either of these two. Whereas positivism is geared towards objective and quantifiable analysis, Interpretivism borders on subjectivity and deals more with qualitative data (Saunders et al. 2003, Bryman and Bell 2015).

Positivist researchers believe that knowledge acquired by observation and which can be measured is acceptable as reliable fact. In positivist studies, the researcher is expected to be independent in carrying out an objective analysis based solely on observable facts with no human interest involved (Bryman and Bell, 2015). Research that borders on generalizations and replicability based on quantifiable or measurable phenomena are often aligned with the positivist approach (Saunders et al., 2003). However, this perspective of the positivist approach also gives rise to criticism. Critics argue that the assumption that things can be quantified presents a situation where any unquantifiable phenomena is left unexplained, thus eliminating critical thinking to some extent (Creswell and Creswell, 2017).

Interpretivism, on the other hand, was proposed as a critique of the limitation of positivism as it integrates human interest in the social phenomena being studied (Saunders et al., 2003). According to this philosophy, there is no delink between the researcher and the social entities or research subjects. The use of interviews is a popular data method applied in interpretivism studies. However, the interpretivism philosophy is not without its limitation; the commonly cited limitation being that the reliability of the study is mostly impaired by personal interest and bias of the researcher and in addition, primary data in such studies cannot be generalised and thus may not be representative (Saunders et al., 2003).

The choice between the two traditional philosophies (positivism and Interpretivism) limits researchers to conduct either quantitative research in the case of positivism or qualitative research in the case of Interpretivism. These two extreme philosophical positions can be viewed as potentially delimiting and therefore, a philosophy that provides a middle ground is argued to be a more practical approach. One such philosophy is the pragmatism philosophy which makes it possible to integrate both the positivism and Interpretivism approach within a study (Morgan 2007, Saunders et al., 2003). The underlying philosophy of pragmatic research is that research can be undertaken from different methodological approach, and thus the use of the mixed methods approach is usually characteristic of this philosophy (Morgan, 2007).

3.3 Research Approach and Methods

There are three main research approaches: deductive, inductive, and abductive. The differences in the approaches can be seen in relation to theory development (Bryman and Bell, 2007). Deductive approach, for example, starts with a general to a specific phenomenon and usually leads to acceptance or falsification of existing theory (Saunders et al., 2003) and aligns with the positivist philosophy. Inductive approach, on the other hand, starts from the study of a specific to a general phenomenon and leads to the formulation of a new theory (Saunders et al., 2003) and aligns with Interpretivism. Abductive approach uses a mix of both general and specific and can lead to modification of existing theory and is associated with pragmatism philosophy.

Research approach also be based on two main classifications, that is an Empirical Research Approach or Non-Empirical Research Approach. The Empirical research approach mainly involves evidence-based research gathered through systematic observation and in contrast, Non-Empirical research approach is evidence-based research gathered through reflection and personal observation (Dan 2017). According to Dan (2017), in the past, empirical methods has been aligned with primary data collection and analysis. However in current times, the use of secondary data analysis are also considered empirical (Kenyon et al., 2016). The current study adopts an Empirical Research Approach using secondary data analysis and within this, the study further adopts a Quantitative research method in line with a deductive approach.

3.3.1 Quantitative research

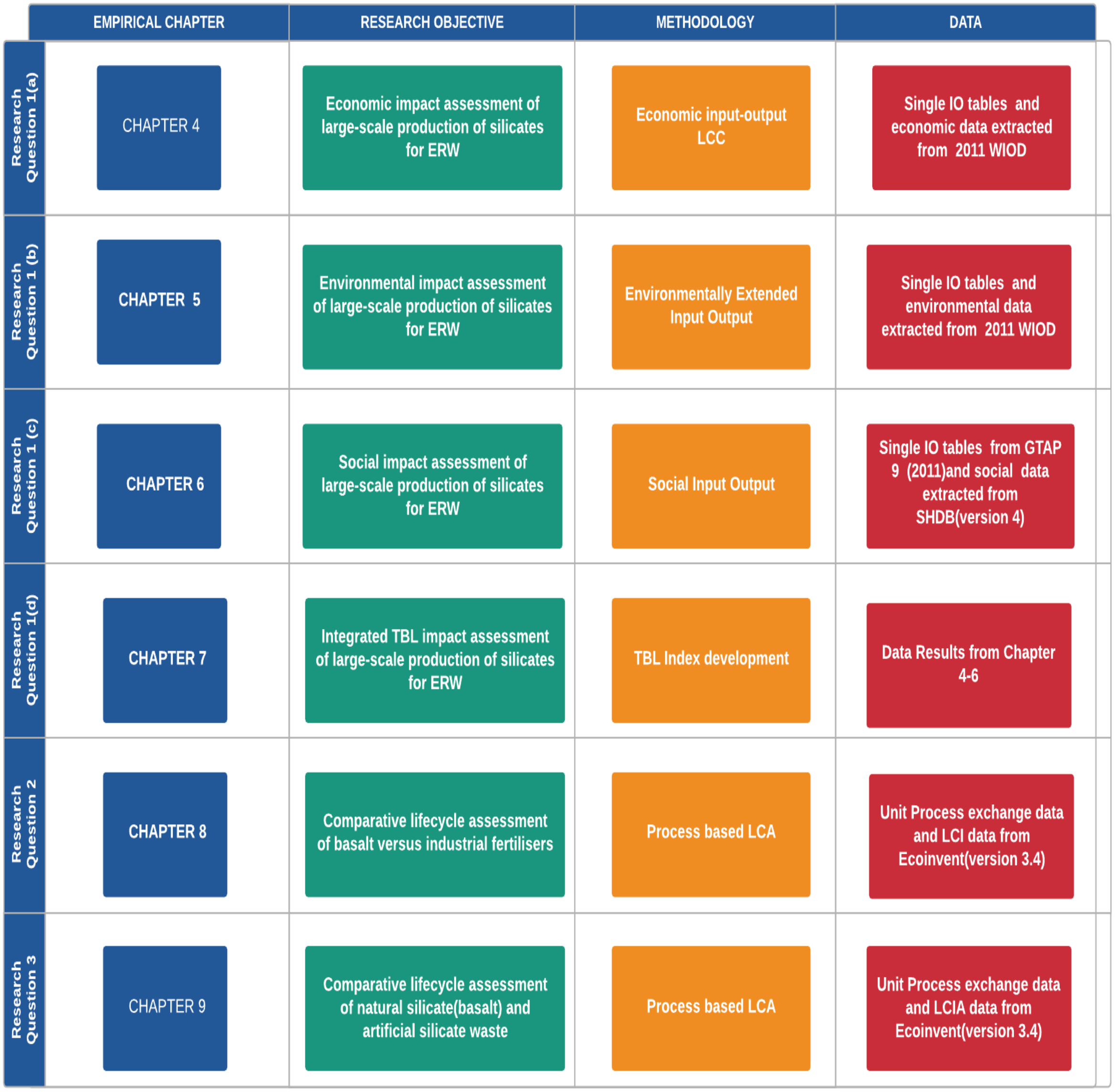
Quantitative research relates to studies that involves estimating, measuring or enumerating things (Saunders at al, 2007). This type of research is usually aligned with the positivist and ontological perspective since it adopts the use of scientific and logical approach to conducting studies (Creswell and Creswell, 2017). Data in quantitative research is numerical in nature and is geared towards testing specific theories (Bryman and Bell, 2015). Research questions formulated in quantitative research identify variables that can be modelled using mathematical equations. It establishes causal relationships among variables and provides insights into the possible inter-connections that exist (Sukamolson 2007).

Creswell and Creswell (2017) relates a deductive approach to research with quantitative research. Accordingly, the research philosophy underpinning the study stems from the positivism philosophy and in line with that a deductive approach is chosen for the research strategy. More on the research strategy employed in the study are discussed below.

3.4 Research strategy employed in the study

This section presents an overview of the data collection and analyses adopted in the current work and the justification for this strategy based on the appropriate and chosen research philosophy (positivism) and approach (deductive) discussed in previous sections. The central aim of this research, which is to quantify the TBL impacts of ERW, requires a detailed quantitative analysis of secondary data. Secondary data is used since ERW is still in the early stages and limited pilot field studies exist where primary data can be collected. Based on the use of the quantitative methods approach, a positivist position is chosen as the appropriate research philosophy for this study. The critical use of quantitative methods in the study allows for quantitative analysis of the ERW supply chain in capturing the associated potential environmental, economic, and social impacts.

An overview of the specific methodology applied in assessing the triple bottom line impacts are considered briefly in the following sections of the chapter but in more detail in the method and data section of relevant analysis chapter where they are used.



	EMPIRICAL CHAPTER	RESEARCH OBJECTIVE	METHODOLOGY	DATA
Research Question 1(a)	CHAPTER 4	Economic impact assessment of large-scale production of silicates for ERW	Economic input-output LCC	Single IO tables and economic data extracted from 2011 WIOD
Research Question 1 (b)	CHAPTER 5	Environmental impact assessment of large-scale production of silicates for ERW	Environmentally Extended Input Output	Single IO tables and environmental data extracted from 2011 WIOD
Research Question 1 (c)	CHAPTER 6	Social impact assessment of large-scale production of silicates for ERW	Social Input Output	Single IO tables from GTAP 9 (2011)and social data extracted from SHDB(version 4)
Research Question 1(d)	CHAPTER 7	Integrated TBL impact assessment of large-scale production of silicates for ERW	TBL Index development	Data Results from Chapter 4-6
Research Question 2	CHAPTER 8	Comparative lifecycle assessment of basalt versus industrial fertilisers	Process based LCA	Unit Process exchange data and LCI data from Ecoinvent(version 3.4)
Research Question 3	CHAPTER 9	Comparative lifecycle assessment of natural silicate(basalt) and artificial silicate waste	Process based LCA	Unit Process exchange data and LCIA data from Ecoinvent(version 3.4)

Fig 3.1 Overview of methodology and data used for analysis chapters

3.4.1 Lifecycle Costing and data source

Aside insights into the environmental consequences of different product alternatives which is provided by the LCA method, the economic value or cost associated with these product options must also be considered for effective decision making (Gluch and Baumann 2004). However, the current LCA method as it is, lacks the ability to evaluate or address the economic cost of products. For this reason, the decision making on alternatives based purely on the environmental advantage that one has over the other is limited and lope sided when the LCA method is used exclusively without consideration for economic cost. To put the environmental results into perspective for effective decision-making, traditional economic cost analysis can be integrated into the LCA method (Heijungs et al. 2013). This approach allows for trade-offs between the environmental and economic performance of the different product options being considered.

In this study, Life Cycle Costing is used for economic sustainability assessment of ERW supply chain. Life Cycle Cost (LCC) assesses the cost-effectiveness of alternate decisions or business decisions from the viewpoint of an economic decision-maker (Norris 2001). In LCC, the cost and benefit monetary flows that impact the decision-maker are considered. Studies that have used LCC has mostly implemented the method for firm-level assessment of products from a micro-level perspective. However, in this study, the macro-level economic assessment of the production of silicates for ERW is carried out using lifecycle costing (LCC) assessment based on the widely accepted economic input-output method.

Studies that have used LCC has mostly implemented the technique for firm-level evaluations of products. Examples of these studies include Lindemann et al (2012), Delucchi and Lipman (2001) and Xu et al (2006). However, the use of LCC in these studies is influenced by the aim of their research which is to extend process-based lifecycle assessment (LCA) by including the economic sustainability pillar. Since one of the research objectives of the thesis is to perform a macro-level analysis, the LCC method must be extended with indicators to cover economy-wide impacts by using an economic input-output framework (Kucukvar et al, 2014). The data on economic indicators are sourced from World Input Output Database (WIOD). The analysis is presented in Chapter 4.

3.4.2 Environmental Lifecycle assessment and data source

Supply chains can be better understood through life cycle assessment because it enables the identification of production processes such as energy, resource, and pollution which businesses can then use for decision making and trade-off analysis. One of the main objectives of this research is to analyze and compare the environmental impacts associated with the ERW supply chain. The environmental impacts are conducted following the three research objectives outlined in the study.

I. **Research Objective 1**: Country and sector level environmental impacts of basalt production for ERW from developed countries (USA, United Kingdom, France, and Germany) and emerging countries (Brazil, Russia, India, and China) are estimated in Chapter 4. The rationale for choosing these countries as previously stated in Chapter 1, is to highlight the fact that these economies represent high GHG contributors in the global crises of climate change. Consequently, the adoption of climate change mitigation interventions, including ERW in such countries, could potentially reduce global emissions. However, as continually reiterated throughout this study, it is vital to highlight the potential environmental impacts in ERW implementation in these economies.

II. **Research Objective 2**: Basalt dust fertiliser versus conventional and industrial Phosphate and Potassium-based fertilisers, namely Triple superphosphate, Single superphosphate, Potassium Hydroxide, Potassium chloride and Potassium carbonate. This analysis is presented in Chapter 8.

III. **Research Objective 3**: Natural silicate(basalt) versus artificial silicates (steel slag, coal ash and cement kiln dust). This analysis is presented in Chapter 9.

Research objectives 2 and 3 follow a comparative LCA style study. This strategy is chosen to highlight the trade-offs between enhanced weathering and the current competing systems in place such as fertilisers which are already being used by farmers (Garcia et al.,2020) and artificial silicates which are also being used for CO_2 sequestration (Renforth,2012).

For the comparative LCA studies, the process LCA methodology is used. Since the analysis is a comparative study, indirect impacts, which are estimated using the environmentally extended input-output methodology, are assumed to cancel out. On the other hand, the environmentally extended input-output methodology is used for research objective 1. Some limitations of the process based LCA is that it is time consuming and also subjected to system boundary problem which arises because it impossible to include all inputs of a product system and therefore the system is truncated at a point Nevertheless, this traditional LCA method is still used in many studies because it provides accurate analysis of potential environmental impacts (Lenzen and Crawford 2009).

Data Source: The macro-level TBL impact assessment requires the use of models that captures inter-connections and transaction at the sector level. Input –Output (I-O) databases are considered suitable for such macro-level economy analysis as they contain data on inter-sectoral monetary transactions, final demand, imports and exports within an economy or country (Nooori et al., 2015; Kitzes, 2013; Gallego et al., 2005). Examples of I-O databases include Global Trade Analysis Project (GTAP), World Input-Output Database, EORA and EXIOBASE. The choice of specific I-O database depends on the objectives of the study and the available data suitable.

For Research objective 1, single country I-O tables were extracted from WIOD (2013 version) which contains data on 40 countries and 35 sectors between 1995-2011. The WIOD also contains data on environmental outputs such as GHGs, energy use, water, material use, acidification, and eutrophication potential.

Emissions data for the fertilisers (Research objective 2) and artificial silicates (Research objective 3) were sourced from secondary lifecycle inventory (LCI), specifically the

Ecoinvent database. The Ecoinvent database is a widely used source containing lifecycle inventory and impact on the inputs and outputs for large number of products and services. The data is regularly updated at consistent periods when new data becomes available.

3.4.3 Social lifecycle assessment and data source

For assessing the social sustainability of ERW, the social lifecycle assessment is used. As explained earlier in Chapter 2 literature review section, there is no consensus on an agreed and widely accepted methodology for SLCA. Therefore, this area leaves room for valuable research contribution. Given that, the study makes a research contribution on SLCA methodologies through an extended input-output methodology to capture social impacts. The method is referred to in this study as social input-output method or simply as the SIO method.

Data Source: Data on social impacts for quantifying impacts is made possible through the social hotspot database (SHDB) created by New Earth B Enterprise(Benoit-Norris et al. 2012). The SHDB contains data on six major themes including Labour Rights and Decent work, Human rights, Human Health, Governance, Community Infrastructure and Socio-economic contribution. In addition, it has over 140 indicators across the six social themes. Data in SHDB is provided at the country and sector level in line with the Global Trade Analysis Project (GTAP) which is also an I-O database containing 57 sectors.

3.4.4 Integrated TBL assessment and data source

To allow for some comparison between social, economic and environmental trade-offs in ERW, the same group of countries are used namely USA, United Kingdom, France and Germany for developed countries and Brazil, Russia, India and China for emerging countries in the integrated TBL assessment. In this way, we can assess the trade-offs among the three sustainability pillars and determine. For example, a country may perform better economically or environmentally but potentially perform relatively worse socially. Sustainability indices are developed for the integrated TBL assessment using data from the individual TBL analysis, and they are presented in Chapters 7. Data for the integrated TBL assessment is based on the results from the individual or single TBL factors evaluated.

3.5 Chapter summary

The research methodology section presented a detailed discussion concerning the research philosophy, research approach and research design employed in the study. Also discussed were the types and sources of data used and how these were analysed. Finally, the theoretical underpinnings of the research that informed the methods used in the study are discussed. To answer the research questions identified, the next six empirical chapters of the study (Chapters 4-9) presents an analysis and discussion of results based on the application of the quantitative methods discussed in section 3.5 of this chapter.

CHAPTER 4 - ECONOMIC IMPACT ASSESSMENT OF LARGE-SCALE SILICATE (BASALT) PRODUCTION FOR ENHANCED ROCK WEATHERING

4.1 Introduction

Research on ERW so far has focused on the technical aspects that is, the carbon dioxide removal (CDR) potential of the technology which has been extensively covered in the literature section of this thesis. The missing element in these studies, however, is the understanding of the supply chain sustainability impacts that are potentially generated as a result of the large-scale silicate production for ERW purposes. This research gap remains the central theme and focus of the current thesis. The need to conduct sustainability assessments associated with ERW in addition to the technical potential of the technique remains a relevant research gap which has been acknowledged in the literature by several authors (Renforth 2012, Moosdorf et al. 2014, Smith et al. 2016, Taylor et al. 2016). In this chapter, the economic pillar of sustainability, specifically with regards to the large-scale production of the crushed silicates, is investigated.

It is worth mentioning that some economic assessment of ERW has been conducted in the literature mostly on the economic cost involved (Schuiling and Krijgsman 2006, Smith et al. 2016, Strefler et al. 2018, Strefler et al. 2015). It is clear however from a review of these studies that the approach used in their economic cost assessment is performed from the micro and firm-level, and so they do not include the knock-on economic cost associated with indirect inputs from other sectors that could result from such large-scale production of silicates. For instance, Strefler et al. (2018), perform a techno-economic assessment using selected economic assessment reports of open-pit mines to assess investment and operation cost associated with mining and grinding of the rocks. Although such micro-level evaluations are essential, it is also critical, especially in terms of policy formulation on ERW that macro-level assessments are carried out if ERW is to become a large-scale climate mitigation initiative. The economic sustainability of enhanced weathering is understudied at macro-level scales, and so its broader implications are not well understood.

The aim of this chapter is to introduce a macro-level economic assessment of the production of silicates for ERW by carrying out lifecycle costing (LCC) assessment using the widely accepted economic input-output method. Studies that have used LCC has mostly implemented the technique for firm-level evaluations of products. Examples of these studies include Lindemann et al. (2012), Delucchi and Lipman (2001) and Xu et al (2006). However, the use of LCC in these studies is influenced by the aim of their research which is to extend process-based lifecycle assessment (LCA) by including the economic sustainability pillar. For instance, in the study by (Heijungs et al. 2013), the authors develop a matrix-based computational method that integrates LCC with LCA method at the firm level. Norris (2001) proposes the use of a software tool called the Total Cost Assessment (TCAce) that is used for estimating both direct costs such as labour, raw material, capital investment and indirect cost such as O&M cost. The TCAce software tool estimates both the direct and indirect cost alongside environmental cost associated with the manufacture of different product alternatives. The integration of LCA and LCC has also been used for the development of an eco-efficiency measure for new product introduction in a study by Yang and Song (2006). However, Swarr et al. (2016) acknowledge that one limitation in integrating LCC with LCA is the cut-off criteria which implies cost incurred by other actors in the product supply chain is not accounted for.

Therefore, since the aim of this chapter is to perform a macro-level analysis, the LCC method must be extended to cover economy-wide impacts. This is particularly important as the production of crushed silicates which mostly takes place in the mining and quarrying sector, requires inputs from other sectors within an economy. Subsequently for complete assessment, it is vital that these feedbacks are captured. The use of direct inputs in the sector such as blast explosives for mining and energy for grinding the rocks is expected, but it is impossible to include and analyze all the possible direct inputs. Furthermore, there is limited information concerning the indirect inputs and processes that take place beyond a single quarry firm that produces crushed silicate rocks. These will take place at different supply chain tier levels, and therefore it is challenging and time-consuming to estimate economic impacts at all the tiers; what is commonly referred to as the upstream impacts (Acquaye et al. 2011, Bode and Wagner 2015). The economic input-output (EIO) method allows for these sectoral interactions and upstream impacts to be captured in the economic analysis and therefore offers a more comprehensive assessment.

In the current chapter, the LCC based on the EIO method is used similarly in studies by (Egilmez et al. 2013, Kucukvar et al. 2014, Hayami et al. 2015, Noori et al. 2015). In the literature, these studies have mainly conducted various sustainability analysis, including economic impacts from a macro-level perspective using input-output tables. In the study by Kucukvar et al (2014), EIO model is used to estimate GDP contributions of various sectors associated with the final consumption and investment within the US economy. In their study, Noori et al., (2015) integrated economic measures including imports, business profits and government tax to estimate the economic impact of wind energy alternatives. The use of the EIO model for sustainability assessments in these studies makes it possible to estimate the direct and indirect economic effects associated with a product supply chain to be accessed, therefore eliminating the cut-off or system boundary problem associated with the traditional firm-level LCC model.

In the above examples of studies, the authors use key economic indicators including GDP contribution, gross operating surplus(GOS) and imports which they obtained from input-output databases and merged these indicators in an EIO model. (Noori et al. 2015; Kukuvar et al., 2014). The GDP indicator reflect the value of goods and services in a country while the GOS indicator reflects the available capital to enable sectors pay expenses such as tax and creditors debt. A high GDP and GOS contribution is considered positive for the economy. Imports on the other hand, is viewed as a negative indicator because it reflects that an economy pays more for inputs from other economies to use in domestic production (Kucukvar et al. 2014). In this chapter, these three economic indicators (GOS, GDP and imports) are used in addition to two others, namely employee hours worked and employee compensation.

National policy decisions on climate change mitigation is largely influenced both directly and indirectly by academic research and therefore the unique national circumstances of countries must also be reflected in such research (Larkin, Kuriakose et al. 2018). The implementation of ERW will differ from country to country, consequently the research should aim to provides insights into how the different countries are impacted economically. Although countries differ, some similarities allow for classification. For instance, ERW in a developed economy such as the United Kingdom or Germany may differ from an emerging economy such as Brazil or China. For this reason, the study focuses the analysis by selecting countries from these two groups of countries that are emerging economies and developed economies.

Overall, eight countries are selected; four from emerging economies (Brazil, Russia, India, and China or also referred to as BRIC nations) and four from the developed economies (USA, UK, France, and Germany). The rationale for choosing these countries is based on two main reasons. Firstly, they form part of the top emitters of GHGs globally (Nejat et al. 2015). Secondly, evidence from previous studies suggest that economic growth in these countries have mainly been associated with an increase in global emissions (Fankhauser and Tol 2005, Tamazian et al. 2009, Pao and Tsai 2010, Knight and Schor 2014). It is therefore expected that such countries are most likely to lead the fight against climate change by adopting climate change mitigation strategies which may include enhanced weathering. In addition, wide-scale implementation of ERW like other climate change mitigation efforts will have to be reflective of national circumstances (Winkler et al. 2006), therefore selecting countries from both emerging and developed economies allow for effective climate policy formulations and decisions for countries with similar national circumstances.

In the subsequent segments of this chapter, first, a comprehensive discussion on the methodology and data source are presented. Next, an analysis of various results on the economic impacts associated with the emerging and developed economies across five economic impact categories; GDP, GOS, imports, employee hours worked and employee compensation.

4.2 Methodology and Data

4.2.1 Input-Output (IO) framework

To capture economy-wide impacts based on the sectoral inter-connections that exist in production (Gallego and Lenzen 2005, Hayami et al. 2015, Camanzi et al. 2017), the research method employed must encapsulate such a framework. As stated in the introductory section of this chapter, economy-wide impacts associated with large-scale production of silicates extends beyond the firm level (that is a single quarry business) due to the inter-dependencies of firms on one another for production. Collecting site-specific data throughout a supply chain would be a time, and cost-prohibitive endeavour (Rebitzer and Hunkeler 2003). When a bottom-up, firm-level data collection approach is used exclusively, there would be cut off or boundary problem (Swarr et al., 2011) because very few companies in a supply chain can be fully assessed.

A preferred top-down approach is the use of an input-output method which makes it possible to capture impacts from extended supply chains (Richardson 1985, Leontief 1986). This is not to suggest that the bottom-up approach is not useful as it offers excellent detail and in-depth view of impacts at the firm level that may be lost through the aggregation of impacts which usually occurs in macro-level analysis such as the input-output method. However, in studies such as this current thesis where the aim is to provide insight into economy-wide impacts associated with production (mining and crushing) of silicate rocks for ERW purpose, the use of the bottom-up approach is inappropriate.

The principle of Input-Output(I-O) analysis was established by Wassily Leontief (1936); a Nobel Prize winner in economics. The framework is based on the structure of the economy in which flow of resources (products and services) recorded as monetary transaction usually in US dollars or other national currencies depending on the source of data. The I-O model is based on inter-sectoral transactions. In various studies (Hauknes and Knell 2009, Guo and Murphy 2012, Chen et al. 2017), inter-industry transactions are used interchangeably with the inter-sectoral transaction, and the same implication is inferred in the current study.

Industries use the products of other industries to produce their products (McNerney et al. 2013). For example, the mining and quarry industry may rely on inputs from other sectors such as electricity and gas sector in order to produce primary aggregates including crushed silicate rocks. The general idea here is that a sector's output of say electricity then becomes an input for the mining and quarrying sector. This implies that an increase in demand for crushed silicates subsequently results in an increase in the electricity and gas sector. These inter-connections are captured in I-O tables which are national accounting data usually compiled by statistical agencies in a country (McNerney et al. 2013). In the I-O table, this inter-industry relationship is known as Intermediate consumption (Z). Other parts of the I-O table show the Final demand(Y) of commodities by households, governments, investment, or exports and the Total Output(X) of a sector.

The relationship between Intermediate consumption (Z), Final demand (Y) and Total output (X) is given by:

$$\mathbf{Z + Y = X} \xrightarrow{\qquad\qquad\qquad\qquad} \textbf{Equation 1}$$

A technology matrix also commonly referred to as the A matrix, is constructed to show the input required to produce a unit output between the sectors. *also known as a matrix of direct requirement.* It is t also known as the direct requirement matrix since the emphasis is on the direct inputs from one sector to another required for production.

Technology Matrix (A), is given by:

$$\mathbf{A} = \frac{\textbf{Intermediate consumption}}{\textbf{Total output}} = \frac{\mathbf{Z}}{\mathbf{X}} \xrightarrow{\qquad\qquad} \textbf{Equation 2}$$

We know from Equation 1 that

$$\mathbf{Z + Y = X}$$

And from Equation 2

$$\mathbf{A} = \frac{\textbf{Intermediate consumption}}{\textbf{Total output}} = \frac{\mathbf{Z}}{\mathbf{X}}$$

$$\therefore \mathrm{Z} = \mathrm{AX}$$

Then $\mathrm{AX} + \mathrm{Y} = \mathrm{X}$

So that $Y = X(1 - A)$

But A is a matrix, therefore

$$Y = X\ (I - A)$$

Where I is an identity matrix. Hence

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \longrightarrow \quad \textbf{Equation 3}$$

$(\boldsymbol{I} - \boldsymbol{A})^{-1}$ in Equation 3 is referred to as the **Leontief Inverse Matrix** or total requirement matrix and it shows cumulative value for both direct and indirect inputs needed in each sector to meet demand for a unit of output. Emphasis is now being placed not just on what goes on within the firm (direct) but on a complete lifecycle assessment such that the upstream impacts which occur in the extended supply chain process are also captured.

4.2.2 Extended Input-Output Framework with Economic indicators

To capture the economic impacts of a product, the I-O analysis can be extended with economic indicators. Five economic indicators are selected in this study namely; Gross operating surplus (GOS), contribution to GDP, and import, employee compensation and hours worked. With the exception of employee hours worked, the other indicators are measured in millions of US dollars. The GDP indicator reflect the value of goods and services in a country while the GOS indicator reflects the available capital to enable sectors pay expenses such as tax and creditors debt (Eurostat 2008, Wiedmann 2009) . A high GDP and GOS contribution is considered positive for the economy. Imports on the other hand, is viewed as a negative indicator because it reflects that an economy pays more for inputs from other economies to use in domestic production (Kucukvar et al. 2014). Employee compensation refers to the total monetary value that employees working in a sector receive. Employees Hours worked represents the total hours worked in each sector for given production output. This indicator is included as it complements the employee compensation in that it provides a realistic indication of how workers are compensated for the hours they put into production.

In this study, GDP, GOS and employee compensation are considered as positive economic impacts based on the assumption these indicators are beneficial to the economy in general. This is because higher GOS and GDP are positive indicators of better livelihood linked to increased employee compensation. On the other hand, imports and working hours are considered negative economic impacts based on the logical assumption that more of these are at a cost to stakeholders. A similar assumption is highlighted in studies by Onat et al. (2014) and Kukucvar et al (2013).

These five economic indicators were selected under the assumptions that the knock-on effects of large-scale production of crushed silicates will impact on the GDP of economies of other firms and sectors for which the mining and quarrying firms depend on for production. The business profits of the firms within these sectors represented by GOS (Onat et al., 2014; Eglimaez et al. 2013), will also be impacted. As most countries are open economies, it expected that the imported inputs for production in the mining and quarrying sector would also be affected. It is also assumed that as demand for crushed silicates increases, employee working hours may potentially increase in addition to employee compensation.

These indicators have been merged with the EIO analysis in studies (Foran et al. 2005, Egilmez et al. 2013, Kucukvar et al. 2014, Onat et al. 2014, Noori et al. 2015) to provide a macro-level sustainability accounting framework using various country I-O tables. For instance, Kucukvar et al. (2013), used economic indicators for their I-O model extracted from US Bureau of Economic Analysis (BEA) and in Foran et al., (2005), the economic indicators are extracted from a 135-sector Australian I-O table. In this current chapter, the data for the economic indicators are extracted from the World Input-Output Database (WIOD); a source of I-O database extensively used in the literature (Timmer et al. 2012, Ibn-Mohammed et al. 2016, Chen et al. 2017, Lu 2017).

Specifically, the 2011 single country I-O tables from the 2013 WIOD version which contains a series of data on 27 EU countries in addition to 13 other major economies is used in this study. Although this is not the current version; the 2016 WIOD version is, the decision to use the 2013 WIOD version allows for a standardised comparison to be made between the TBL factors which are carried out in Chapter 7 of the thesis based on the same year; that is 2011 WIOD for EIO-LCC and EEIO in chapter 4 and 5 respectively, and 2011 GTAP for SIO in Chapter 6. Furthermore, WIOD is the only I-O database that contains a wide range of economic and environmental indicators.

The economic sustainability metrics (GOS, GDP, Imports, Compensation and Hours worked) are introduced into the I-O framework by constructing the 'economic direct intensity matrix' (eDiM) which measures sectoral economic intensities per unit of output produced. The eDiM is calculated by dividing the sectoral output of an economic indicator or metric (GDP, GOS, import, compensation, hours worked) by the sector’s total output which can then be interpreted for example as the GDP per dollar of output or per kg of output produced. The total intensity matrix is constructed as a product of the economic direct intensity matrix, and Leontief matrix also referred to as the multiplier matrix.

Hence the lifecycle supply chain economic impact of a product is represented as:

Economic Direct Intensity Matrix ×Leontief Matix x Final Demand

Or simply as:

$$\boldsymbol{Total\ Economic\ impact = eDiM(I - A)^{-1}Y} \qquad \textbf{Equation 4}$$

4.2.3 Limitations and Assumptions of the EIO Model

The EIO model is based on some assumptions that gives rise to some limitations (Hendrickson et al., 1998 and Acquaye and Duffy 2010). These are explained below:

Homogeneity Assumption and Aggregation: Within the EIO model there is an assumption that a sector use the same or identical inputs to produce its outputs. (Oppon et al, 2018). For instance, within the Metals, Mining and Quarrying sector the homogeneity assumption implies all firms within the sector use the same inputs of electricity or fabricated metals to produce. However, in reality this is not the case as within the sector, there are similar but different output within a sector. For instance, output from primary aggregates may be sand or gravels and not just crushed silicate rocks such as basalt. However, such distinction is lost due to the aggregation of sectors within the I-O databases.

Linear Proportionality Assumption: The linear proportionality assumption exists with the EIO model because the framework assumes that it takes the same quantity of production inputs to satisfy an increase in demand. In other words, there is a fixed ratio in production inputs used in production. However, this is not always the case, because there is the possibility that as demand increases, there could be non-linear increase in production inputs ratios.

Despite these assumptions and related limitations, the use and results from I-O model is still considered valid to a large extent (Hendrickson, 1998) and is advocated for especially in instances where lack of comprehensive or detailed data exist ***(***Tukker and Dietzenbacher, 2013).

4.3 Analysis and Results

In this section, findings of the application of EIO-LCC method for each of the five economic impacts are presented and discussed. For each impact category, the diagrams shown relate to three distinct key findings explained below:

I. ***Impact per kg basalt produced:*** This is the economy-wide impact measured as GDP, GOS, import, compensation and hours worked per kilogramme of basalt produced. The value considers all economic-related impacts due to the sectoral interactions required in the production of crushed basalt, which takes place in the mining and quarry sectors of the selected countries. The relevance of this finding is that it gives policymakers a more holistic view of the potential economic impacts associated with producing basalts for ERW and allows for standardised comparison among different countries.

II. ***Direct and Indirect impacts:*** This finding shows how much of a total economic impact generated is as a result of the direct and indirect purchase of inputs in producing the basalt. As discussed in the method section, the mining and quarry sector relies on direct inputs from other sectors which are accounted for by the matrix of direct requirement, that is the technology matrix. However, the production of these direct inputs also requires inputs not directly related to mining and quarrying of basalt, namely the indirect inputs. The economy-wide impact is a total of these direct inputs and indirect inputs. Consequently, it can be inferred that these results in direct economic impacts and indirect economic impacts. The relevance of this finding is that it indicates whether the production of basalt relies heavily on direct inputs or indirect inputs. It shows where policy should be targeted in addressing economic sustainability impacts; that is whether at the first-tier supply chain where direct inputs are sourced or at the second-tier, third-tier, etc. where indirect inputs are sourced.

III. ***Sectoral Contribution:*** The sectoral contribution to an economic impact shows the percentage contribution of each sector to the total impact associated with crushed basalt production. The relevance of this finding is that it provides an industry or sector level insight and, shows the relevant sectoral hotspots (that is, sectors with relatively high impact). For easy analysis and comparison of the results, the 35 WIOD sectors are aggregated into nine sectors, and a full list is available in the appendix.

4.3.1 Gross Domestic Product (GDP)

In this section, results of GDP potential per kg of basalt ($ per kg) produced in both the developed and emerging economies are presented. The relevance of this result is to show the potential positive addition of GDP to a country or economy generated from the production of crushed basalt for ERW. From Fig 4.1a, the result shows that among the emerging economies, China has the highest GDP potential per kg produced that is ~$15 per kg, followed by India with approximately $6/kg basalt produced. Russia and Brazil have the lowest GDP potential per kg basalt produced, that is, $4.8 and $4.6 respectively. Among the developed economies, both the USA and France have equally high GDP per kg basalt produced that is ~$10/kg followed by Germany, which has $9 per kg produced. The GDP potential per kg produced in the UK, which is $7.4/kg is the lowest among the developed countries. Overall the results show that the developed economies have high GDP per kg basalt produced compared to the emerging economies.

For the emerging economies, from Fig 4.1b results shows that the direct GDP contribution generated per kg unit output in Brazil, Russia and India, that is 58%, 60% and 70% respectively are higher than GDP indirectly generated except for China where the GDP contribution generated indirectly (approximately 58%) is higher than the direct impacts. For the developed economies, the direct GDP per unit output in the USA (70%), the UK (75%) and Germany (60%) are higher than the indirect GDP generated. In the case of France, there is an equal split of 50% each between direct and indirect GDP impacts.

In Fig 4.1c, the sectoral contribution of Quarrying, Metals and Minerals to GDP in both the emerging economies and the developed economies is over 60%, followed by the Services sector. The exception, however, is in China where both the Machinery and Equipment sector and the Services sector have the highest sectoral contribution to GDP approximately 25% each. The Quarrying, Metals and Minerals in China only contribute 10% to GDP.

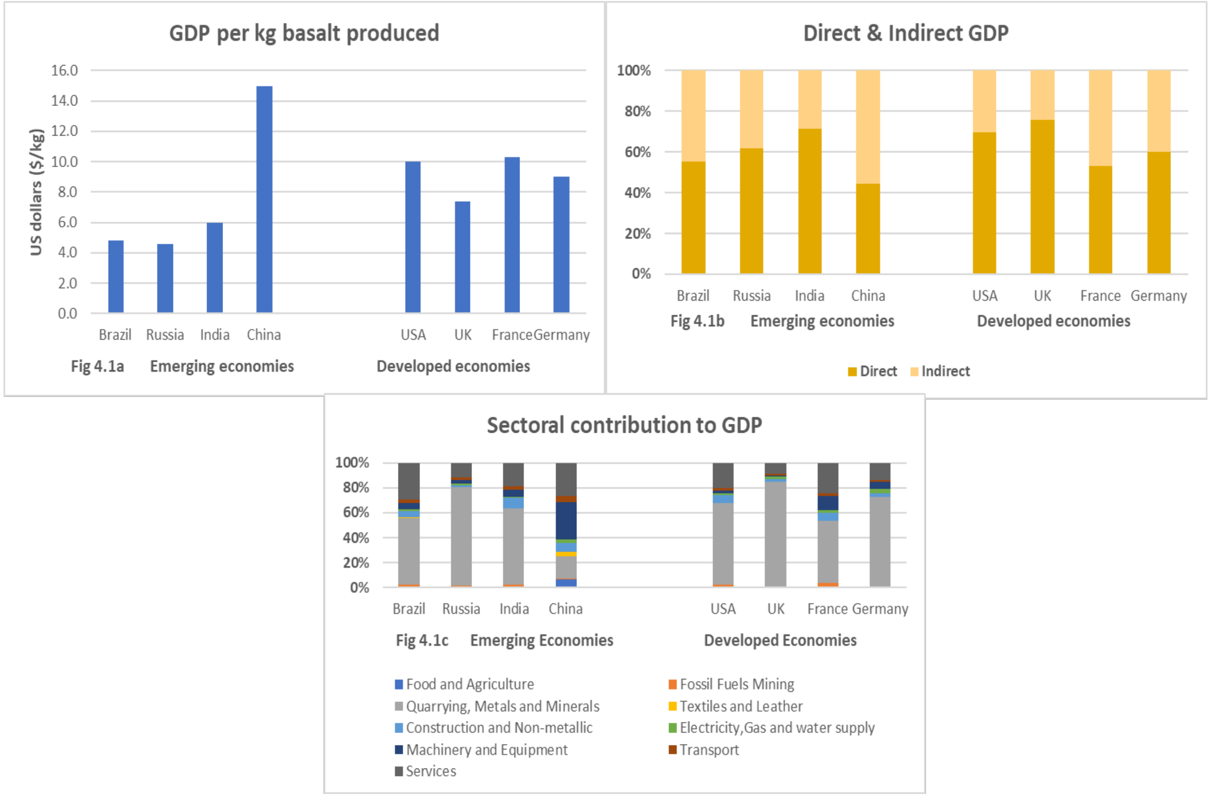


Figure 4.1: GDP per kg basalt produced, Direct & Indirect GDP and Sectoral Contribution to GDP

4.3.2 Gross Operating Surplus (GOS)

In this section, results of GOS potential per kg of basalt produced in both the developed and emerging economies are presented. GOS is an indication of the profits that businesses have after accounting for expenses such as tax and labour payments. The findings of GOS potential per kg basalt produced is relevant in indicating how competitive in terms of potential profit generation a country stands to benefit in large-scale silicate production industry. Findings shown in Fig 4.2a shows that among the emerging economies, China has the highest GOS potential of $6 per kg basalt produced followed by India, which has $4 per kg produced. Russia and Brazil have the lowest GOS potential, that is $2.8 and $2 per kg produced, respectively. For the developed economies, the USA has the highest GOS potential of $6.5/kg, $5/kg followed by the UK, which has ~$4.8 per kg produced. The GOS potential for France and Germany is at similar levels that are approximately $4/kg in $4.2/kg, respectively.

In Fig 4.2b, results suggest that for emerging economies, direct GOS impacts are generated directly especially in the case of Russia (~70%), India (~80%) and China (~55%). However, for Brazil, the GOS impacts occurring indirectly (~54%) are slightly higher than the GOS impact directly occurring (~48%). For developed economies, direct GOS impacts are higher in the USA (~75%) and the UK (80%). In France, there is an equal split of 50% between direct and indirect GOS impacts. For Germany, the direct GOS impacts which are ~58% are slightly higher than the indirect impacts per unit output (~42%).

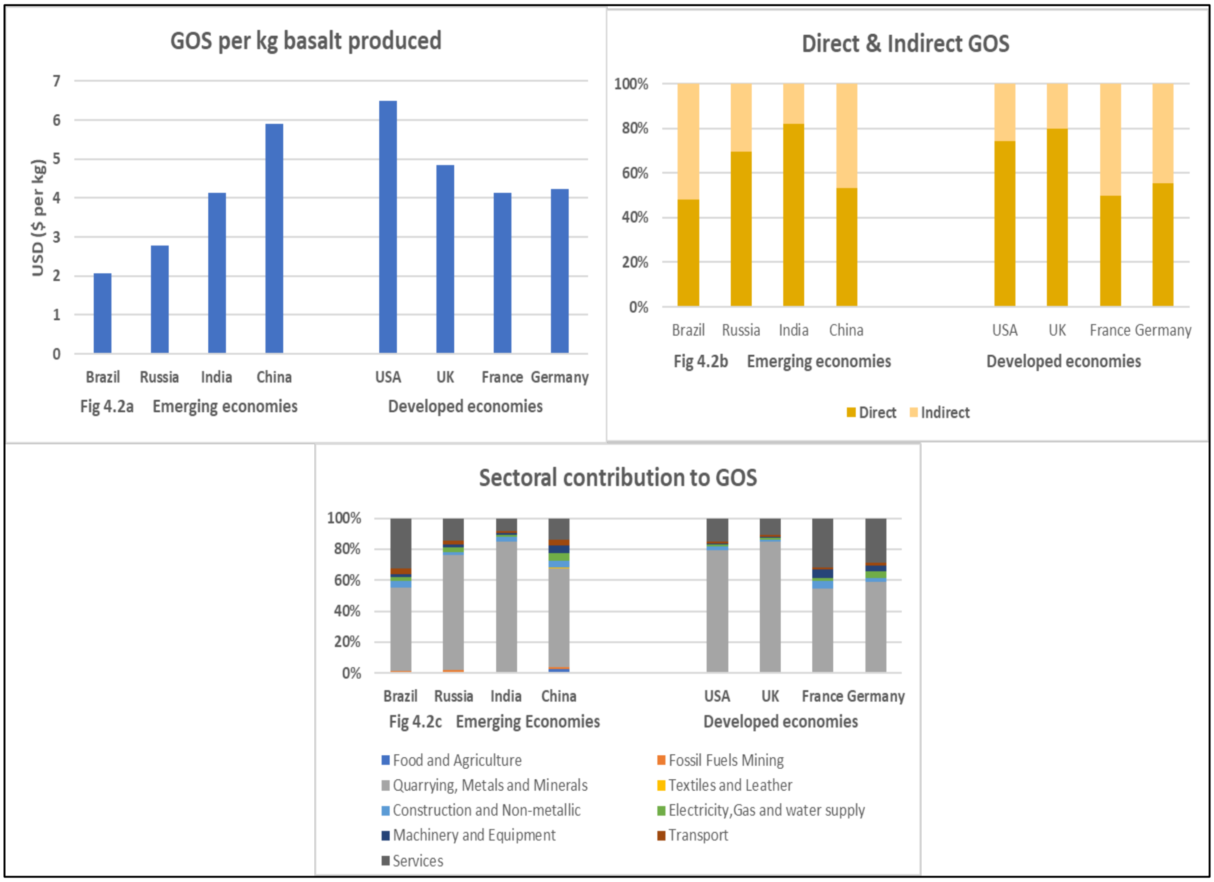


Figure 4.2: GOS per kg basalt produced, Direct & Indirect GOS and Sectoral Contribution to GOS

Sectoral contribution to GOS is dominated by the Quarrying, Metals and Minerals sector across both emerging and developed economies followed by the Services sector (Fig 4.2c). In China, there is some noticeable impact contribution from the country's Electricity, Gas and Water supply, Machinery and Equipment and the Fossil Fuels Mining sector totalling up to 10%. In Brazil, the Services sector contribution to GOS, which is approximately 25% is relatively higher compared to Russia, India and China where the sectoral contribution from their Services sector is approximately an average of 10%. In the developed economies, France and Germany's Services sector has a higher sectoral contribution to GOS relative to USA and UK, that is approximately 25%. Overall, the results show that sectors including Fossil Fuels Mining, Construction and Non-metallic, Electricity, Gas and Water supply have a relatively minimal sectoral contribution to GOS.

4.3.3 Imports

In this section, results of an import per kg of basalt produced in both the developed and emerging economies are presented. With regards to import per kg basalt produced shown in Fig 4.3a, China and Brazil have the highest potential of approximately $0.13/kg and$ 0.12/kg respectively compared to Russia and India which has less than $0.025/kg. This finding implies that the production of a kilogram of basalt in Brazil and China requires more imported inputs than their counterparts in Russia and India. In the case of the developed economies, imports are significantly higher than the BRIC countries (emerging economies). The UK has the highest import per kg basalt produced of approximately $0.32/kg. In the case of Germany and the USA, they also have very high import levels that are $0.2/kg and $0.16/kg, respectively. However, among the developed economies, France has the lowest imports suggesting that the production of crushed silicates relies more on domestic inputs than imported inputs.

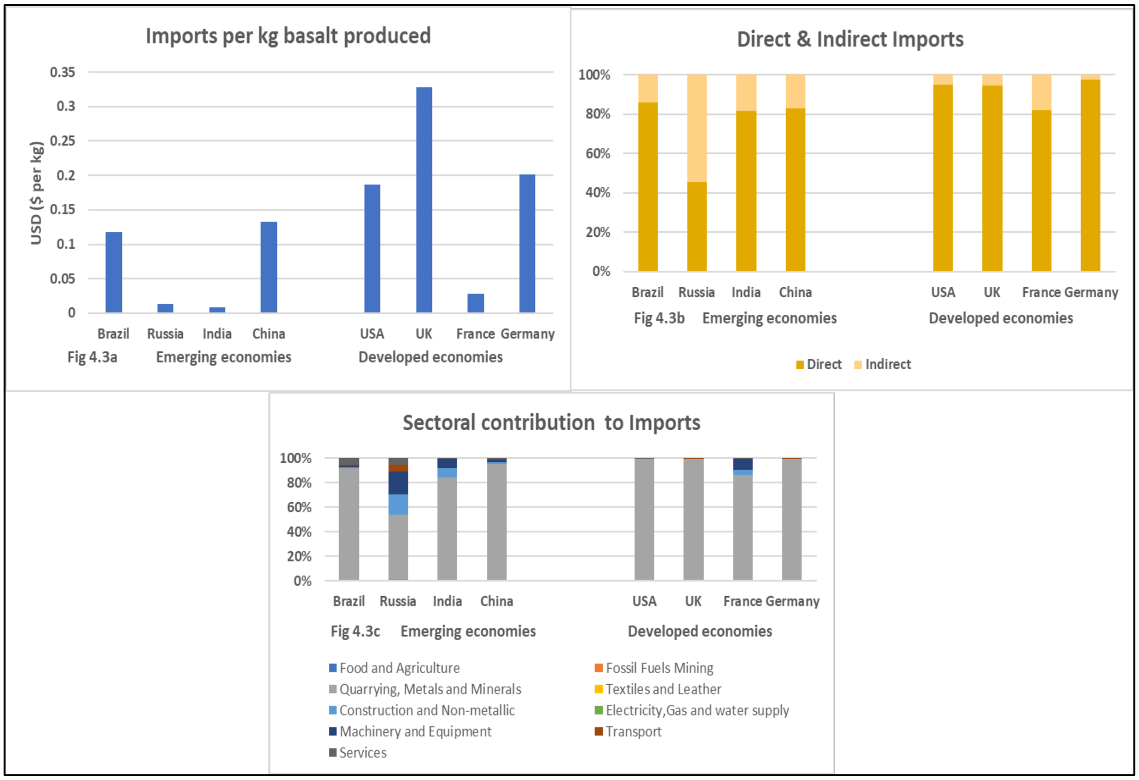


Figure 4.3: Imports per kg basalt produced, Direct & Indirect Imports, and Sectoral Contribution to Imports

In Fig 4.3b, results show that for the emerging economies specifically Brazil, India and China, the proportion of direct imports is an average of 80% except for Russia where it is

45% implying indirect imports are higher than direct imports. For all the developed economies proportion of direct imports to indirect imports is an average of 95%.

In terms of sectoral contribution to imports (Fig 4.3c), within the developed economies, a relatively significant proportion of the impact contribution is attributed to the Quarrying, Metal and Mineral sector. In the USA, the UK, and Germany, averagely 98% contribution to imports comes from Quarrying, Metal and Mineral sector. However, in the case of France, the sectoral contribution from their Quarrying, Metal and Mineral's sector is slightly lower in comparison, that is approximately 88%. In the case of the emerging economies, similar results to developed economies are seen in that the highest sectoral contribution to imports is from their Quarrying, Metal and Mineral sector.

To gain more insights into how imports differ among the countries, results on the mining and quarrying sector specifically are included in this section. Such analysis is also relevant since consumption for silicates is produced from the Quarrying, Metals and Minerals sector(M&Q).

Table 4.1a: Sectoral contribution of domestic inputs for production in the Quarrying, Metals and Mineral sector

	Emerging Economies				Developed Economies			
Sectors	**Brazil**	**Russia**	**India**	**China**	**USA**	**UK**	**France**	**Germany**
Food and Agriculture	0%	0%	1%	1%	0%	0%	0%	1%
Mining (Fossil Fuels)	4%	7%	7%	5%	3%	0%	4%	1%
Quarrying, Metals and Minerals	14%	12%	8%	22%	21%	27%	12%	11%
Textiles and Leather	1%	0%	0%	1%	0%	0%	0%	0%
Construction and Non-metallic	9%	7%	30%	12%	16%	9%	16%	7%
Electricity, gas and water supply	4%	23%	10%	15%	4%	9%	6%	14%
Machinery and Equipment	7%	7%	14%	17%	4%	4%	19%	11%
Transport	7%	8%	9%	8%	7%	7%	2%	7%
Services	54%	37%	22%	19%	45%	44%	41%	48%

For all the developed countries, the most considerable contribution of domestic inputs comes from the Services sector; USA (45%), UK (44%), France (41%) and Germany (48%). This is mainly accounted for by the Renting of machinery equipment and other business activities (see full sector aggregation). The quarrying, metals and mineral sector is the second largest contributor for Brazil (14%), Russia (12%), China (22%), USA (21%) and UK (27%). For India, Germany, and France, only 8%, 12% and 11% of inputs are provided from the M&Q sector, respectively. In the case of Brazil and Russia highest contribution to domestic inputs; 54% and 37% respectively are sourced from their Services sector. For India, the country's Construction and Non-metallic sector provide the highest contribution to domestically sourced inputs. China, however, relies more on their mining and Quarrying sector in terms of domestic inputs representing 22% of the f total value of domestic intermediate consumption.

Table 4.1b: Sectoral contribution of inputs for imported production in the Quarrying, Metals and Mineral sector

	Emerging Economies				Developed Economies			
Sectors	**Brazil**	**Russia**	**India**	**China**	**USA**	**UK**	**France**	**Germany**
Food and Agriculture	0%	1%	0%	1%	0%	0%	0%	1%
Mining (Fossil Fuels)	3%	2%	3%	4%	2%	2%	7%	3%
Quarrying, Metals and Minerals	27%	12%	11%	45%	62%	59%	10%	38%
Textiles and Leather	1%	1%	0%	0%	0%	0%	0%	0%
Construction and Non-metallic	7%	25%	37%	10%	9%	4%	29%	13%
Electricity, gas, and water supply	1%	0%	0%	0%	0%	1%	0%	5%
Machinery and Equipment	16%	35%	42%	28%	11%	11%	41%	20%
Transport	3%	12%	1%	3%	3%	7%	2%	9%
Services	42%	12%	6%	8%	12%	15%	10%	11%

Table 4.1b shows the contribution of sectors to total imported inputs for production. For the developed economies (USA, UK, and Germany), the highest value of imported inputs comes from M&Q sectors of other economies, specifically 62%,59% and 38%

respectively. We see that whereas in the case of domestic inputs where the highest proportion of inputs are sourced from the Service sector, for imported inputs developed economies rely heavily on imports from mining and quarrying sectors of other economies. The exception, however, is in the case of France, where only 10% of imported inputs are from the mining and quarrying sectors of other countries. Most imported inputs for production in France's mining and quarrying sector comes from the Machinery and Equipment sector of other countries.

For the emerging economies, the sectoral contribution of imported inputs widely differs from country to country. For Brazil, the highest imported inputs (42%) comes from the Services sector whereas, for Russia and India, highest imported inputs (35% and 42% respectively) comes from Machinery and Equipment sector. In the case of China, the highest value of imported inputs (45%) for production in their Mining and Quarrying sector also comes from the Mining and Quarrying sector of other economies.

4.3.4 Employee Compensation

In this section, results of employee compensation per kg of basalt produced in both the developed and emerging economies are presented. Employee compensation can be debated as either a cost or a benefit, depending on the stakeholder (Smeeding., 1983). For workers, higher employee compensation is considered good as it promotes welfare and livelihood for workers. On the other hand, for employers and business owners, it can be seen as more of a cost than a benefit as an increase in compensation paid to workers can affect the bottom line profits. However, in this study, employee compensation is considered in the view of workers' economic wellbeing, and therefore is considered a benefit. Such that, countries that pay relatively high employee compensation per kg basalt produced is considered as potentially more economically sustainable.

In Fig 4.4a, the result shows that compensation is highest in China that is ~$2 per kg silicate produced followed by Russia and India with $1.4 and $1.2 per kg silicate produced, respectively. Brazil has the lowest; approximately $0.75 per kg silicate produced. With regards to the developed economies, Germany pays the highest compensation of roughly $3 per kg silicate produced compared to the UK, which has the lowest compensation of $1 per kg silicate produced. The USA and France are at similar levels in terms of compensation that is approximately $2.25 per kg silicate produced. Overall results in Fig 4.4a suggests that compensation is relatively high in the developed economies than in the emerging economies. However, an interesting finding is that Russia, India, and China all potentially pay higher compensation compared to the UK, although the latter UK is a developed country.

In Fig 4.4b, the result shows that proportion of direct to indirect employee compensation is significantly higher in Russia (70%) and India (80%) compared to China (55%) and Brazil (45%). For the developed economies, the proportion of employee compensation in the USA (60%), the UK (55%) and Germany (70%) is higher than in France, which is 40%.

In terms of the sectoral contribution to compensation (Fig 4.4c), the Quarrying, Metals and Mineral sector has the highest contribution in both the emerging economies and the developed economies. For the emerging economies, Russia, India, and China the M&Q sector contributes an average of 80% in these countries while in Brazil sectoral contribution from the Quarrying, Metals and Mineral sector is 50%. Aside from the Quarrying, Metals and Mineral sector, the second-highest sectoral contribution to compensation comes from the Services sector. In the USA, UK and Germany, the sectoral contribution from the Services sector is an average of 20%. France has the highest sector contribution in the service sector of approximately 38%. Overall, the results indicate that across both emerging and developed economies, sectors such as Manufacturing and the Construction and Non-metallic sector have relatively less contribution to compensation.

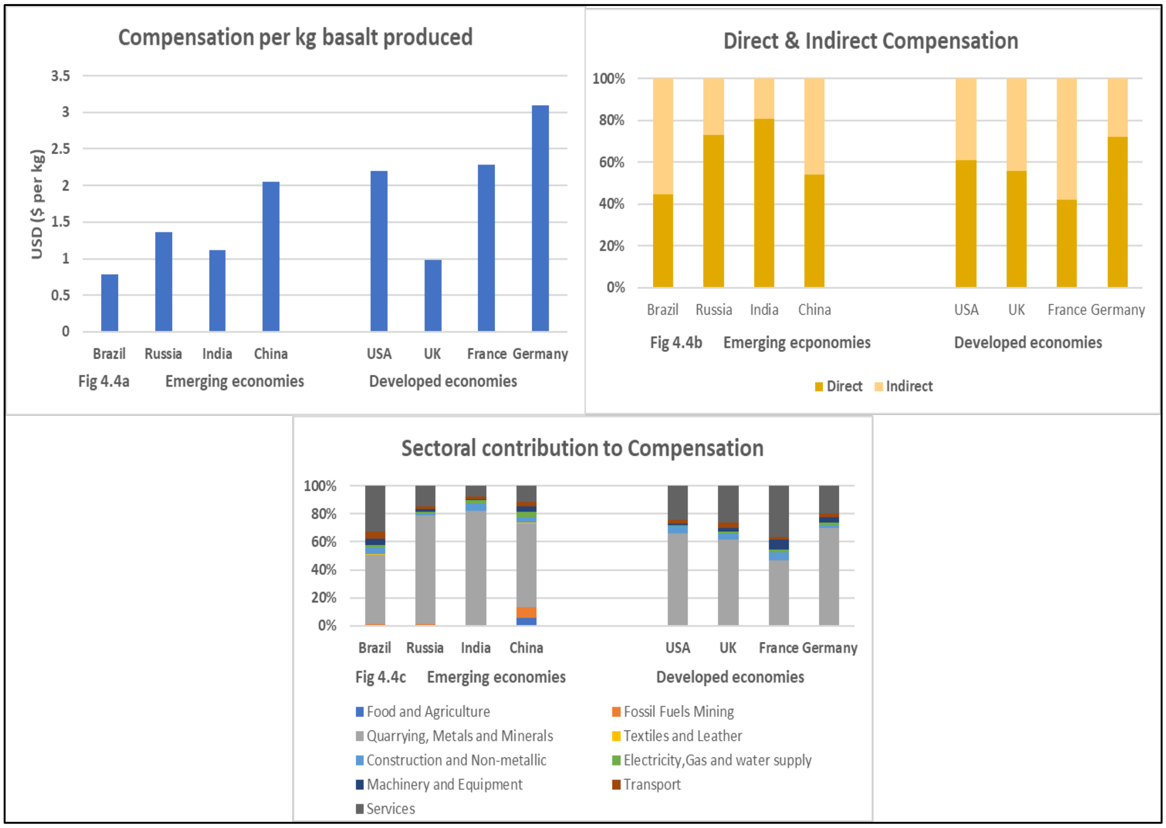


Figure 4.4: Compensation per kg basalt produced, Direct & Indirect GOS and Sectoral Contribution to GOS

4.3.5 Employee Hours worked

In this section, results of hours worked per kg of basalt produced in both the developed and emerging economies are presented. The hours worked in the production of silicates is relatively very low in the developed economies (less than 0.2hr/kg) than in the emerging economies. Two possible reasons could account for this result. Firstly, the low hours worked could be because of relatively higher production technology efficiency in developed economies than in the emerging economies such that less labour is required for production. Secondly, the result could be linked to the fact that the developed economies import more than the emerging economies in the production of the silicates as shown by the relatively high imports shown previously in Fig 4.3a. In the case of the emerging economies, the hours worked per kg in India (~1.2hr/kg), and China (1.15hr/kg) are relatively higher in Brazil and Russia. Comparison between employee compensation paid and hours worked, reveals that whereas the emerging economies have relatively higher hours worked in the production of basalt, their compensation is low compared to developed economies where the number of hours worked is low but the compensation paid is relatively higher.

For emerging economies, indirect hours worked per unit output worked in Brazil (85%), Russia (70%) and China (65%) is higher than direct hours except for India where the proportion of direct hours worked is higher than indirect hours worked per unit output. Comparing hours worked in developed economies we see that for USA and Germany the direct hours worked is higher than indirect; that is 60% each, respectively. However, for the UK and France, the indirect hours worked per unit output is higher than the direct hours per unit output.

In terms of sectoral contribution to hours worked (Fig 4.5c), for Brazil, the Services sector has the highest contribution of 60% followed by the Quarrying, Metals and Minerals sector contributing approximately 20% to total hours worked. In India, Quarrying, Metals and Minerals mineral sector is the highest contributor to working hours which is 80%, followed by the Construction and Non-metallic sector accounting for 10% of total hours worked.

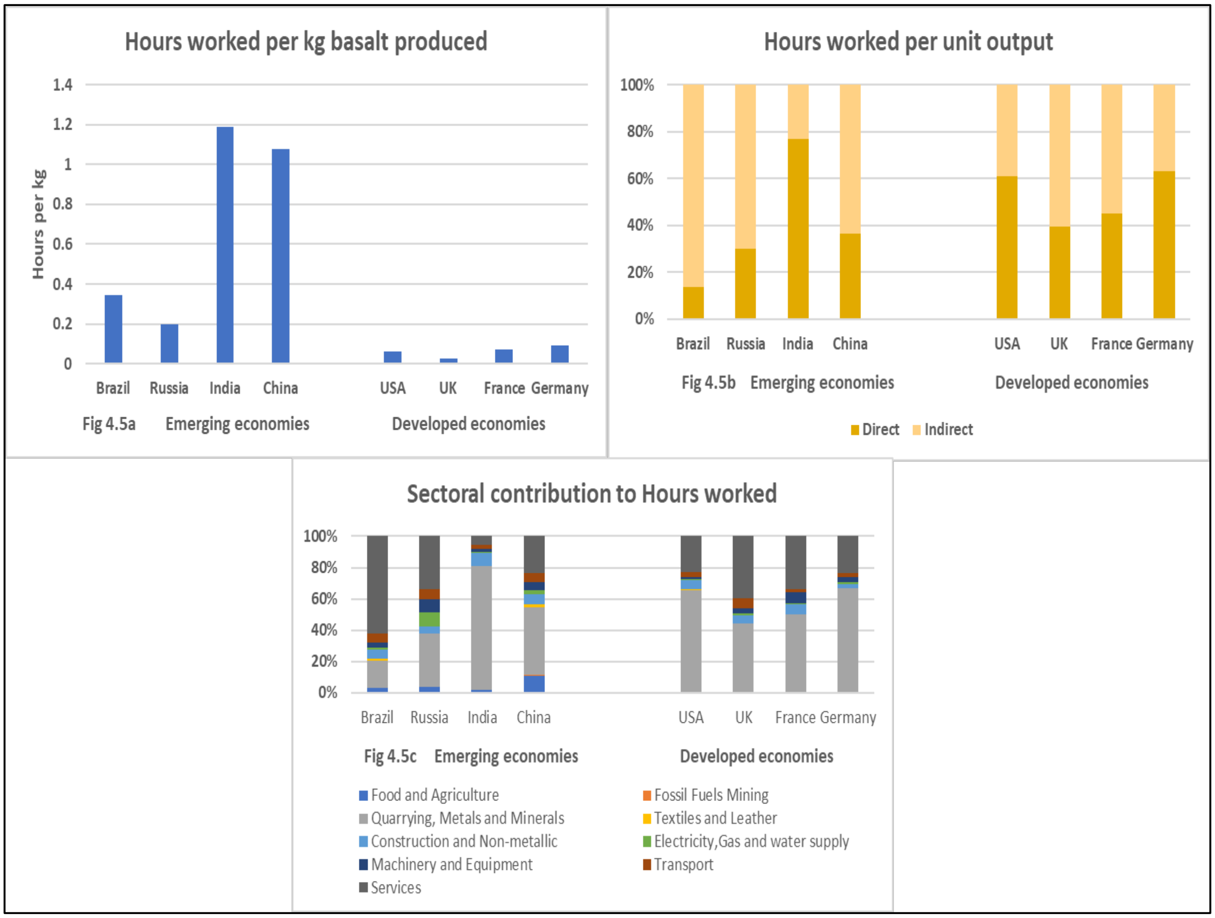


Figure 4.5: Hours worked per kg basalt produced, Direct & Indirect Hours worked and Sectoral Contribution to Hours worked

4.4 Discussion and Conclusion

From the results presented, it is seen that the economies of developed countries analysed stand to benefit more from large-scale basalt production compared to emerging economies. Although results are shown based on a functional unit of a kg basalt produced, such a fundamental analysis can easily be scaled up to see how countries are impacted if production is large scale in the millions of tonnes. In particular, the GDP and GOS are found to be relatively high in these economies despite the results showing that they rely more on imported inputs from other economies. Based on this finding, the results suggest that for these economies, there may be a relatively less economic incentive to rely on domestic input for basalt production since they can still have high positive economic impacts. In China's, however, the situation appears different as they have high GDP and

GOS than USA, UK, France, and Germany. Interestingly China's production depends heavily on imported inputs from other countries.

The focus on intermediate consumption within the Quarrying, Metals and Minerals (QMM) sector shown in Table 4.1a and 4.1b highlights critical patterns in how the different sectors of the economy will potentially be affected economically. Among the two sectors that make up the Quarrying, Metals, and minerals sector, (that is Basic Metals and Mining and Quarrying) it is the mining and quarrying (M&Q) sector that contributes the highest, understandably so since that is the sector in which production of basalt takes place.

In terms of domestic inputs for production in Quarrying, Metals and Mineral (QMM), the findings reveal that the Services sector is a crucial sector with regards to domestic inputs across most of the emerging and developed economies except for China and India. This is mainly because the economic impacts from the Trade sector, which is grouped under the Services sector (see appendix for sector groupings) is one of the highest within that sector classification. However, in the case of imported inputs, the critical sector is no longer the Services sector but the QMM sectors of the exporting country where the production of inputs takes place, as shown in Table 4.1b. This is seen especially among all the developed economies and in China among the emerging economies. However, for Russia and India, their imported inputs are Machinery and Equipment sectors of the countries they import from.

One key highlight from the results shown is the differences in the relationship between employee compensation and the employee working hours among emerging and developed economies. Employee compensation is high in the developed economies despite requiring relatively low working hours, but for the emerging economies, employee compensation is inadequate regardless of the high working hours in production. The low working hours possibly suggest that developed economies are more technically efficient in mining and quarrying sector such that they do not depend on a large number of human labour. However, this assertion cannot be entirely supported by the analysis and results presented in this chapter since such an assessment was not included in the study. The plausible explanation for this which is captured by the results of the study is that developed economies rely more on imported inputs compared to their counterparts in the emerging economies and therefore subsequently generating relatively less employee working hours in the actual production of large-scale silicate.

Another key highlight in the analysis presented is the share of impacts attributed to direct and indirect inputs associated with basalt production. This result is incredibly helpful in informing policymakers on where to target strategies for mitigating negative impacts (such as imports and working hours in this case) and for expanding positive impacts (GDP, GOS and employee compensation). Although for almost all five economic impacts, the direct inputs were mostly responsible for a high share of impacts, in some cases the impacts resulting from indirect inputs needed for basalt production were the highest contributor to total impacts. For instance, 60% of employee compensation associated with basalt production in Brazil and France are as a result of indirect inputs required for basalt production. Again, for most of the emerging economies, specifically Brazil, Russia and China, the proportion of working hours generated from the production of indirect input accounts for roughly 85%, 70% and 65% of total working hours respectively (Fig 4.5b).

In terms of imports, the UK has the highest proportion of imported inputs per kg of basalt produced. These findings support a 2006 recommendation by the British Geological Survey report (Brown et al. 2008), which concluded that UK's reliance on imported aggregates should be reduced and instead recommended an increase in indigenous production. It is evident from the results of this study that almost fourteen years later, the situation remains the same. A similar production pattern is seen in the case of the USA, which has the second-highest import per kg basalt produced. The implication of this study concerning the large-scale production of crushed basalt for ERW is that whereas developed countries will potentially benefit economically from basalt production in terms of (GOS, GDP and employee compensation), emerging economies that rely more on indigenous production do not benefit as much economically as compared to the developed economies although the latter depends so much on imports to meet the demand for crushed basalts.

4.5 Chapter Summary

In this chapter, the potential economic impacts associated with the production of crushed silicates were assessed for eight countries, belonging to two separate groups: emerging economies (Brazil, Russia, India and China) and developed economies (the USA, UK, France and Germany). Five economic impact categories were included in the assessment; namely, gross domestic product (GDP), gross operating surplus (GOS), imports, employee compensation and hours worked. The economic-input output model was used in estimating the economy-wide impacts associated with the functional unit of a kg basalt. Results presented for each category were organised into three key findings, that is economic impact per unit output, direct and indirect economic impact, and sectoral contribution. In the next chapter, the sustainability assessment is extended to cover environmental impacts using the same group of countries.

CHAPTER 5 - ENVIRONMENTAL IMPACT ASSESSMENT OF CURRENT SILICATE PRODUCTION FOR ENHANCED ROCK WEATHERING

5.1 Introduction

The sustainability impacts (economic, environmental, and social) of negative emission technologies (NETs) including enhanced rock weathering must be assessed if large scale deployment is to take place successfully. In the previous chapter, the economic sustainability of large-scale production of silicate (basalt) was evaluated for eight countries grouped under an emerging and developed economies. The key finding from the study (Chapter 4) is that there is more economic value added in the production of crushed basalt (silicate) for ERW in developed economies in comparison to their counterparts in emerging economies. An answered question, however, is how do these economic 'gains' or 'losses' relate to associated environmental externalities. (International Resource et al. 2011) considers ecological–economic decoupling as key to a more sustainable form of development. Consequently, it is critical that the potential environmental impact associated with crushed basalt production for ERW be assessed in order to put any economic gains from the same process into perspective.

A study by Larkin et al. (2018) enumerated conditions, including environmental externalities where the large scale deployment of negative emission technology may fail at scale among the big global emitters. According to the authors, the big emitters made up of 25 nations including the selected countries in this study (Brazil, Russia, India, China, USA, UK, France and Germany) contribute to 80% of global CO_2 emissions associated with energy and industry. Based on scenario pathway analysis, it is reported that some NETs particularly BECCS and CCS may fail at scale if the environmental externality that comes with their large-scale deployment is not addressed (Larkin et al. 2018, Smith et al. 2019).

In the same way, the large-scale silicate production for use in enhanced weathering is expected to generate environmental externalities and these must be critically assessed (Smith et al. 2016, Smith et al. 2016, Lefebvre et al. 2019, Garcia et al. 2020). Towards achieving the 2 °C objective under the Paris Climate Agreement, the unintended sustainability impacts of large scale deployment of NETs including environmental and social impacts have been identified as an essential research priority (Fuss et al. 2016). In this current chapter, assessment is focused on the environmental sustainability of enhanced weathering based on large scale production of crushed silicate rock. Specifically, the current chapter is aimed at answering research question 1(b) of the thesis which centres on the macro-level environmental impacts associated with basalt production for ERW.

There are limited studies on the environmental sustainability dimension of NETS and in particular enhanced weathering. Smith et al (2016) looked at the GHG emissions, energy and land use impact of ERW, BECCS, DAC, AF while (Smith 2016) considered similar impacts for soil carbonation sequestration and biochar. New study by Smith et al. (2019), discusses the contribution of ERW regarding specific SDGs, but their research does not go further actually to estimate environmentally-related impacts. In a study by Fuss et al. (2016), although the authors acknowledge ERW as a NET, the focus of their review on research priority areas focuses primarily on BECCS and afforestation. In another study (Lefebvre et al. 2019), the lifecycle assessment method (LCA) is employed in estimating seven potential environmental impacts of enhanced weathering with basalt rock. Their study (Lefebvre et al. 2019) however is based on a micro-level process-based LCA and therefore is subject to the system boundary problem (Brentrup et al. 2004, Heijungs et al. 2010).

The system boundary arises because it is not possible to capture all processes and inputs required in making a product. Therefore, a limit is usually defined within which environmental impacts are confined. The challenge with this approach is that the upstream environmental impacts which may extend beyond the firm level and include several suppliers in the extended supply chain are not captured (Huang et al. , Hayami et al. 2015). It is essential to include the upstream supply chain environmental impacts in order to identify where hotspots are located. Subsequently, this will therefore assist decision-makers in developing a holistic and comprehensive policy which ensures that solutions are not created by a mere shift of the environmental burden to less visible portions in the supply chain (Acquaye et al. 2011). A macro-level sustainability assessment of technologies is therefore needed to address this challenge.

In addition, no study has been done that specifically compares individual country environmental performance of ERW. In this study, the environmental performance of eight selected emerging and developed economies in the large-scale production of basalt is presented. Therefore, this study serves as a good starting point in developing targeted country policies on large scale production of crushed silicate rock such as basalt for enhanced rock weathering. The dynamics of each mining and quarrying sector differs for each country. Therefore, the environmental sustainability concerns of ERW implementation in terms of associated environmental impacts associated with silicate production will also differ. Assessing the environmental performance of ERW in economies must therefore account for these differences to give a better understanding into why some economies may perform better environmentally than others when ERW is rolled out on a wide scale (Fuss et al.,2016).

Furthermore, for some countries, they may need to import crushed silicates from other countries. For instance, in Chapter 4, one of the key findings is how developed economies especially the UK and USA engaged in relatively high imported inputs for its mining and quarrying sector as part of its intermediate consumption. This implies the exporting countries will bear any environmental damage associated with the imported inputs since that is where the production of the inputs takes place (Oppon et al. 2018). The introduction of trade dimension in EIA acknowledges the fact that in the large-scale production of silicates for ERW, environmental impacts may extend beyond national boundaries. Subsequently, when the trade dimension is excluded from such environmental impact analysis of supply chains, it does not give an true reflection of the scope of environmental damage (Ghertner and Fripp 2007). It is therefore vital to estimate the magnitude of these embodied environmental impacts in trade. To achieve this aim, models that capture trade interactions are required, and one such model is the environmentally extended input-output (EEIO) model (Gallego and Lenzen 2005, Wiedmann et al. 2007). The EEIO model is used as the methodology in the current study to estimate environmental impacts among the selected countries.

The study focuses on the critical processes in enhanced weathering, which is mining and crushing of the silicate's rocks. These fundamental processes have been identified as energy-intensive and the hotspot in the ERW process (Lefebvre et al. 2019). However, beyond energy use, other environmentally related impacts are equally critical to the sustainability of ERW. These impacts may also extend to other sectors within an economy because of the increased demand for crushed silicates rocks and the inter-dependencies of industries within an economy. The need for macro-level assessment of ERW stems from the fact that to produce, firms rely on inputs from other firms which may belong to other sectors. For instance, to produce the crushed silicates, mining and quarrying firms will require inputs from other sectors within an economy. It is crucial to see what the potential environmental impacts are and how they spread across sectors in an economy as a result of the increased demand for the crushed silicates.

In the following sections of this chapter, first, a detailed discussion on the methodology and data source is presented. Next, a presentation and analysis of various results on the environmental impacts associated with the emerging and developed economies across five environmental impact categories; on energy use, global warming potential (GWP) or greenhouse gas emissions (GHG), material use, acidification potential and eutrophication potential.

5.2 Methodology and Data

5.2.1 Input-Output (IO) framework

The input-output (IO) framework employed in the economic impact assessment of ERW in Chapter Four is used in the current chapter as the basis for the environmental impact assessment of silicate production. As explained in the previous chapter, the IO framework developed by Wassily Leontief (1936) shows the monetary or economic flow of resources centred on the idea of inter-industry transactions. To capture economy-wide impacts based on the sectoral inter-connections that exist in production (Gallego and Lenzen 2005, Hayami et al. 2015, Camanzi et al. 2017), the research method employed must encapsulate such a framework. Like the economy-wide impacts (in Chapter Four), the environmental impacts also extend beyond a single quarry firm that produces crushed silicates, due to the inter-dependencies of firms on one another for production.

Collecting site-specific data throughout a supply chain would be a time and cost-prohibitive endeavour. When a bottom-up, firm-level data collection approach is used exclusively as in the case of process-based LCA framework, very few companies in a supply chain can be fully assessed. The use of the IO framework, which is a top-down approach ensures there is no boundary problem. However, the IO framework must be extended with environmental outputs to capture environmental impacts. Such a framework is known as an Environmentally extended input-output (EEIO) which has been used extensively in other studies for macro-level environmental impact assessment (Kitzes 2013, Yang et al. 2017, Liu, Huang et al. 2018).

In the current study, a recap of the equations and matrices involved in an I-O framework is first presented, after which a comprehensive overview of the EEIO model is presented. In the I-O table, the inter-industry relationship is known as Intermediate consumption (Z). Other parts of the I-O table show the Final demand(Y) of commodities by households, governments, investment, or exports and the Total Output(X) of a sector.

The relationship between Intermediate consumption (Z), Final demand (Y) and Total output (X) is given by:

$$\mathbf{Z + Y = X} \xrightarrow{\hspace{6cm}} \textbf{Equation 1}$$

A technology matrix also commonly referred to as the A matrix, is constructed to show the input required to produce a unit output between the sectors. *also known as a matrix of direct requirement.* It is t also known as the direct requirement matrix since the emphasis is on the direct inputs from one sector to another required for production.

Technology Matrix (A), is given by:

$$\mathbf{A} = \frac{\textbf{Intermediate consumption}}{\textbf{Total output}} = \frac{\mathbf{Z}}{\mathbf{X}} \xrightarrow{\hspace{3cm}} \textbf{Equation 2}$$

We know from Equation 1 that

$$\mathbf{Z + Y = X}$$

And from Equation 2

$$\mathbf{A} = \frac{\textbf{Intermediate consumption}}{\textbf{Total output}} = \frac{\mathbf{Z}}{\mathbf{X}}$$

$$\therefore \mathrm{Z = AX}$$

Then $\mathrm{AX + Y = X}$

So that $Y = X(1 - A)$

But A is a matrix, therefore

$$Y = X\,(I - A)$$

Where I is an identity matrix. Hence

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \xrightarrow{\qquad\qquad} \quad \textbf{Equation 3}$$

$(\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}$ in Equation 3 is referred to as the **Leontief Inverse Matrix** or total requirement matrix and it shows cumulative value for both direct and indirect inputs needed in each sector to meet demand for a unit of output. Emphasis is now being placed not just on what goes on within the firm (direct) but on a complete lifecycle assessment such that the upstream impacts which occur in the extended supply chain process are also captured.

5.2.2 Environmentally Extended Input-Output (EEIO)

To capture the environmental impacts of a product, the I-O analysis can be extended with environmental indicators. The inter-linkages and transactions between sectors implies that the environmental externality associated with silicate production beyond the relevant sector where production takes place will be captured (Oppon et al., 2018).

Let:

E_{jp} Signify the direct environmental output for any sector j in country p. These are energy use, global warming potential (GWP), material use, acidification potential and eutrophication potential expressed respectively as MJ, $CO_{2\text{-eq}}$, MJ, Kg SOx and kg NOx per kg silicate produced. The data is retrieved from the WIOD environmental satellite account.

Given thatX_{jp} is the total industry production output expressed in million $, the direct intensity matrix (DiM) of any industry j in a particular country p is given by:

$$\mathbf{DiM} = \frac{\textbf{Direct Environmental Output}}{\textbf{Total Industry Output}} = \frac{\boldsymbol{Ejp}}{\mathbf{Xjp}} \qquad \textbf{Equation 4}$$

DiM is the matrix representation of direct environmental intensity matrix (unit/$) of all industries in each country within the EEIO framework (Oppon et al., 2018).

Given that Eq. (3) represents the total requirements needed to produce the output x for a given final y, it implies that if the environmental externality per unit industrial output is DiM, then the total environmental impacts are represented below as Eq. (5):

$$\boldsymbol{Total\ environmental\ impact = DiM(I - A)^{-1}Y} \qquad \textbf{Equation 5}$$

In Eq. (5), the use of the Leontief inverse matrix represented by$(\boldsymbol{I - A})^{-1}$ in the analytical framework ensures complete supply chain visibility of all economic activities associated impacts within the EEIO in what Hoekstra and Wiedmann (2014) describe as the ability to capture both direct (operational) and indirect (supply-chain) components of environmental impacts Oppon et al, 2018).

5.2.3 Limitations and Assumptions of EEIO model

The EEIO model is based on some assumptions that gives rise to some limitations (Hendrickson et al., 1998 and Acquaye and Duffy 2010). These are explained below:

Homogeneity Assumption and Aggregation: Within the EIO model there is an assumption that a sector use the same or identical inputs to produce its outputs. (Oppon et al, 2018). For instance, within the Metals, Mining and Quarrying sector the homogeneity assumption implies all firms within the sector use the same inputs of electricity or fabricated metals to produce. However, in reality this is not the case as within the sector, there are similar but different output within a sector. For instance, output from primary aggregates may be sand or gravels and not just crushed silicate rocks such as basalt. However, such distinction is lost due to the aggregation of sectors within the I-O databases.

Linear Proportionality Assumption: The linear proportionality assumption exists with the EIO model because the framework assumes that it takes the same quantity of production inputs to satisfy an increase in demand. In other words, there is a fixed ratio in production inputs used in production. However, this is not always the case, because there is the possibility that as demand increases, there could be non-linear increase in production inputs ratios.

Despite these assumptions and related limitations, the use and results from I-O model is still considered valid to a large extent (Hendrickson, 1998) and is advocated for especially in instances where lack of comprehensive or detailed data exist (Tukker and Dietzenbacher, 2013).

5.3 Analysis and Results

In this section, different results for each environmental impact category for two groups of countries, that is emerging economies (Brazil, Russia, India, China) and developed economies (USA, UK, France, Germany) are presented. The environmental impacts are energy use and material use measured in MJ, GWP measured in kg $CO_{2\text{-eq}}$ acidification potential measured in kg SOx and eutrophication potential measured in kg NOx. The impacts measured are related to a functional unit of kg of crushed silicates associated with a cradle to gate system boundary.

5.3.1 Energy Use

In this section, results for energy use associated with crushed silicate production are presented.

.

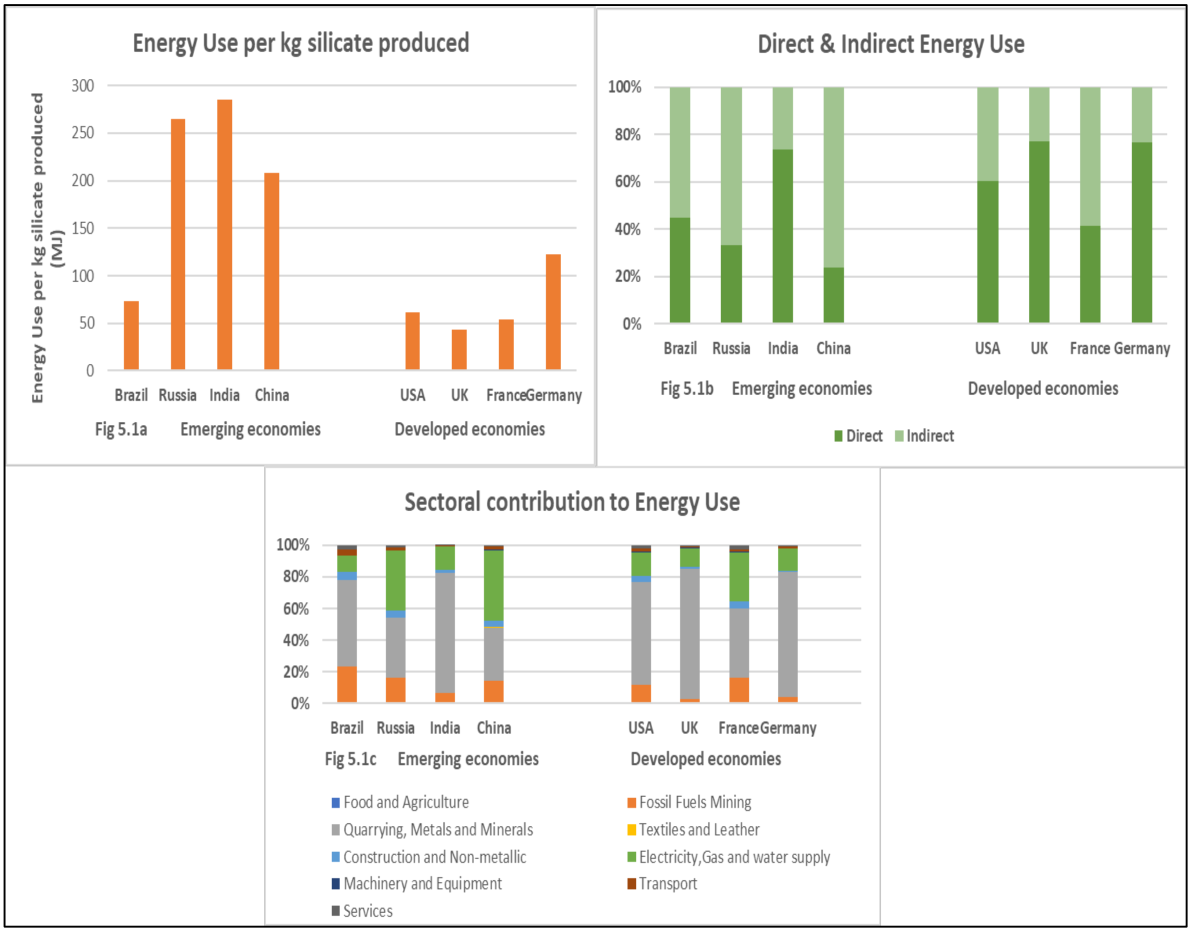


Fig 5.1: Total energy use per kg silicate produced, Direct & Indirect energy use and sectoral contribution of energy use impacts

Low energy use is considered better than high energy use since it results in less resource consumption and also less environmental impacts. Energy use in producing silicates (Fig 5.1a) is relatively highest in India (~280MJ/kg) and Russia (260MJ/kg) compared to China (~210MJ/kg). Brazil is the lowest in terms of energy use among the emerging economies that is ~70MJ/kg. Among the developed economies, Germany has the highest energy use of 125MJ,/kg, which is almost twice the energy use in Brazil. However, generally, the results indicate that energy use in producing silicates in the developed economies is significantly lower than emerging economies. Notably, the UK has the lowest energy use of approximately 40MJ per kg of silicate produced. USA and France have similar energy use; 60MJ and 50MJ per kg silicate produced, respectively.

For the emerging economies, apart from India, a large proportion of the energy use impact per unit output occur indirectly, which is a result of indirect inputs (Fig 5.1b).

Indirect energy use in Brazil is approximately 58%, Russia approximately 70% and China, ~80%. The exception is India, where about 75% of the energy use impacts occur directly within their mining and quarrying sector. In the developed economies specifically the USA, UK and Germany, direct energy use impacts generated is significantly higher than indirect energy use; 60% for the USA and 78% for UK and Germany, respectively. The situation is different however in France, where more of the energy use impacts are generated indirectly, that is 60%. This implies that in producing crushed silicates in France, the high disproportionate energy use impacts are as a result of the indirect inputs from other sectors with the economy and not the direct inputs.

Sectoral distribution of the total energy use associated with producing kg output of crushed silicates is shown in Fig 5.1c. In Brazil, the Quarrying, Metals and Minerals sector is the highest contributor to energy use with 60%, followed by the Fossil Fuels Mining sector, which accounts for 25% of energy use. In Russia, Quarrying, Metals and Minerals sector is the highest with 40% contribution to energy use, followed by the Electricity, Gas & Water supply sector accounting for ~35%. Energy use impacts in India is mostly accounted for by the Quarrying, Metals and Minerals, contributing 75%. The Electricity, Gas and Water supply sector in China is responsible for the highest contribution of 45% of the total energy use impacts while the Quarrying, Metals and Minerals sector is the second highest with 33% contribution. Energy use in the Quarrying, Metals and Minerals sector for the USA, UK and German contributes the highest to energy use impacts; 65%, 80% and 78% respectively which is significantly higher when compared with France (45%). The Electricity, Gas and Water supply sector is the second-highest contributor to energy use impacts in all the developed economies. In France, the contribution from the Electricity, Gas and Water supply sector is approximately 30% which is higher than the USA, UK and Germany where sector contribution is an average of ~15%.

5.3.2 Global Warming Potential (GWP)

In this section, results for GWP associated with silicate production are presented. GWP among the emerging economies (Fig 5.2a) shows that China has the highest impact of 530kg $CO_{2\text{-eq}}$ per kg silicate produced followed by India and Russia with approximately 450kg $CO_{2\text{-eq}}$ and 350kg $CO_{2\text{-eq}}$ per kg produced respectively. Brazil has the lowest GWP potential of ~110kg $CO_{2\text{-eq}}$ per kg produced. For the developed economies USA stands out as having relatively the highest GWP of ~260kg $CO_{2\text{-eq}}$ /kg followed by Germany which has GWP of 100kg $CO_{2\text{-eq}}$ /kg. The GWP of producing silicates in the UK and France are however very low; approximately less than 10kg $CO_{2\text{-eq}}$ /kg each.

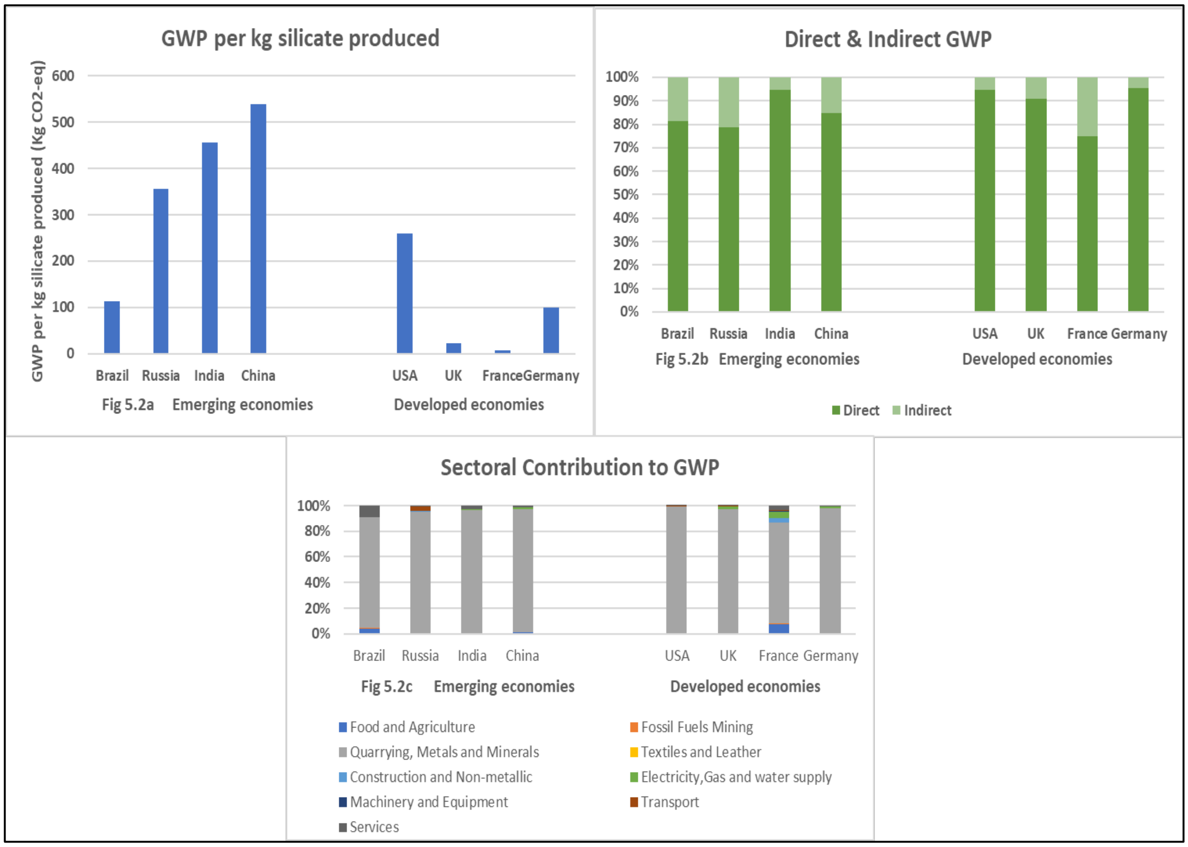


Fig 5.2: Total Global warming impact (GWP) per kg silicate produced, Direct & Indirect GWP and sectoral contribution of GWP impacts

Results in Fig 5.2b show that the direct GWP is higher than indirect GWP for all countries in both emerging and developed economies. The results indicate that an average of 80% of GWP impact occurs directly across all four countries in emerging and developed economies, each with an average of 20% accounted for as indirect GWP.

The sectoral impact of producing the crushed silicates is concentrated within the Quarrying, Metals and Minerals sector in both emerging and developed economies (Fig 5.2c). There are some few exceptions where relatively significant impact contribution is seen from the Services sector (9%) in the case of Brazil and the Transport sector (3%) in the case of Russia and Food and Agricultural sector (85%) in the case of France.

5.3.3 Material Use

The total material use associated with the production of per kg silicates is shown in Fig 5.3a. Among the emerging economies, material use in India is the highest with approximately 900MJ per kg silicate produced followed by China which requires 400MJ/kg. However, material use in Germany is higher among all the countries (both emerging and developed) with potential material use of approximately 1200MJ/kg. The UK has the lowest material use of ~ 40MJ per kg of silicate produced. Material use in USA (250MJ/kg) and France(350MJ/kg) is higher than Brazil(180MJkg) and Russia(200MJ/kg).

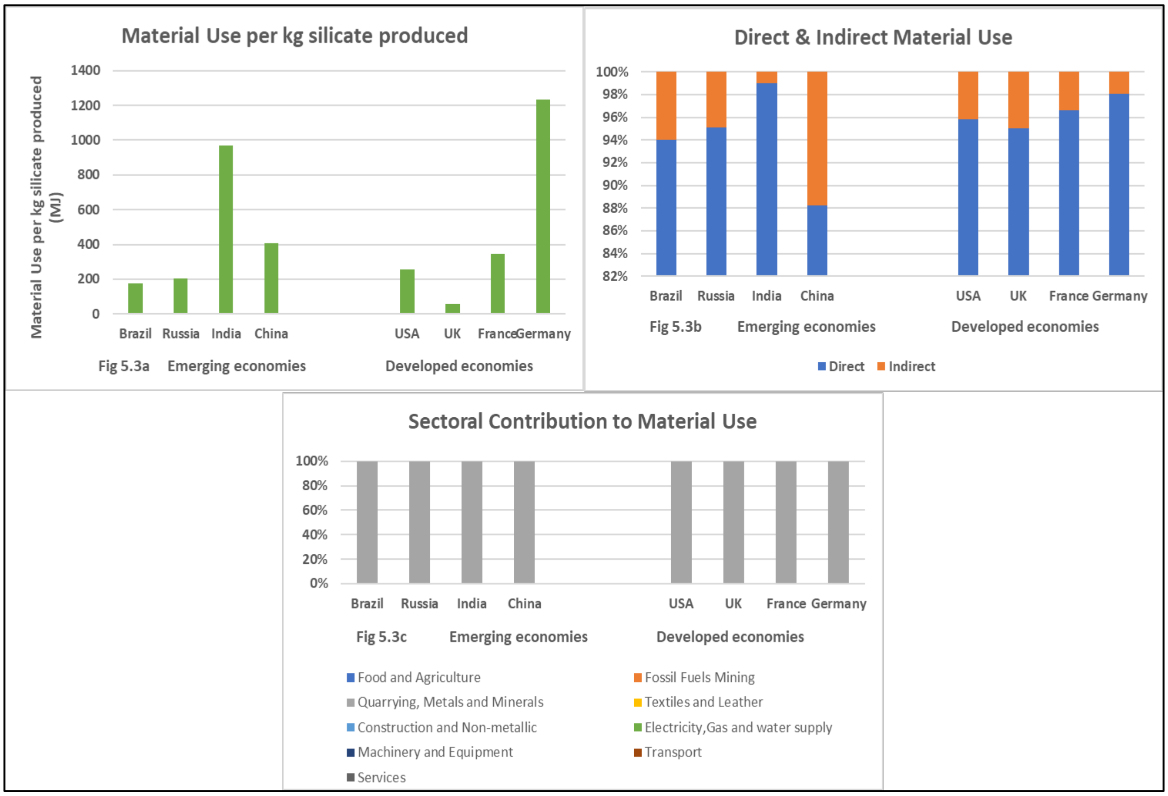


Fig 5.3: Material use per kg silicate produced, Direct & Indirect Material use and sectoral contribution of Material use

Results in Fig 5.3b show that direct material use is higher than indirect impacts in both emerging and developed economies. In Brazil, Russia and India, direct material use is 94%, 95% and 99% respectively; significantly higher than direct material use impact in China, which is 88%. Among the developed economies, direct material use is highest in Germany (98%) followed by France, the USA and the UK where direct material use is 96.5%, 96% and 95% respectively. Sectoral contribution to material use (Fig 5.3c) is mainly accounted for by the Quarrying, Metals and Mineral sector across all the countries in both emerging and developed economies.

5.3.4 Acidification Potential (AP)

In this section, results for acidification potential associated with silicate production is presented.

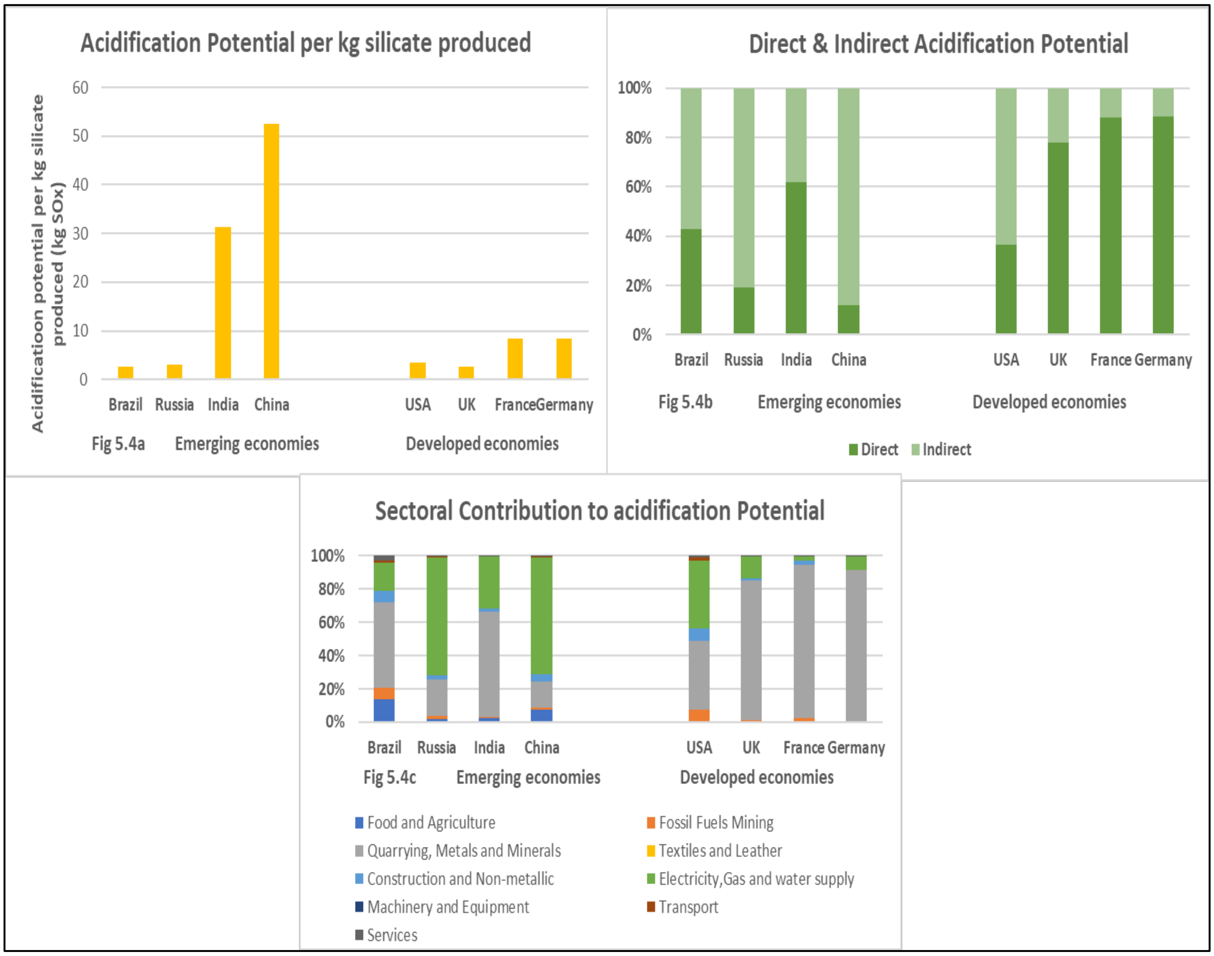


Fig 5.4: Acidification Potential (AP) per kg silicate produced, Direct & Indirect Material use and sectoral contribution of Material use

Results on total acidification potential per kg produced silicate (Fig 5.4a) shows China and India have the highest acidification potential of ~52kg SO_x and 30kg SO_x per kg silicate produced, respectively. Acidification potential in France and Germany which is approximately 9kg SO_x /kg is higher than the developed countries USA (0.4 kg Sox/kg) and UK (0.3 kg SO_x /kg) and emerging economies Brazil (0.3 kg SO_x /kg) and Russia (0.4 kg SO_x /kg).

For direct and indirect acidification potential impacts (Fig 5.4b), results show that in the emerging economies, most of the AP impacts generated occur indirectly; 60% for Brazil, 80% for Russia and 90% for China. The exception is in India, where 60% of AP impacts are direct. The reverse occurs in the developed economies where most of the impacts generated occur directly, that is 80% for the UK and 90% for France and Germany. The exception is in the USA, where approximately 60% of acidification potential impacts generated are indirect impacts.

In the sectoral distribution of acidification potential impacts, it is evident from the results shown in Fig 5.4c, that the Electricity, Gas and Water supply sector in Russia and China is the hotspot contributing 70% to AP impacts in both countries while for their emerging economy counterparts Brazil and India, the highest AP contribution is attributed to the Quarrying, Metals and Minerals sector that is ~50% and 60% respectively. The contribution of acidification potential impact from USA's Electricity Gas and Water supply sector and Quarrying, Metals and Minerals sector accounts for 80% of total AP impact; 40% in each sector, respectively. The Quarrying, Metals and Minerals sector in the UK, Germany and France is the hotspot for acidification potential impacts associated with silicate production with the sector contributing approximately 80%, 95% and 90% respectively.

5.3.5 Eutrophication Potential (EP)

In this section, results for eutrophication potential (EP) associated with silicate production are presented. India has the highest eutrophication potential of~44kg NO_x per kg silicate production followed by China, which has 26kg NO_x/kg. Among the emerging economies, eutrophication potential is lowest in Brazil that is 9kg NOx/kg.

Eutrophication potential in the UK is the highest among the developed economies; approximately 12kgNO_x per kg silicate produced. Germany has the lowest of ~4 kg NO_x/kg.

In Fig 5.5b, the results show that the EP impact in emerging economies, specifically Russia and China have more indirect impacts within the Quarrying, Metals and Mineral sector that is 60% and 70% respectively. In Brazil, 50% of the EP impacts occur both directly and indirectly, whereas, for India, 80% of the impacts generated are direct. For the developed economies, direct EP impacts are relatively far high than indirect EP impacts, especially in the UK and France where direct EP impacts account for ~85% for both countries.

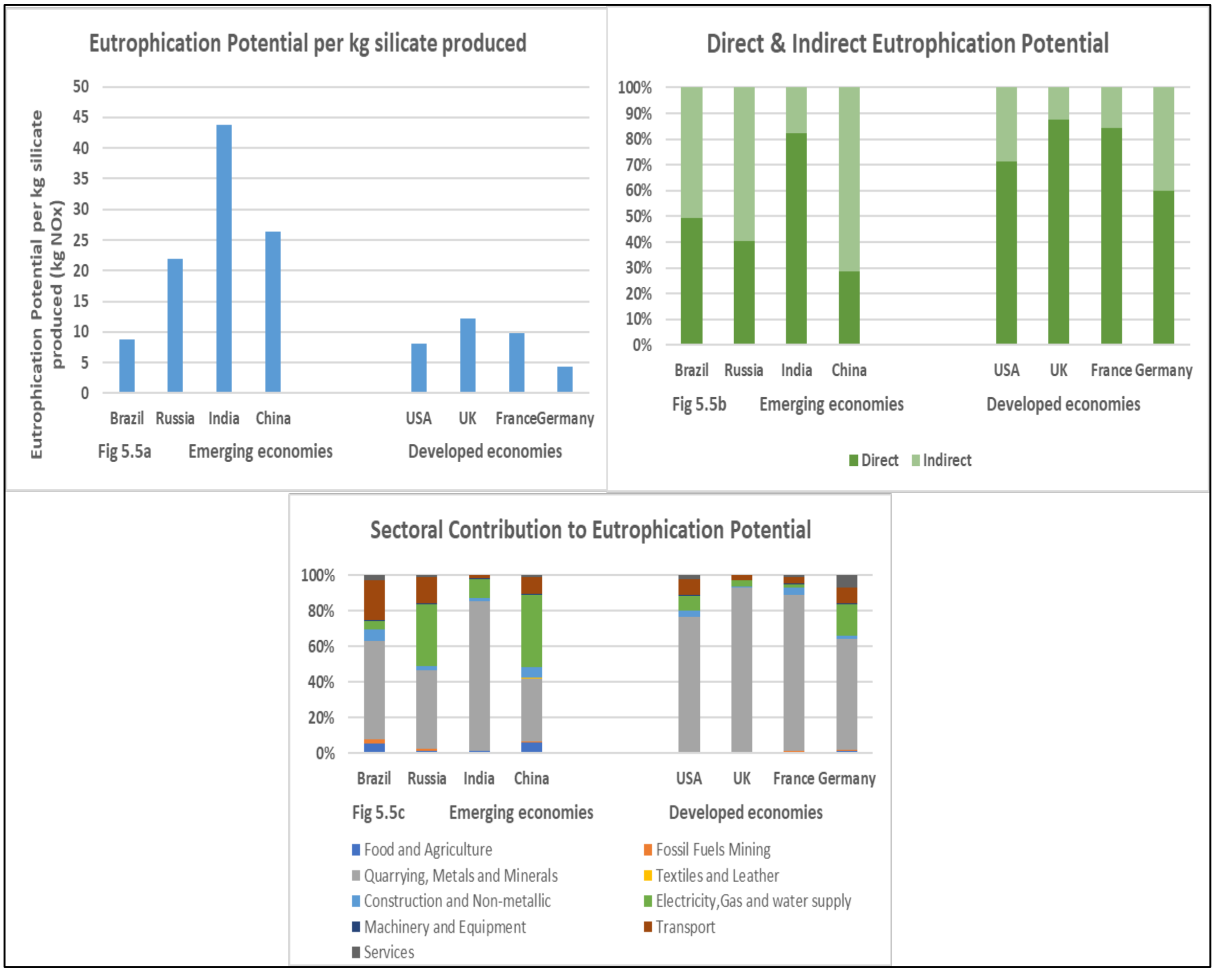


Fig 5.5: Eutrophication Potential (EP) per kg silicate produced, Direct & Indirect Eutrophication Potential and sectoral contribution to Eutrophication Potential

The sectoral distribution of the total eutrophication impact (Fig 5.5c) shows that for most countries, the Quarrying, Metals and Mineral sector is the highest distribution contributing an average of 70%. The exception, however, is in China where it is the Electricity, Gas and Petroleum sector that receives the highest share of the associated eutrophication potential impact representing approximately 40%. Aside the Quarrying, Mining and Quarrying sector where about 45% of EP impacts are distributed to, EP impacts in Russia's Electricity, Gas and Petroleum is the second-highest share of total impacts contributing approximately 35%. The transport sector in Brazil receives the second-highest percentage of eutrophication potential impacts, that is about 23% of the total impacts.

5.3.6 Domestic and Import production in the Mining and Quarrying sector

The results shown so far indicate that the Quarrying, Metals and Minerals sector which comprises two sectors namely Quarrying and Mining sector and Basic Metals and Minerals sector (see sector aggregation in Appendix) has the highest sectoral contribution to the environmental impacts in most of the countries across the two groups (emerging and developed economies). The highest contributor comes explicitly from the Mining and Quarrying sector (hereafter referred to as the M&Q sector) and therefore an in-depth analysis of production patterns in the sector mainly, the domestic and import related production can provide a contextual explanation as to why the potential environmental impacts estimated differ among the emerging and developed economies. To do this, the intermediate consumption of the countries' input-output table must be considered. Intermediate consumption refers to the sector by sector consumption of production inputs which takes place within domestic boundaries (domestic consumption) or are imported (imported consumption). Total intermediate consumption, therefore, is a sum of domestic consumption and imported consumption.

Figure 5.6 shows the percentage share of intermediate consumption that involves domestic consumption and the percentage that is imported consumption of inputs from sectors within other countries. The results show that overall, domestic consumption is higher than imported consumption in the M&Q sector for all the countries. However, the imported consumption in the developed countries is relatively far higher compared to that of emerging economies. For the emerging economies, imported consumption constitutes an average of less than 10% compared to developed economies where imported consumption is an average of 20%. The UK's mining and quarrying sector particularly have the highest imported consumption of approximately 30%. The significance of this result is that it supports the assertion that in some instances, developed economies experience less negative environmental impacts within their national boundaries by 'leaking' such impacts via imported inputs produced in other countries (Oppon et al. 2018). This is particularly possible since the imports are not included in the technology matrix in the EEIO model used in the study, which is a similar approach used in studies including (Sánchez-Chóliz and Duarte 2004, Guan and Hubacek 2007, Peters et al. 2007).

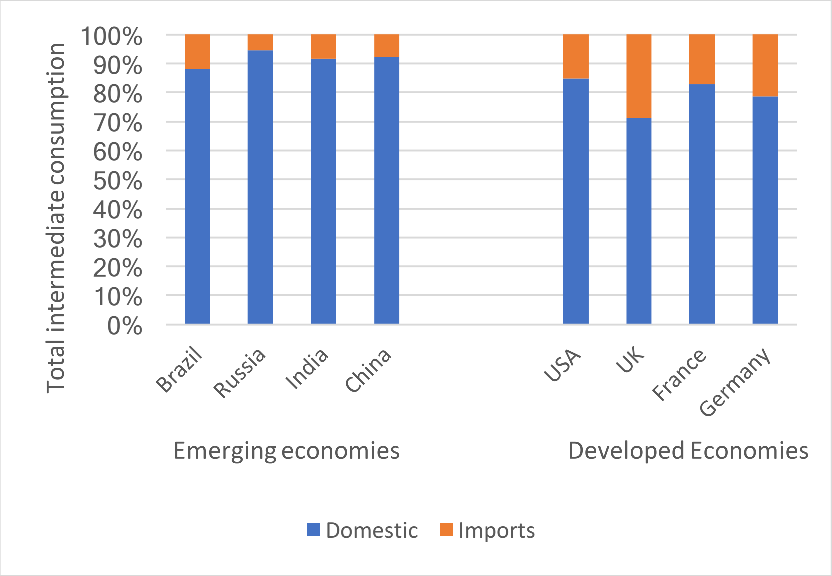


Fig 5.6 Comparing intermediate domestic and imported consumption within the M&Q sector.

Next, in Figure 5.7 we take a look at the "M&Q to M&Q" intermediate consumption to determine how much a country relies on domestic inputs, (that is from within its mining and quarry sector) and imported inputs (that is from mining and quarry sector). This is different from results in Figure 5.6 which show interactions between the Mining and Quarrying sector and all other sectors (such as Transport, Fossil Fuels, Services sector, etc.) within and outside a country. For the emerging economies, apart from India, a large proportion of inputs for production are mainly sourced domestically from the country's mining and quarrying sector. For Brazil, Russia, and China, only approximately 30%, 5% and 20%, respectively of production inputs are imported from mining and quarrying sector in other countries. For India, however, the results suggest they import approximately 50% of inputs from other countries. In the case of the developed economies, inputs for production within the mining and quarrying sector are mostly imported for mining and quarrying sectors in other countries. For USA, UK and Germany, approximately 40%, 50% and 60% are imported respectively from mining and quarrying sectors of other countries. The exception is the case of France where only 10% of inputs are imported from mining and quarrying sectors of other countries which suggest that France relies more on domestic inputs within its M&Q sector for silicate production.

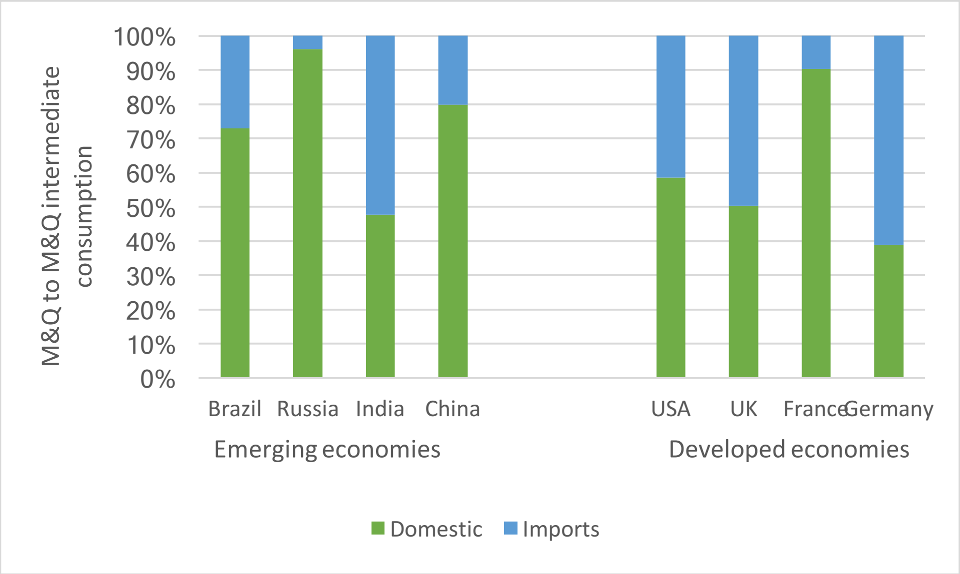


Figure 5.7 Comparing M&Q to M&Q intermediate consumption

5.3.7 Environmental impact intensities

Environmental impact intensity refers to the impact per unit of output produced derived by dividing total environmental sector by the total output in that sector. This is recorded in the direct intensity matrix (DiM) shown in Eq (4) of the methodology section. Such an analysis is fundamental as it shows the environmental production efficiencies (depicted by a relatively low intensity) or inefficiencies (characterised by relative high intensity). For instance, if the total GHG emissions in a given sector are 500 kg $CO_{2\text{-eq}}$ and total output is \$1000, then GHG intensity is 0.5kg $CO_{2\text{-eq}}$ per \$ output. In this section, we compare the total sectoral environmental impact and environmental sectoral intensities. The aim is to find out whether a country may have high sectoral environmental output but lower sectoral intensities which suggests that overall the country has better environmental production efficiency in producing crushed silicates for ERW.

Energy Use Intensity

In Fig 5.8a, results show the total energy consumption in the M&Q sector of each country obtained from the Environmental satellite accounts in WIOD. In this figure, China's M&Q sector consumes the highest energy among the BRIC or emerging economies, whereas the USA's M&Q sector also leads in terms of highest sectoral energy use among the developed economies. However, the story is different in terms of total energy intensity in the M&Q, shown in Fig 5.8b. Total energy intensity indicates the energy use per unit of output and is derived by dividing total energy use by total output. In this figure, China's energy intensity is lower than in Russia and India. This implies that to produce a unit of output in China's sector requires less energy use than Russia and India. In the case of India, despite having the lowest energy use in relation to Russia and China, (excluding Brazil), the findings show that the country's M&Q sector requires more energy input in producing an output. Energy intensity reflects energy efficiency and therefore, it can be concluded that in comparison to Russia and China, India is less energy efficient with regards to mining and quarrying of silicates for enhanced weathering.

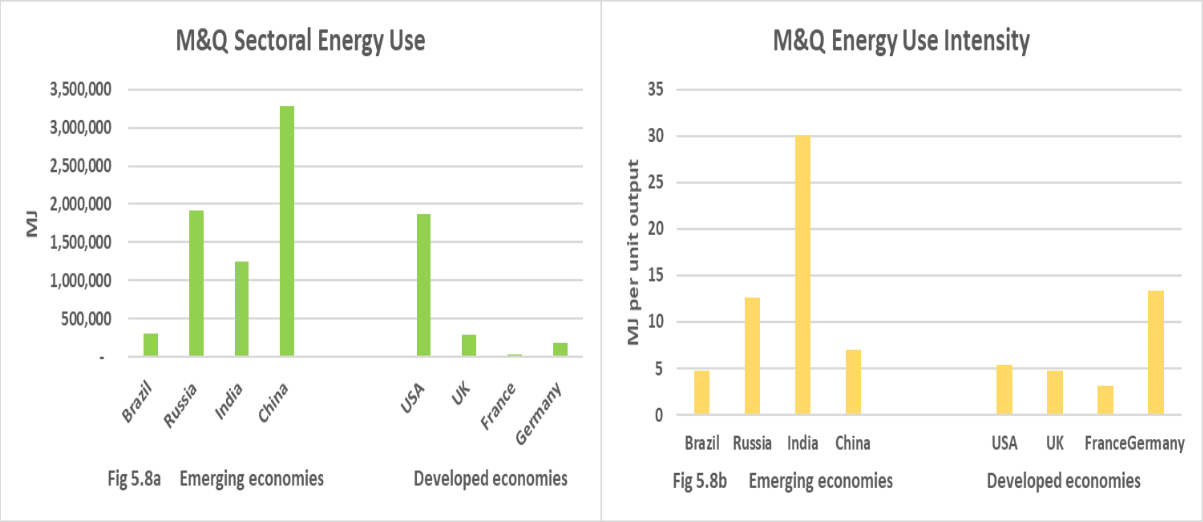


Figure 5.8 Sectoral Energy Use and Intensity in Mining and Quarrying(M&Q) Sector

Global warming potential (GWP) Intensity

Global warming potential (GWP) looks at the total greenhouse gases (carbon dioxide, methane and nitrous oxide) in an economy associated with the production of crushed silicates. In Fig 5.9a, results show that total GWP in the Mining and Quarrying sector is generally very low for the developed economies (UK, France & Germany) except the USA compared to the emerging economies. However, in terms of GWP intensity in the sector (Fig 5.9b), which refers to the GWP per unit output, the USA and Germany have a relatively higher intensity than the UK and France. For emerging economies, China's Mining and Quarrying sector have the highest total GWP, followed by Russia. In terms of GWP intensity, India is higher than Russia despite India having a lower total GWP in its Mining and Quarrying sector than Russia, as shown in Fig 5.9a.

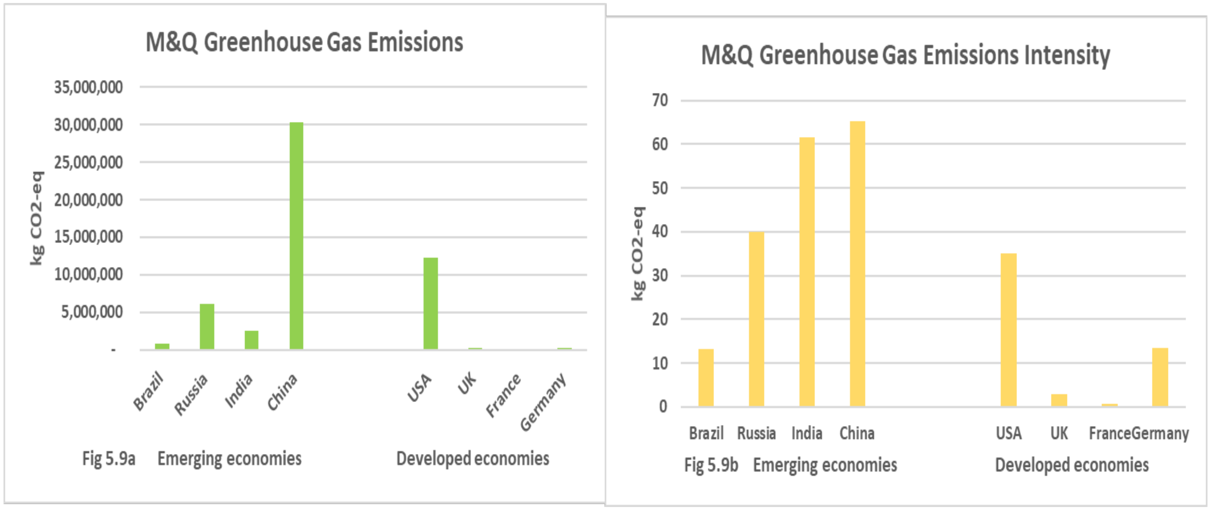


Figure 5.9 Sectoral Greenhouse Gas Emission and Intensity in Mining and Quarrying(M&Q) Sector

Material Use Intensity

Comparing the total material use (Fig 5.10a) with material use intensity (Fig 5.10b) in the mining and quarrying sectors of the countries reveals some interesting and surprising results. Among the emerging economies, although China has the highest material use; however, in terms of material use intensity, it is second to India. Similar conclusions can be drawn from developed economies where although the USA's mining and quarry sector has the highest material use, it is rather Germany that has the highest material use intensity. Material use intensity in India's Mining and Quarrying sector is the highest;

~140MJ per unit output produced followed by China which is ~60MJ per unit output. However, Germany's mining and quarry sector surpass that of India.

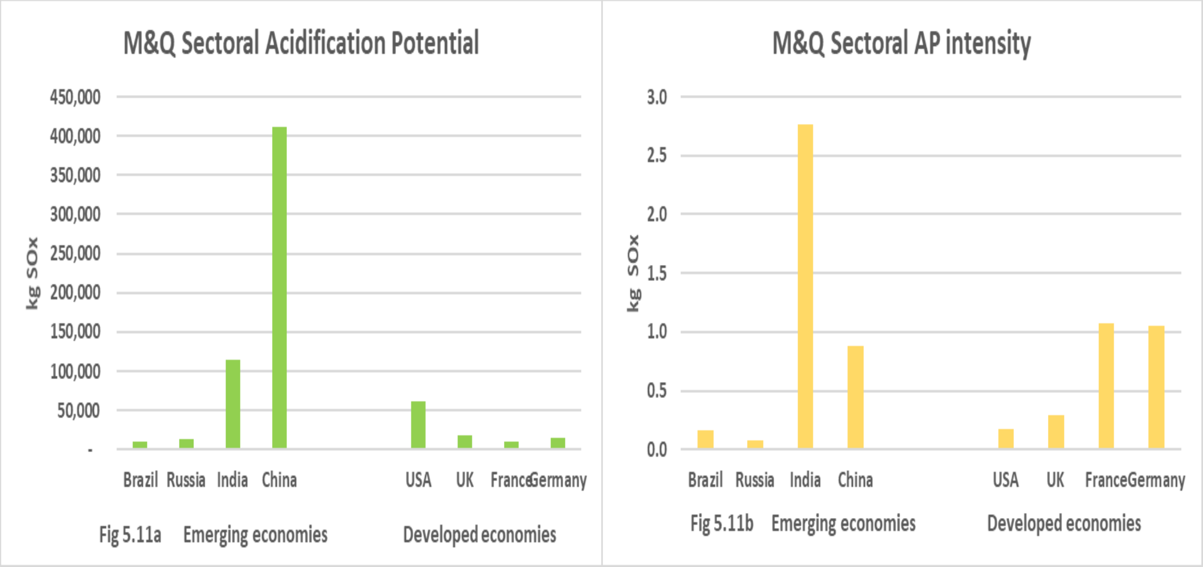


Figure 5.10 Sectoral Material Use and Intensity in the Mining and Quarrying sector(M&Q)

Acidification Potential intensity

In Fig 11a, results show that the total acidification potential impact on China's Mining and Quarrying sector is the highest, followed by India. Acidification potential in Brazil and Russia is the lowest among the emerging economies. However, in terms of AP intensity (Fig 11b), India surpasses China as the emerging economy with the highest AP intensity associated with silicate production. For the developed economies, the USA has the highest acidification potential in its Mining and quarrying sector. However, in terms of acidification potential intensity, Germany and France have the highest despite having relatively lower total AP in their Mining and Quarrying sector whereas the lowest USA has the lowest AP intensity.

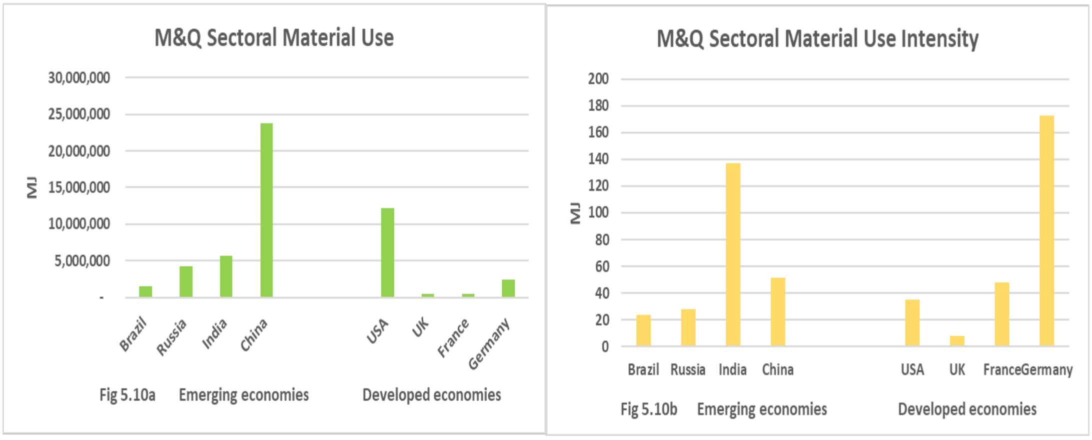


Figure 5.11 Sectoral Acidification Potential (AP) and intensity in Mining and Quarrying(M&Q) sector

Eutrophication Potential intensity

Total eutrophication potential in the Mining and Quarrying sector (Fig 5.12a) is highest in China and USA's among the emerging economies and developing economies, respectively. However, with regards to eutrophication potential intensity (Fig 5.12b), it is India and the UK's mining and quarrying sector that has the highest among the emerging economies and developed economies, respectively.

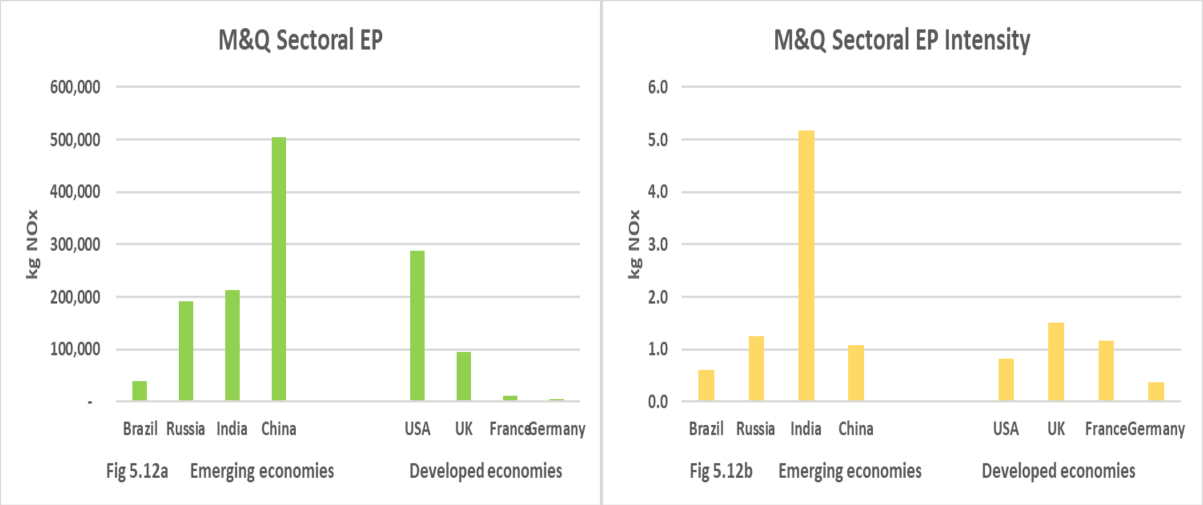


Figure 5.12 Sectoral Eutrophication Potential (EP) and intensity in Mining and Quarrying(M&Q) sector

5.4 Discussion and conclusion

The analysis and results presented in this current chapter provide an insightful outlook into the environmental sustainability of ERW, specifically in relation to the mining and quarrying sector. Selection of production inputs for intermediate consumption which comprise both domestic and imported input is paramount in determining the extent of environmental externalities associated with crushed silicate production supply chain. Environmental impacts related to imported inputs are not captured within the producing country (that is the exporting country) which under-estimates the potential impacts within the national boundary (Ghertner and Fripp 2007, Ibn-Mohammed, Koh et al. 2016, Oppon, Acquaye et al. 2018). The M&Q sectors in the developed economies mostly rely on more imported inputs from the M&Q sectors of other countries in order to produce crushed silicates (Fig 5.7). Such high imported inputs confirm the industrial outsourcing concept (York et al. 2004) which explains that developed countries through their imports can reduce their environmental material and energy use impacts. Among the environmental impacts estimated, countries like the UK appear to have relatively low impacts, especially in energy use, GWP and material use. In line with the industrial outsourcing thinking, it can be explained that the UK's low environmental impact is due to the high imported inputs in their intermediate consumption (Fig 5.6 and 5.7).

In relating the results of this chapter to that of economic impacts assessed in Chapter four, an important finding can be made which addresses some popular theories on the relationship between economy and environment. The Ecological Modernisation Theory (EMT), is one of the prominent theories that have been used to explain how economic growth in modern economies can lead to environmental improvements (Mol and Spaargaren 2000). The underlying assumption of EMT is that developed economies through their modern production technologies can drastically reduce their material and energy use in industrial sectors (Mol and Sonnenfeld 2000, Mol and Spaargaren 2000).

The findings of the current study, however, prove contradictory to the EMT. We see this, especially in the case of Germany, where results showed that their energy and material use in the production of silicates is the highest among all the countries despite being classified as a developed economy. In terms of sectoral energy use and material use in Germany's M&Q sector (Fig 5.8 & 5.10), the country appears to perform better in that they have relatively low impacts in these two categories compared to emerging economies like China, India and Russia or even their developed economy counterpart the USA, which might suggest that the EMT theory holds. However, a look at the energy and material use impact intensities reveals that the country performs poorly. This finding, therefore, aligns with a similar conclusion by York et al (2004) which states that the EMT may not always hold in some cases.

The results are particularly important in policy formation and decision on increasing crushed silicate production sustainably for use for ERW purpose. For countries where the environmental impact from producing these crushed silicates result in more environmental damaging impacts, perhaps a better solution would be to look at artificial silicates (e.g. steel slag, cement kiln dust, coal ash) which reduces the need to mine and quarry natural silicate rocks. In this regard, artificial silicates may fit perfectly into circular economy agenda and present an opportunity to reduce environmental impacts if countries tapping into these secondary sources would reduce the need for countries to mine and quarry large quantities of silicates for ERW purpose.

5.5 Chapter Summary

The current chapter presented analysis and results based on a multi-country study of macro-level environmental sustainability impacts of ERW particularly in the production of silicates. The environmental extended input output (EEIO) framework is used in estimating potential environmental impact associated with mining and quarrying of crushed silicates. Five environmental impact categories were assessed including energy use, global warming potential, material use, acidification potential and eutrophication potential. Results presented also included total environmental impact per kg produced, direct and indirect impact and sectoral contribution to total environmental impact. To this point in the study, two pillars of sustainability has been assessed; that is, economic impact in Chapter Four and environmental impact in the current chapter. To complete the triple bottom line assessment of silicate production in ERW supply chain, the next chapter (Chapter Six) presents the analysis and results associated with the potential social risk impact.

CHAPTER 6 – SOCIAL RISK IMPACT ASSESSMENT OF CURRENT SILICATE PRODUCTION FOR ENHANCED ROCK WEATHERING

6.1 Introduction

It is essential to know how the production of silicate rock mining and crushing for ERW impacts on society. However, as reiterated through the previous chapters of the thesis (Chapter 2 & 3), the social angle of sustainability, in general, has not received much focus as compared to the economic and environmental sustainability pillars in assessment studies. The inter-dependence between sectors implies that in large scale production of silicate rocks for ERW, the social impact will also extend beyond the specific relevant industry where production takes place, that is the mining and quarrying (M&Q) sector. It, therefore, implies that similar to models used in Chapter 4 & 5, the method for assessing the social impact of large-scale silicate production should be able to capture both local and upstream social impacts on sectors affected by the ERW production supply chain.

An appropriate method for such an analysis requires researchers and practitioners to use a social lifecycle assessment method (SLCA) which measures social impacts along a product's lifecycle stages (Traverso et al., 2018; Van Haaster et al.,2017; Ekener-Petersen and Moberg 2013). However, there is no standardised and easy-to-use SLCA method as in the case of the environmental lifecycle assessment methods, which is commonly used for environmental impact assessment. The significance of the social sustainability dimension is essential and therefore attempts to develop SLCA methodologies and application is highly recommended (Martínez-Blanco et al. 2014). Although guidelines for SLCA has been published (Andrews 2009, Benoît and Mazijn, 2009), these are merely guidelines and do not provide any specific and generally accepted methodology for conducting social lifecycle assessment.

The current chapter, therefore, makes methodological contribution to supply chain social sustainability analysis by proposing a quantitative social input-output (SIO) model. The SIO is based on an extension of the economic input-output model (Wiedmann and Lenzen, 2008).

The proposed SIO model takes a system-wide view of embodied social impacts in product supply chains and allows for impacts to be measured from a lifecycle perspective (Hauschild et al.,2008). In addition, the SIO is set up similarly to the environmental extended input-output method (Richter et al., 2019; Moran et al., 2015) and therefore also allows for country and sectoral level analysis of embodied social risk in global supply chains. This proposed model aims to make it possible to identify and quantify the social issues of concern within supply chains and the countries and sectors where these are most likely to occur. These social issues range from human rights, labour rights health and safety and other social themes that tend to affect stakeholders such as workers within a supply chain mainly. Table 6.1 shows an overview of the selected impact categories measured in the study, including some examples of the sub-categories, indicators and risk measured in the SHDB.

The SIO model allows for a macro-level analysis of social impacts. Supply chain social assessment from the macro-level perspective is vital because of knock-on effects which extend beyond a single firm to several partner organisations within many sectors both within and outside a country’s borders. In doing this, the large-scale social consequences are captured along the extended supply chain life cycle stages (Van Haaster et al., 2017). The current chapter, therefore, fills this gap by using the proposed SIO model to quantify the social impacts related to crushed silicates production for ERW. The next section focuses on how this is specifically carried out particularly how the SIO method is set up and the data sources used.

Table 6.1 Overview of Impact categories and examples of indicators, sub-categories and risk in SHDB

Impact Category	Sub-category	Indicator	Risk
Labour rights and Decent Work	Wage Assessment	Country minimum wage, living wage, country's non-poverty line	Risk that sector average is lower than country's minimum wage, living wage, country's poverty guideline
	Poverty	Percent of population living under poverty line	Risk of wages being under relevant poverty line
	Child Labour	Total child labour, Percent of total child labour in sector	Risk of total child labour, risk of total child labour in sector
	Unemployment		Risk of high unemployment
Health and Safety	Occupational Toxics & Hazards	Disability-adjusted life years due to occupational-related Mesothelioma	Risk of loss of life years by mesothelioma due to occupation
		Silicosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	Risk of loss of life years by silicosis due to airborne particulates in occupation
	Occupational Injuries & Deaths	Non-fatal injuries by country	Risk of non-fatal injuries by country
		Fatality Rate of injuries by country	Risk of fatal injuries by country
Human Rights	High conflict zones	Overall High Conflict	Overall Risk for High Conflict
	Indigenous Rights	Number of laws to protect indigenous according to ILO NATLEX, Indigenous Sector Issues Identified	Risk that a country does not provide laws to protect indigenous, Risk that indigenous people are negatively impacted at sector level
Community	Access to Improved Drinking Water	% Total Access to an Improved Source of Drinking Water	Risk of no access to an Improved Source of Drinking Water-total
	Smallholder v. Commercial Farms	Percentage of family-owned farms in country, Percentage of commercially-owned farms in country, Smallholdings Land % < x hectares	Risk of low family ownership in Agriculture, Forestry, Fishing, Risk in relation to commercial ownership in Agriculture, Forestry, Fishing Risk of low land holdings for small agriculture
	Access to an Improved source of Sanitation	Total Access to an Improved source of Sanitation	Risk of no access to an Improved source of Sanitation total
Socio-economic Contributions	Contributions to Value Added	Payments to agricultural and other low-skilled workers	
		Payments for natural resources	
		Payments for land	
		Total economic output	

6.2 Methods and Data

In this section, the main data source for social impact assessment is explained in detail. Next, an explanation of the methodological steps in the proposed SIO model based on I-O analysis is presented.

6.2.1 Social Hotspot database

Significant breakthrough and advancement in SLCA have been made since the creation of the social hotspot database (SHDB). Since its introduction, it has been applied on different studies involving social impact assessment of products (Pelletier et al., 2018; Shemfe et al., 2018; Zimdars et al., 2018; Martinez-Blanco et al., 2015; Ekener-Petersen et al., 2014; Norris et al., 2014). An earlier version of the SHDB released in 2016 had data on five social impact categories, namely labour rights and decent work, human rights, health and safety, government, and the local community. In 2018 however, the recent version was introduced, which included the socio-economic impact category. The Social Hotspot Database is developed by a team of researchers at Harvard University and New Earth B. It contains data on potential social impacts or risk compiled at country and sector-specific levels (Norris et al. 2013). The database is structured into twenty-two social theme tables which falls under six social impact categories, namely labour rights and decent work, Human Rights, Health and Safety, Governance, Community and Socio-economic contribution. In addition, there are several social sub-category indicators under each of the social themes.

The unit of measurement for a social issue or risk in the SHDB is worker hours. Data on worker hours help identify where human activity is occurring in supply chains. Worker hours play the role of what environmental LCA refers to as an “elementary flow”– the basic or first-order “intervention” by a production process that ultimately is linked to outcomes or impacts of interest. Heymann (2010) consider it essential to identify who performs much of the vital work in supply chains. Dreyer et al (2010) suggests some potential activity variables (also referred to as product relation factors), the most common variable being worker hours.

Even though worker hours may be less directly linked to issues related to local communities and society, they remain to date the most meaningful activity variable that is used to assess the scale of an issue within the context of the supply chain as a whole.

The SHDB is founded on the Life Cycle Attribute Assessment (LCAA) developed by Norris (2006) which involves quantifying the percentage (%) of an activity variable that possesses an attribute of interest (e.g. high risk of a social issue). The results can be expressed in the following way if LCAA is used for the purpose of communication: for example, % of workers hours that present a high or very high risk of child labour, or % of worker hours which are paid a fair wage (Zamani et al, 2018). The risk for a given sub-category indicator are characterised under different levels social indicator; low risk, medium risk, high risk and very high risk (Mancini et al 2018). In this study, the sub-category indicators of high and very-high risk were included in the analysis to emphasize the social hotspot needing much attention.

In terms of countries and sectors, SHDB is structured similarly to the Global Trade Analysis Project (GTAP). The GTAP database (version 9) is a global database describing bilateral trade patterns, production, consumption and intermediate use of commodities and services with 129 regions for 57 economic sectors for the years 2004, 2007 and 2011 (Oppon et al, 2018). New Earth B developed the labour intensity data by dividing GTAP data on wage payments by country and sector average wage. New Earth B collected the data on the average wage. This provides estimates of worker hours for each sector (57) in each of the GTAP country/region (140). Thus, the SHDB estimates the quantity of worker-hours associated with lifecycle process of a product supply chain for a given output (Mancini et al, 2018).

6.2.2 Social Input-Output (SIO) Framework

In the current chapter, a recap of the equations and matrices involved in an I-O framework is first presented, after which a discussion of how the framework is extended in the SIO model is illustrated. In the I-O table, the inter-industry relationship is known as Intermediate consumption (Z). Other parts of the I-O table show the Final demand(Y) of commodities by households, governments, investment, or exports and the Total Output(X) of a sector.

The relationship between Intermediate consumption (Z), Final demand (Y) and Total output (X) is given by:

$$\mathbf{Z} + \mathbf{Y} = \mathbf{X} \xrightarrow{\qquad\qquad\qquad} \textbf{Equation 1}$$

A technology matrix also commonly referred to as the A matrix, is constructed to show the input required to produce a unit output between the sectors. *also known as a matrix of direct requirement.* It is t also known as the direct requirement matrix since the emphasis is on the direct inputs from one sector to another required for production.

Technology Matrix (A), is given by:

$$\mathbf{A} = \frac{\textbf{Intermediate consumption}}{\textbf{Total output}} = \frac{\mathbf{Z}}{\mathbf{X}} \xrightarrow{\qquad\qquad} \textbf{Equation 2}$$

We know from Equation 1 that

$$\mathbf{Z} + \mathbf{Y} = \mathbf{X}$$

And from Equation 2

$$\mathbf{A} = \frac{\textbf{Intermediate consumption}}{\textbf{Total output}} = \frac{\mathbf{Z}}{\mathbf{X}}$$

$$\therefore \mathrm{Z} = \mathrm{AX}$$

Then $\mathrm{AX} + \mathrm{Y} = \mathrm{X}$

So that $Y = X(1 - A)$

But A is a matrix, therefore

$$Y = X\,(I - A)$$

Where I is an identity matrix. Hence

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}\boldsymbol{Y} \xrightarrow{\qquad\qquad} \textbf{Equation 3}$$

$(\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}}$ in Equation 3 is referred to as the **Leontief Inverse Matrix** or total requirement matrix and it shows cumulative value for both direct and indirect inputs needed in each sector to meet demand for a unit of output. Emphasis is now being placed not just on what goes on within the firm (direct) but on a complete lifecycle assessment such that the upstream impacts which occur in the extended supply chain process are also captured.

To account for the social impact associated with silicate production, the I-O framework can be extended with a social extension matrix to compute impacts. The social extension matrix is constructed first by developing a 'social intensity matrix'. The social intensity matrix ($\mathrm{S_{IM}}$) can be compared to the 'D_{IM}, direct intensity matrix' such as in the case of the EEIO model. The difference is that, whereas the direct intensity matrix in the EEIO model measures sectoral emission intensities per unit of output produced, the social intensity matrix within the SIO model is a measure of sectoral direct risk-working hours (or simply risk-hours) per dollar of output.

$Let\ S = \{s_{kj}\}$ be the sectoral direct risk-working hours derived for a social risk indicator k (e.g. forced labour, child labour, excessive working hours, etc.) across j industry, obtained from the SHDB. There are varying risk levels for a given social indicator, but for this study, the focus is on high and very high-risk indicators. For impact aggregation, a weight of 5 is applied for high-risk indicators while a weight of 10 is applied for very-high risk indicators which are in line with the recommendation from the SHDB supporting documentation.

Given that Eq. (3) represents the total requirements needed to produce the output x for a given final y, it implies that if the social direct risk hours per unit industrial output is SiM, then the total social impacts are represented below as Eq. (4):

$$\boldsymbol{Total\ social\ impact = SiM(I - A)^{-1}Y} \qquad \textbf{Equation 4}$$

In Eq. (4), the inclusion of the Leontief inverse matrix represented by$(\boldsymbol{I - A})^{\boldsymbol{-1}}$ in the SIO analytical framework ensures complete supply chain visibility of all economic activities capturing both direct (operational) and indirect (supply-chain) components of social impacts.

6.3 Analysis and Results

For uniformity and easy comparison, analysis and results presented in this chapter follow the same approach as used the previous chapters 4 & 5. For each social impact category (Labour rights and decent work, Health and Safety, Human Health, Community and Socio-economic impact), three key results are shown.

i. Risk-hours per kg of basalt produced
ii. Direct & indirect risk
iii. Sectoral contribution to risk impact

In addition to these results, the number of high and very-high risk indicators for Labour rights and decent work, Health and Safety, Human Health, Community Infrastructure are shown. The socio-economic contribution is excluded in this result because they are not measured in risk-hours but dollars. Details of the risk indicators in the social themes for each country are included in Appendix B.

6.3.1 Labour rights and decent work

In this section results on the social impact relating to labour rights and decent work are presented. Overall, the results in Fig 6.2a and Fig 6.2b show that there is more social risk exposure in emerging economies than developed economies concerning labour rights and decent work. One interesting finding in the study is that despite results showing both China and USA as having the same number of very-high risk indicators (14), there is a notable difference concerning the total risk hours associated with per kg crushed silicates production in these countries.

Among the emerging economies, results show India as having the highest number of risk indicators with regards to labour rights and decent work issues; 18 very-high risk and 14 high-risk indicators. These indicators correspond to a total of 193.7 risk-hours associated with per kg production of crushed silicates. Although Brazil has the same number of high-risk indicators as India (that is 14 high-risk indicators), the country has relatively the lowest risk hours (38.4 risk hours per kg produced) among all the four emerging economies. This is explained by the fact that there were only four very-high risk indicators identified within the supply chain. Russia and China have a similar number of high-risk indicators, 11 and 12, respectively. However, the two countries differ in terms number of very-high risk indicators identified within the supply chain with Russia having seven and China with ten very-high risk indicators. Subsequently, results show China as having significantly high-risk hours per crushed silicate produced, that is 93.2 risk-hours than Russia, which has a total of 51.9 risk-hours.

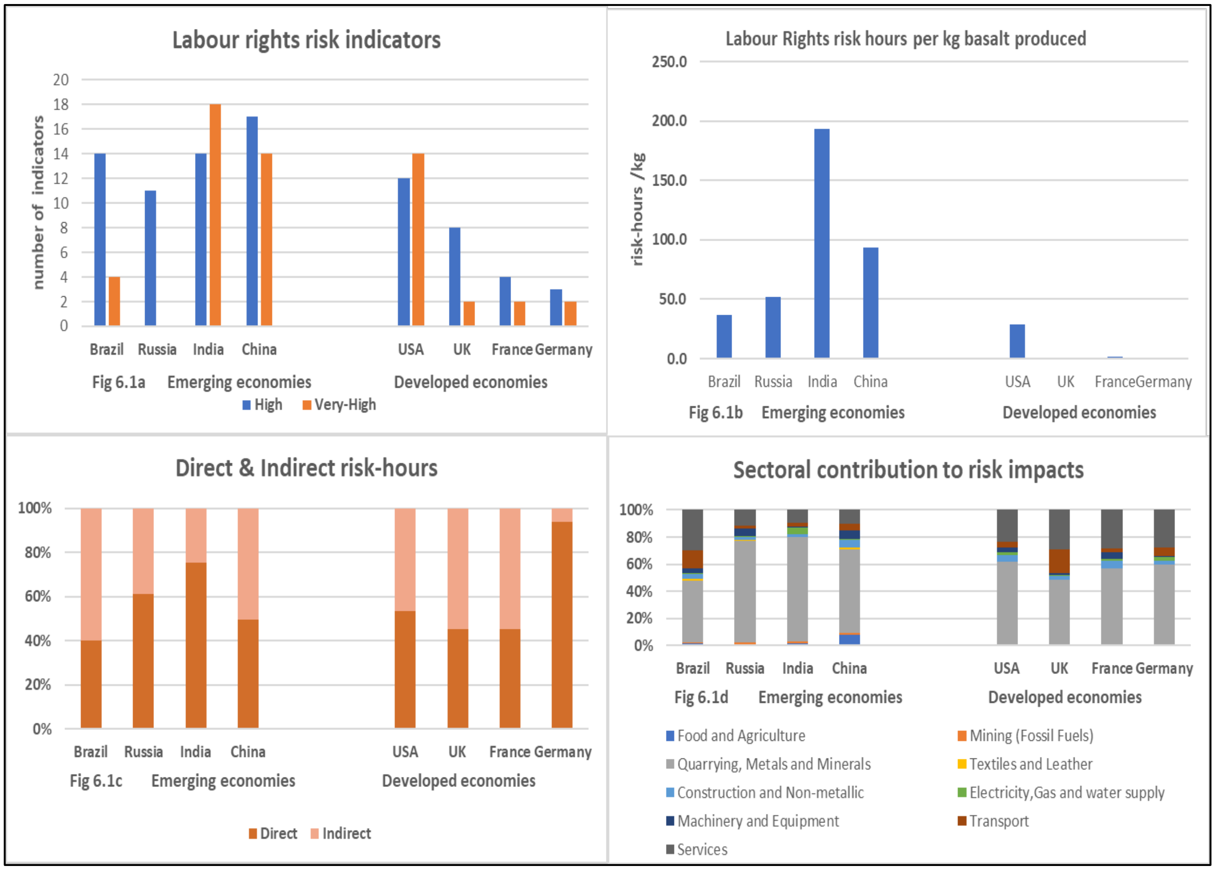


Fig 6.1: Labour rights and decent work risk impact

In the case of developed economies, the country with the highest number of risk indicators identified is the USA, which has six high-risk indicators and 14 very-high risk indicators. This result explains why the USA has the highest risk hours of 28.8 per kg of crushed silicate produced. Aside from the USA, the second-highest of risk indicators identified was in the UK, which has eight high-risk indicators and two very-high risk indicators. However, despite the relatively high number of indicators identified, the UK has the lowest risk hour of 0.2 risk-hours per kg with regards to labour rights and decent work social theme. France and Germany have the same number of very-high risk indicators identified that is 2. In terms of very-high risk indicators, France has slightly more than Germany, that is 4 and 3, respectively, and this translates to a total of 1.2 and 1.1 risk hours per kg produced respectively.

In terms of direct and indirect risk-hours (Fig 6.2c) for Brazil, the indirect impacts, 60% are more than the direct impacts. For China, there is an equal split of direct and indirect risk-hours, that is 50% in each case. For Russia and India, the direct risk-hours 60% and 75% are relatively higher than in Brazil and China. With the developed economies, direct risk-hours on labour rights is highest in Germany, representing 90%. For the UK and France, the indirect risk-hours, which is 65%, exceeds the direct risk hours. For the USA, there is an equal split between direct and indirect risk-hours.

In the sectoral distribution labour rights and safety risk, it is evident from the results shown in Fig 6.1d that the QMM sector has the most risk exposure. However, in some countries, the impacts are more pronounced than others. For instance, among the emerging economies, sectoral contribution to risk-hours from Brazil's QMM sector (~50%) is relatively less compared to Russia (~80%), India (~80%), and China (~60%). Brazil's Services and Transport sector account for 35% of risk-hours in labour. Although the QMM sector in the developed economies accounts for highest sectoral contribution to labour risk-hours, the second-highest contribution, which is from the Services sector is relatively high compared to the service sector in emerging economies. In the UK, results show that the Transport sector with sector contribution of ~20% is the third sector with the highest contribution to labour risk-hours in the country.

6.3.2 Health and Safety

In this section results on potential health and safety risk associated with basalt production are presented. Similar to results shown on labour rights and safety risk, whereby the emerging economies have the highest health and safety risk compared to developed economies (Fig 6.2a and 6.2b). China has relatively the highest risk hours of 119.2 per kg of crushed silicates produced concerning health and safety issue, which corresponds to 5 high risk and 14 very-high risk indicators in the supply chain. India has the second-highest risk hours of 65 corresponds to 8 high risk and five very-high risk indicators. In the case of Russia, there are 52.1 risk hours of health and safety concern which corresponds to 15 high risk and three very-high risk indicators. Brazil has the lowest risk hours of 19.6. However, it must be noted that aside the seven high-risk indicators identified, there were no very-high risk indicators identified in Brazil supply chain.

For developed economies, although the USA has the highest risk hours of 4.1 per kg of crushed silicate produced, it has a relatively low number of risk indicators identified;5 high risk and two very-high risk indicators. The UK has 12 high risks, and one very high-risk indicator correspond s to a total of 1.9 risk hours per kg crushed silicates produced. France has ten high-risk indicators and two very-high risk indicators corresponding to 2.9 risk hours. In the case of Germany, nine high risk and two very-high risk indictors were identified corresponding to 3.2 risk hours related to health and safety. For direct and indirect risk-hours(Fig 6.2c) and sectoral contribution (Fig 6.2d) to risk impacts results show a similar pattern as presented in Labour rights and decent work.

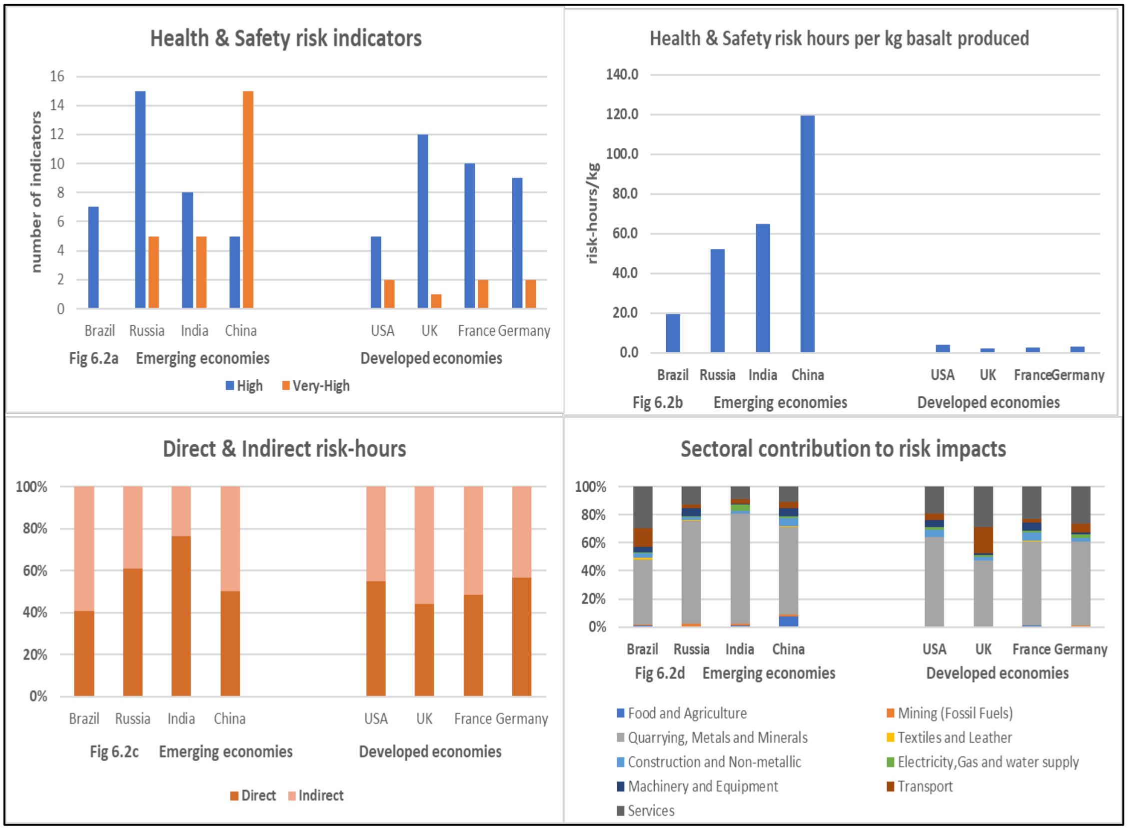


Fig 6.2 Health and Safety risk impacts

6.3.3 Human Rights

In this section results on human rights risk are presented. The findings show some unexpected results with regards to human rights risk in emerging economies. For China, seven indicators were identified for both high and very high risk, and this corresponds to relatively the highest risk hours of 73.4 per kg crushed silicates produced among the four emerging economies. In the case of India, results show that despite having high-risk indicators, specifically 14 high risk and four very-high risk indicators, these correspond to relatively low-risk hours of 9.6 per kg. Russia and Brazil were found to be at similar risk levels in terms of human rights risk, with Brazil estimated to have 25.2 risk hours and Russia

27.2 risk hours. However, similar to the health and safety issue impact category, there was no very-high risk indicator identified for Brazil except eight high-risk indicators identified. For Russia, seven high risk and four very-high risk indicators were identified.

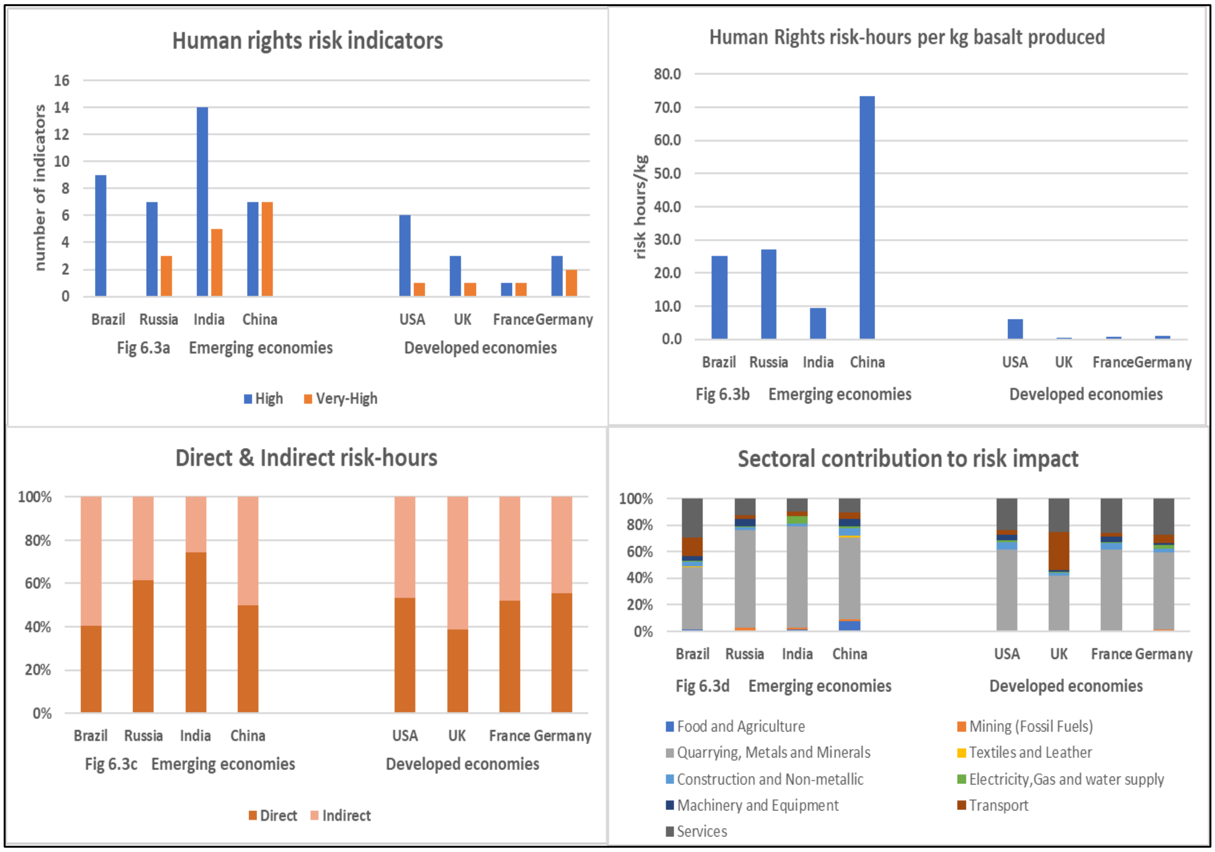


Figure 6.3 Human rights risk impacts

For the USA, a total of 6 risk hours/kg are identified associated with the basalt production, which comes from 6 high-risk andone1 very-high risk indicators identified. For the UK, results show 0.5 risk hours per kg corresponds to three high and one very-high risk indicators identified. The same number of high and very-high risk indicators were identified in France, which corresponds to 0.7 risk hours/ kg of crushed silicate produced. Germany has 1.1 risk hours/kg, which comes from three high risk and two very-high risk indicators.

Again, a similar pattern, as discussed in labour rights and health and safety risk, is seen for direct and indirect risk-hours and sectoral contribution with regards to human rights. A slight difference is, however, seen in the case of the UK where the sectoral contribution from the Transport sector (25%) is higher than observed in Labour rights and health and safety which was 20%.

6.3.4 Community

In this section results on community infrastructure risk is presented. India has the highest community risk (33.5 risk hours per kg) associated with crushed silicate production, which corresponds to 5 high and one very-high risk indicators identified. Brazil follows it with 14 risk hours per kg which corresponds to five high-risk indicators but no very-high risk indicator. China has 11.8 risk hours per kg corresponds to three high risks, and one very-high risk. Russia had the least risk hours of 0.04 per kg, which comes from one high and very-high risk indicator each.

Across all the four developed economies, one high and very-high risk indicators were identified each. However, the USA has the relatively the highest risk hours per kg, that is 2.5/kg. Both the UK and France are estimated to have 0.2 risk hours per kg produced. Germany has only 0.004 risk hours per kg. Overall, the results show that developed economies have significantly lower community risk compared to the developed economies.

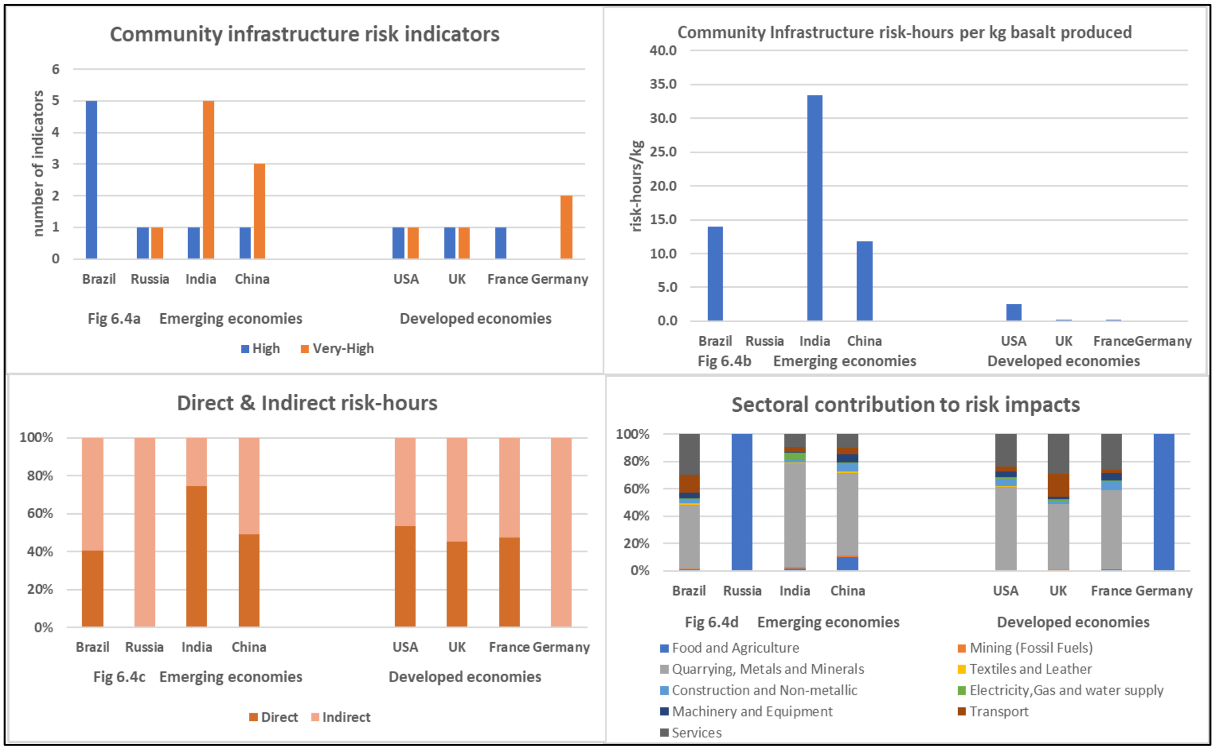


Fig 6.4 Community infrastructure risk impacts

For direct and indirect risk hours, the pattern observed for community infrastructure risk differs from the social risk (Labour rights and safety, Health & Safety and Human rights) discussed in previous sections. Specifically, the main difference can be seen for Russia and Germany, where the results show that for indirect risk hours dominates with direct impacts being very low. In terms of sectoral contribution, the Food and Agriculture sector in Russia and Germany is where social risk impacts associated with community infrastructure is mostly high. For the other countries belonging emerging and developed economies, the QMM sector has the highest percentage contribution to risk related community infrastructure.

6.3.5 Socio-Economic Contributions

In this section, we show estimates for socio-economic contribution measured in USD for every 1kg of crushed silicate rocks within an economy. Among the BRIC countries, India has the highest potential socio-economic impact of ~ $8.4 per kg or crushed silicate produced.

The second BRIC country that stands to benefit from significant impact is China with potential socio-economic impact of ~$5.4. Brazil and Russia have a relatively low socio-economic impact, approximately $4.3 and $3.8, respectively. In comparison, countries such as the UK, Germany and France have less than $1 in terms of potential socio-economic impact. Only the USA has a slightly higher impact, which is ~$1.4. Although the estimates are dependent on the assumption and scenario used in this study (that is producing to meet final demand of $25 per kg), the results are still representative as the use of different final demand figure will only not necessarily change the outcome of the overall results.

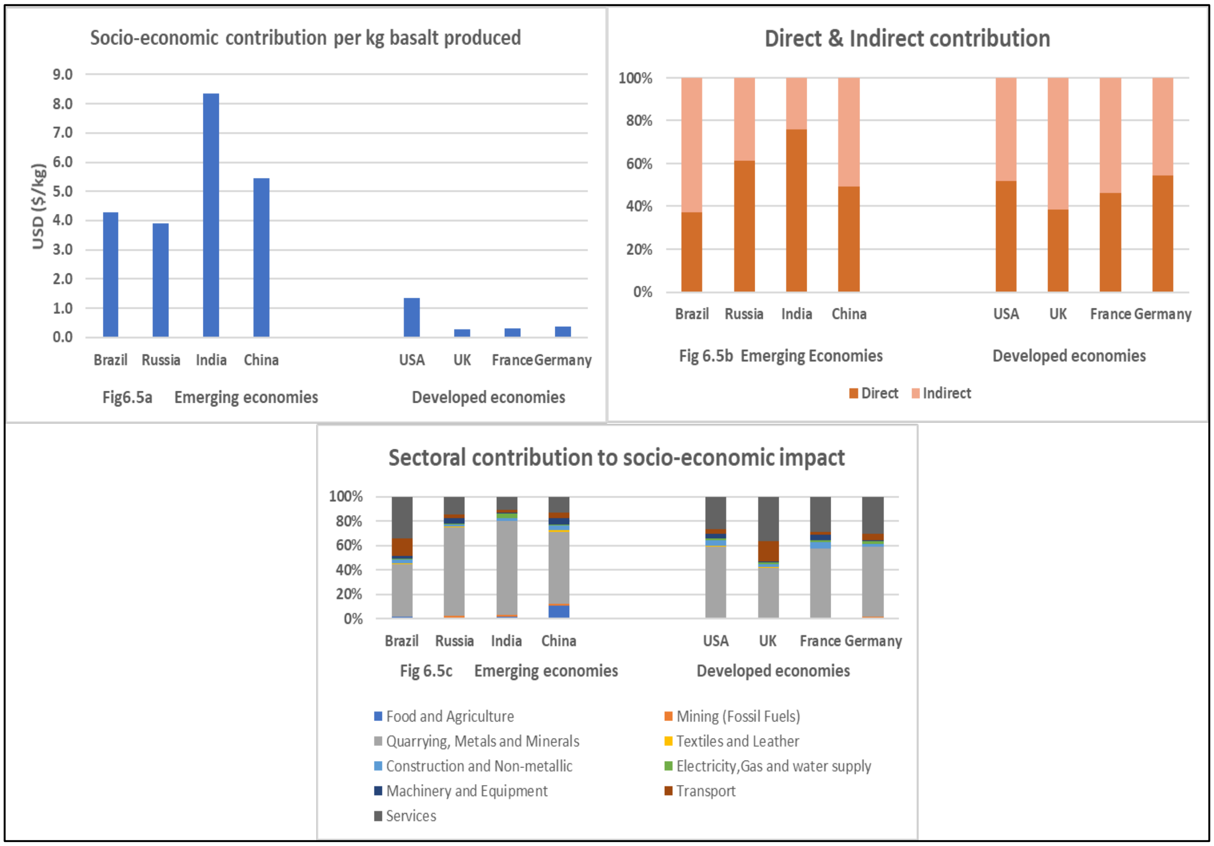


Figure 6.5 Socio-economic contribution impacts

6.4 Discussion and Conclusion

The proposed SIO model used in the study, which is based on an extension of the I-O framework has been used to estimate potential social impact risk associated with basalt production for ERW. Developing the SIO model on the I-O framework makes it possible to capture social impacts from a macro-level perspective and beyond a single mining and quarry firm. In particular, direct and indirect risk-hours associated with the use of direct and indirect inputs in basalt production was presented, which indicates how the risks are displaced beyond the M&Q sector where direct production takes place. In addition, the sectoral contribution also increases visibility by highlighting the sectors that will be most impacted by the large-scale production of basalt for ERW.

The analysis and results presented to a large extent, validate various conclusion by other researchers on social issues between emerging and developed economies and therefore increases the reliability of the model. Overall results show that for the impact categories relating to Labour rights, Health & Safety, Human rights, and community infrastructure the production of basalt has very high negative risk impacts for emerging economies compared to developed economies. The case is, however, different with regards to socio-economic impact category, whereby the emerging economies perform better than developed economies. The selected indicators that were considered in the socio-economic contribution impact category are provided in the appendix section.

The SHDB has been the backbone of data source for the SIO model and provides relevant data social impact at the country and sector level. There are limitations, however, in terms of data incompleteness for some of the social indicators under the social impact categories (Traverso et al.,2018). In particular, for community infrastructure, although results show that Russia has relatively very low-risk hours, this, may be due to inadequate data availability. Various authors that have used SHDB for quantitative social impact assessment acknowledges the data limitations with the database (Ekener-Petersen et al. 2014, Moran et al. 2015, Petit et al. 2018, Traverso et al. 2018, Valente et al. 2018). However, on the other hand, the SHDB should be viewed as a good initiative and contribution to developing more quantitative SLCA methodologies.

The current study makes a vital methodological contribution to social sustainability assessment in supply chains. By including the social risk impacts of basalt production, the chapter completes the sustainability assessment presented in Chapters 4 & 5, which focused on economic and environmental sustainability. Sustainability assessment of supply chains is incomplete and indeed narrow when social issues are excluded from the evaluation. Several studies have emphasised the crucial link and impact between social performance on overall organisational performance (Yawar and Seuring, 2017; Waddock and Graves, 1997). There are real-life examples of organisations whose social sustainability of their products has been questioned and, in some cases, these have led to a damage in their reputation which ultimately affects bottom line profits (Brammer and Pavellin, 2006, Fombrun and Shanley, 1990). Social issues along supply chains should, therefore, not be decoupled from environment and economy sustainability performance of supply chains (Petit et al., 2018).

6.5 Chapter Summary

The chapter presented analysis and results based on a multi-country study of macro-level social sustainability of ERW. The generic IO model is extended to characterise the potential social impact associated with mining and quarrying of crushed silicates in a proposed social input-output (SIO) model. Five social impact categories were assessed namely Labour rights and decent work, health and safety, human rights, community infrastructure and socio-economic contribution. Results presented and discussed included number of risk indicators per given social impact category, total social risk impact per kg basalt produced, direct and indirect impact and sectoral contribution to total social risk impact. To this point in the study, three pillars of sustainability have been assessed that is the economic impact in Chapter 4, environmental sustainability in Chapter 5 and social impact in the current chapter. The next chapter (Chapter 7) will present analysis and results associated with integrated TBL assessment based on the results from the previous three chapters.

CHAPTER 7: INTEGRATED TRIPLE BOTTOM LINE ASSESSMENT OF SILICATE PRODUCTION FOR ENHANCED ROCK WEATHERING

7.1 Introduction

The preceding studies (Chapters 4-6) focused on the economic, environmental, and social assessment of ERW production supply chain. In this current chapter, integrated TBL results from these chapters are presented. The overall aim is to compare the countries across all three TBL factors and rank them. Furthermore, a country may do well economically, but may not perform well either environmental or socially and therefore, it is important that the potential trade-offs among the TBL factors are shown. Such an analysis provides further insight for individual countries to identify which area of sustainability needs improvement concerning the production of crushed silicates.

7.1.1 Measuring Triple Bottom Line impacts

There is no commonly accepted approach for estimating integrated TBL supply chain impacts (Wang and Lin 2007). According to Slaper and Hall (2011) the lack of a standardised method for TBL measurement should be considered as an opportunity for researchers and practitioners to develop frameworks that allow for TBL assessment from different perspectives such as geographic boundaries. In line with this thinking, various authors have attempted to make some valuable methodological contributions in the area of TBL assessment (Halog and Manik 2011; Onat et al. 2014; Onat 2015).

The challenge with an integrated TBL analysis is the common unit problem (Slaper and Hall, 2011). This problem arises because each of the TBL factors has a different unit of measurement. Slaper and Hall (2011), suggest two approaches of tackling the unit problem. The first approach involves monetizing each TBL factor. The challenge, however, with this approach is that not all the TBL factors especially relating to environmental and social impacts can be monetized. The second approach they suggest which is more preferred involves calculating the TBL in terms of an index. The use of an index eliminates the unit problem and allows for comparing sustainability performance between entities (Slaper and Hall,2011).

An example of a study that uses an index system for integrated TBL measurement is the lifecycle sustainability dashboard (LCSD) framework first introduced by Traverso and Finkbeiner in 2009. The LCSD is a simple but broad presentation of LCSA impacts based on graphical representation (a cartogram). The methodological framework of the LCSD is based on an overall sustainability performance index, underpinned by the individual index for economic, environmental, and social. The LCSD model uses the Dashboard of Sustainability tool; a software tool created by Joint Research Centre of Ispra in Italy which assesses overall sustainability performance which they term as policy performance index and individual index for each TBL factor (Hardi and Semple, 2000). Dashboard of sustainability tool, which is supported by the International Institute of Sustainable Development (IISD) presents results using graphical representation(cartogram) based on chromatic scale and ranking score. Traverso et al. (2012) applied the LCSD on natural hard floor coverings.

Wang and Lin (2007) use a quantitative TBL framework for sustainability analysis at the corporate level. Their TBL framework is based on a sustainability index system. The authors use a 'sustainability optimisation' model. Their study acknowledges the fact that sustainability can be conducted from either a macro-level which covers regional or national level or micro-level which covers the corporate level. The methodological approach taken in the study is the same approach taken in the study by Traverso et al. (2012), and Wang and Li (2007) where an overall sustainability index, is developed underpinned by individual index set is developed for each TBL factor.

The sustainability index model presented in this study is in line with the use of I-O frameworks which has been used in the previous three chapters. Some authors refer to this method as triple bottom line input-output analysis (TBL-IO) (Onat et al., 2014; Wang and Lin 2007; Foran et al.,2005). While former I-O LCA models estimate environmental impacts, TBL-IO model in addition estimates economic and social impacts as well (Kucukvar, 2013). The first comprehensive TBL input-output analysis developed by Foran (2005a) was used for macro-level industrial assessment of Australia's economy. Their model was called the Balancing Act and was based on economic, environmental, and social indicators for over 100 sectors. In study by Kucukvar et al (2014) and Elglimez et al, 2014, also used a TBL-IO model in a sustainability study on asphalt payment and food sector, while Noori et al (2013) employed the model on sustainability of wind.

Study by Onat et al. (2014) also performs a macro-level lifecycle sustainability assessment of US buildings based on the TBL-IO. Their study used 16 macro-level indicators categorised under three economic, environmental, and social impacts. For this study, 15 macro-level indicators are used grouped under the TBL factors; 5 indicators under each TBL factor (Fig 7.1).

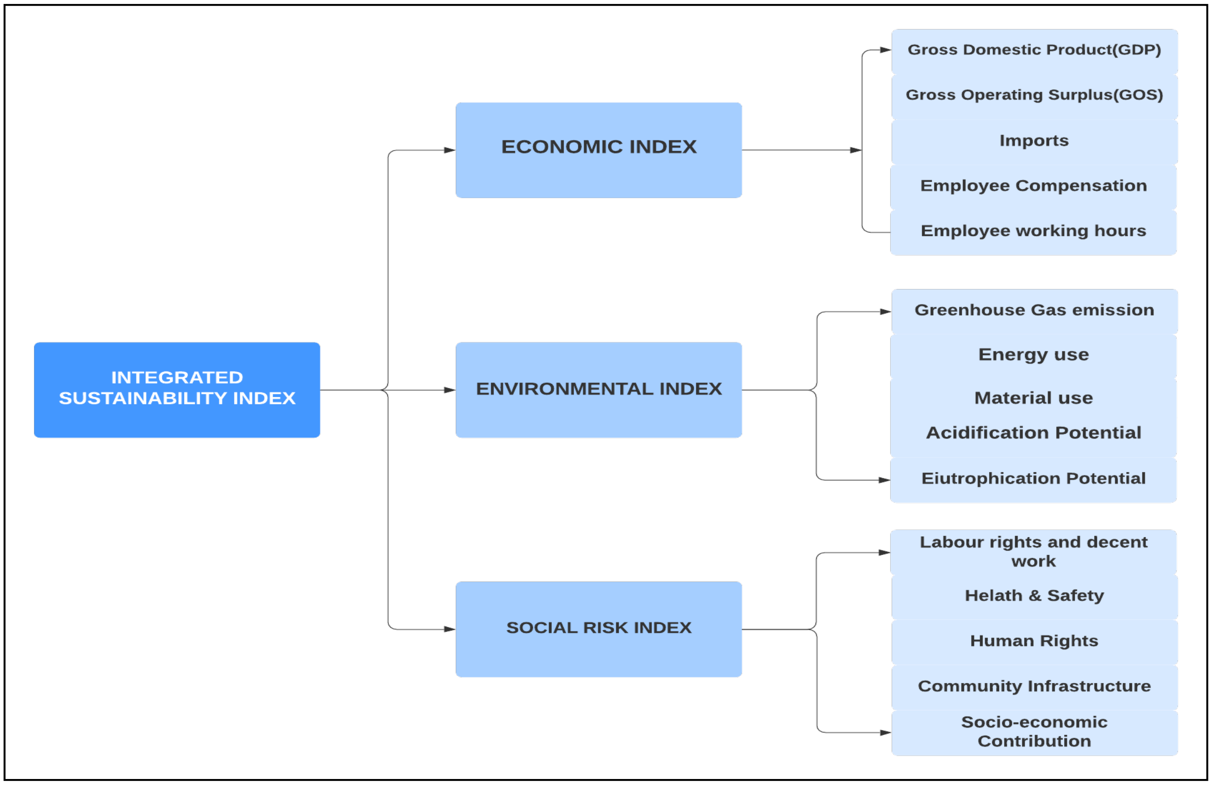


Figure 7.1 Overview of macro-level indicators used in constructing sustainability indices

In measuring the TBL impacts of silicate production for ERW, the current study is informed by similar approaches in the studies discussed above. The method and data section which follows next illustrates in detail the specific method that is used in estimating the integrated TBL indices.

7.2 Method and Data

The use of indices has several advantages. Indices are useful tools in benchmarking the performance of countries in complex issues (Saltelli, 2007). They are also helpful in presenting a summary of multi-dimensional issues. By summarising complex issues into relatable values, indices also enhance easy communication with relevant stakeholders. In addition, when periodically calculated at regular time intervals, they can be used to access country progress in achieving a set goal or target. These advantages influenced the decision to use indices in the current study.

Despite the pros of using indices, there are some limitations associated with the use of indices that must also be highlighted. For instance, the use of indices presents some challenges such as over-simplification of issues which could lead to misleading policy signals. Also, the results are subject to the selection of the different methods used in calculating the index. For instance, the choice and number of indicators, the normalisation and weighting method can all influence the values obtained. In dealing with these challenges, transparency is critical so that more useful and guiding interpretations can be made. The methodological framework and data used before the construction of the index must be transparent and issues which have been clearly outlined to avoid any misinterpretation of the index (OECD,2008). In line with this, the IO framework which is the fundamental methodology used in the macro-level TBL analysis of the ERW supply chain is illustrated in detail in the method sections in chapter 3, 4 & 5. Sensitivity analysis is also included in determining how robust the results are.

The steps used for developing the indices are shown in Figure 7.2 and these closely align with the recommendations of the OECD handbook on composite index (OECD, 2008).

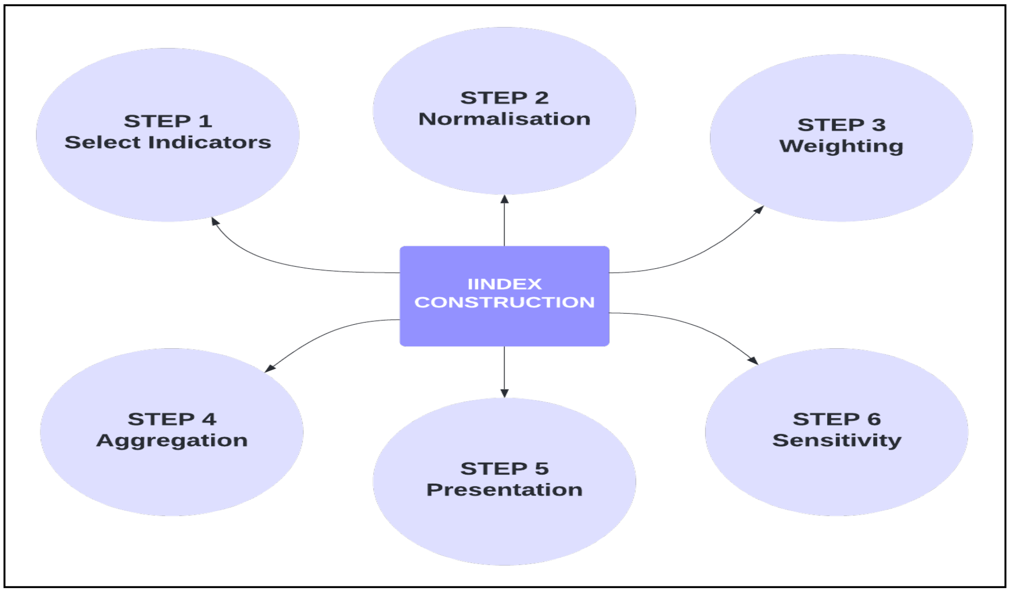


Figure 7.2: Steps used in index construction

In Chapters 4,5 & 6, an I-O framework is used to analyse the economic, environmental, and social impacts of silicate (basalt) production, which occurs in the Mining and Quarrying sector. The complete data results for impacts per kg produced (shown in the appendix) is selected and used as the basis for developing indices for the integrated TBL (step 1). The units for the various impact categories differ among the TBL factors. For useful comparison between, for instance, GWP, which is measured in CO_2-eq and energy use measured in MJ, the units must be eliminated by normalising the data (step 2). According to the handbook on composite indicators, there are different normalisation methods that can be used, such as the distance to reference method, max-min method and z-score, method (OECD, 2008). In the current study, the distance to reference (DTR), also known as the distance to target method is used. In this method, values are normalised in relation to a reference value, usually the maximum (best) value in a given impact category.

Therefore, the normalised value of an impact category in a country is estimated based on its ratio to the maximum value in the given impact category and is estimated using EQ1 below:

$$\boldsymbol{W}xp = \frac{xp}{\mathrm{Max(n)}} \qquad \text{Eq. (1)}$$

$\boldsymbol{w}xp$ is the normalised impact x (example GDP, energy use, health & safety, etc.) in country p

xp is the estimated raw data impact for kg basalt produced in country p.

Max$_{(n)}$ refers to the maximum value across all 'n' number of countries for a given indicator

Step 3 in the construction of the index involves a weighting of impacts. Weighting is usually applied to reflect the relative importance of some impacts over others. However, in the current study, the assumption is that all impacts are equally important and therefore, an equal weighting of 1 is applied as recommended by the handbook. If impacts were considered more important than others, then methods such as data envelopment analysis(DEA) and analytical hierarchical process (AHP) would be used which are usually used in situations of unequal weighting (OECD, 2008).

Estimating individual TBL index

Based on the normalised and weighted values estimated in Eq (1), an index is calculated for each TBL factor as a measure of sustainability performance in a country through aggregation (Step 4). This is carried out using the additive aggregation method, which is a linear summation of weighted normalised impacts (OECD, 2008). The individual TBL indices are referred to in the study as an economic index, environmental index and social risk index. The economic index score (EC index) is a combined weighted and normalised value of all the economic impact categories (GDP, GOS, imports, employee compensation, and working hours). It indicates the overall economic sustainability performance of countries in producing silicates for ERW. The economic sustainability index score (EC index) is estimated as follows, as shown in Eq (2):

$$EC_{index(p)} = \sum_{n=5}^{Wxp} = \left(Wxp_1 + Wxp_2 + Wxp_3 + Wxp_4 + Wxp_5\right) \qquad \text{Eq. (2)}$$

The environmental index score (EN index) is a combined normalised weighted value of all the environmental impact categories (GWP, energy use, material use, acidification, and eutrophication potential). It indicates the overall environmental sustainability performance of countries in producing silicates for ERW. The environmental index score (EN index) is estimated as follows, as shown in Eq (3):

$$EN_{index(p)} = \sum_{n=5}^{Wxp} = \left(Wxp_1 + Wxp_2 + \ Wxp_3 + Wxp_4 \ + Wxp_5 \ \right) \qquad \text{Eq. (3)}$$

The social index score (SR index) is a combined weighted value of all the social risk impact categories (labour rights, Human health, Human rights, Community infrastructure and socio-economic contribution). It indicates the overall social sustainability performance of countries in producing silicates for ERW.

The social risk impact index score (SR index) is estimated as follows, as shown in Eq (4):

$$SR_{index(p)} = \sum_{n=5}^{Wxp} = \left(Wxp_1 + Wxp_2 + \ Wxp_3 + Wxp_4 \ + Wxp_5 \ \right) \qquad \text{Eq (4)}$$

Estimating the overall sustainability index

After estimating the individual TBL index, (EC index, EN index and SR index), an overall sustainability index is calculated that is the Lifecycle sustainability assessment index score. Lifecycle sustainability assessment index score (LCSA index) represents an integrated TBL for each country based on the combined weight of all the impact categories under each sustainability pillar.

The impact categories that are included in the three TBL factors may be negative or positive. Therefore, these must be reflected in the overall sustainability index score for a country. The way to view an impact as positive or negative can be rationalised as whether the impact is a benefit or cost to the economy, environment or society, such that positive impacts are considered as a benefit while negative impacts are considered as a cost. In the Economic index score (EC index), GDP, GOS and employee compensation are positive impacts while imports and working hours are considered as negative. For the Environmental index score (EN index), all the impacts, including GWP, energy use, material use, acidification, and eutrophication potential, are considered as a negative impact. For the Social risk index score, all impacts including labour rights, health and safety, human rights and community infrastructure are considered negative while socio-economic impact contribution is positive.

The combined sum of the EC index, EN index and SR index make up the LCSA index score which provides an overall sustainability performance measure for a country with regards to the production of crushed silicate rocks. The LCSA index is represented as Eq (5) :

$$\boldsymbol{LCSA_{index(p)}} = EC_{index(p)} + EN_{index(p)} + SR_{index(p)} \qquad \text{Eq. (5)}$$

7.3 Analysis and Results

Analysis and results based on the method described in the previous section are presented here. The specific results presented are as follows:

- Sustainability performance based on weight and rank: First, the normalised weight of each impact that makes up the index are presented. This makes it possible to identify which impact has the strongest influence on the sustainability index score for a given country (Brazil, Russia, India, China, USA, UK, France and Germany). Based on such an analysis, we can identify and focus on the impacts that are relatively high in a country and justify where operational practices and policies should be targeted. In addition, a ranking for each of the impacts is also shown, which allows for comparison between countries in showing how the countries perform against each other in a given TBL impact category.
- Integrated sustainability indices: This shows results for integrated individual and overall TBL sustainability impact of crushed silicate production represented by the EC index, EN index, SR index and LCSA index.

7.3.1 Individual sustainability based on weight and rank

In this section results on the economic impact are presented. Figure 7a shows impacts based on a weight scale from 0 to 1. The closer a value is to the outer circumference, the higher the weight while values closer to the inner circumference indicates lower weights. Presenting the results in this way helps to easily identify which indicator has the highest contribution to each country's overall Economic index score (EC index score). This can also be interpreted as the 'hotspot' in terms of the overall economic impact of ERW.

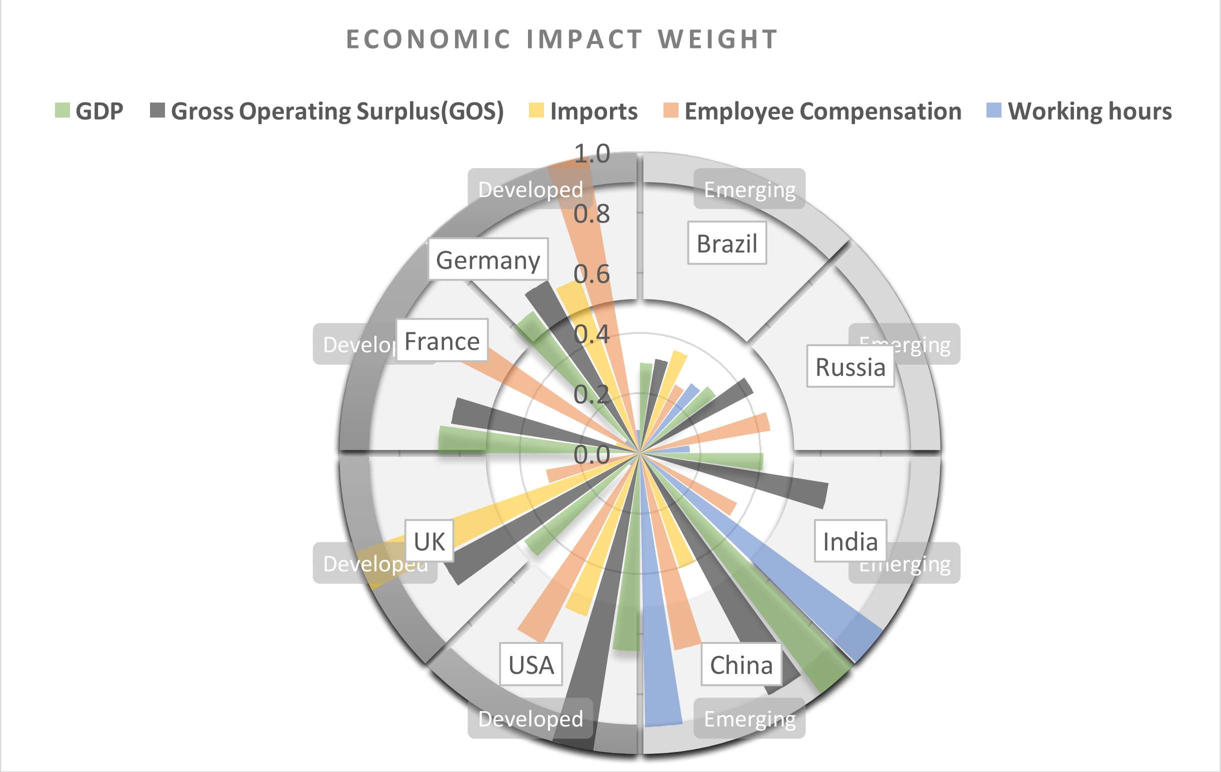


Figure 7.3: Economic Impact weight for emerging and developed economies

From Fig 7.1, it can be observed that most of the impacts are skewed to the left of the graph (that is the developed economies) depicting that economic impacts are higher in these countries compared to the emerging economies (located on the right side of the graph). An impact with a weight of 1 or closer to 1 has a higher contribution to the country's EC index. For Germany, employee compensation is the highest contributing impact, in the case of UK, the weight of imports is the highest contributor to the country's EC index. For the USA, GOS is the highest contributor to the country's EC index. For

France, both GDP and employee compensation have the highest contribution to the country's EC index.

For the developed economies, the highest contributor to the country's EC index in Brazil is attributed to the weight of import. For Russia, it is the GOS that has the highest contributor to the country's EC index score. Working hours in India is the highest contributor to the country's EC index whilst for China, it is GDP.

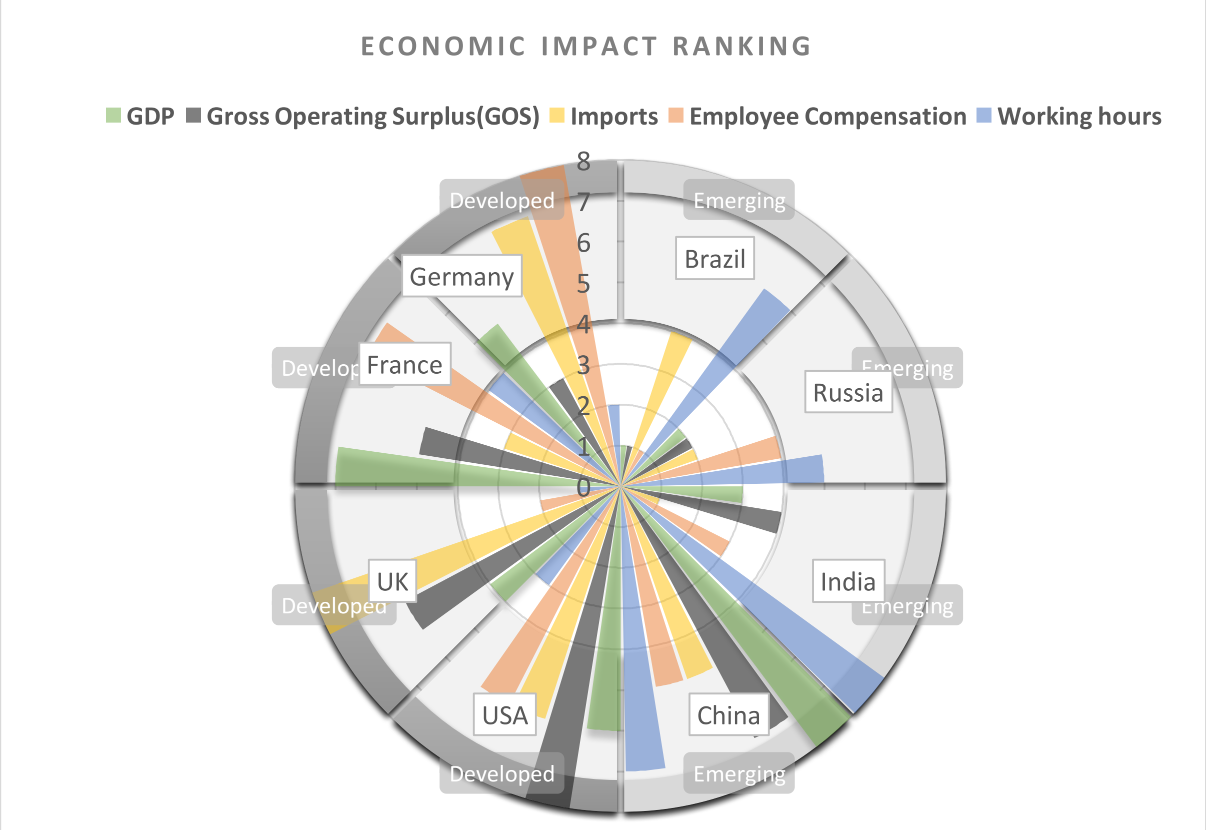


Fig 7.4: Economic impact ranking between developed and emerging economies

Figure 7.2 shows impacts based on the rank scale from 1 to 8. The closer a value is to the outer circumference, the higher the rank position while values closer to the inner circumference indicates lower rank position. Presenting the results in this way enables easy comparison between economic impact categories. In other words, it shows how a country fairs in comparison to another country in a given impact category. Countries on the left side of the graph, which shows developed economies are ranked higher in most of the economic impact categories compared to emerging economies.

With GDP, China has the highest rank position, followed by France as the second highest. The implication is that in the production of silicates, China and France's economy potentially benefit more from a positive increase in their GDP compared to the other countries within the developed and emerging economies. The lowest-ranked countries for GDP are Russia and Brazil.

For the GOS category, USA has the highest rank position, followed by China as the second-highest ranked in terms of GOS. This means that in the production of silicates, USA and China's economy potentially benefit more from a positive increase in their GOS compared to the other countries within the developed and emerging economies. Similar to the GDP, the lowest rank countries for GOS is from Russia and Brazil.

For the employee compensation category, Germany is the highest-ranked country, followed by France as the second-highest ranked country. This means that in the production of silicates, Germany, and France's economy potentially benefit more from a positive increase in their employee compensation compared to the other countries. Lowest ranked countries for employee compensation are Brazil and the UK.

For the Import category, UK is the highest ranked country, followed by Germany. This means that in the production of silicates, UK and Germany's economy potentially loses more from a negative increase in their import compared to the other countries within the developed and emerging economies. Lowest ranked countries for imports are India and Russia.

For the working hours category, India is the highest-ranked country, followed by China. This means that in the production of silicates, India and China's economy potentially loses more from a negative increase in their working hours compared to the other countries within the developed and emerging economies. Lowest ranked countries for working hours are the UK and Germany. As identified in Chapter 4, working hours and imports are considered a negative economic indicator because idea less working hours or imports in the production of silicates is considered better and economically sustainable.

Environmental impact

In this section results on the environmental index score for countries are presented. Contrary to the economic impacts where impacts are skewed towards the developed economies (Fig 7.1), in the case of environmental impact (Fig 7.3), the impacts are skewed more towards the emerging economies. For Germany, material use is the highest contributing impact on the country's EN index score. In the case of the UK, the weight of eutrophication potential is the highest contributor to their EN index. With regards to the USA, global warming impact is the highest contributor to the country's EN index while for France's EN index score, material use is the highest contributor.

For the emerging economies, the highest contributor to EN index score for Brazil, Russia and India is attributed to energy use. In the case of China, the highest contributors to the country's EN index score are global warming impact and acidification potential.

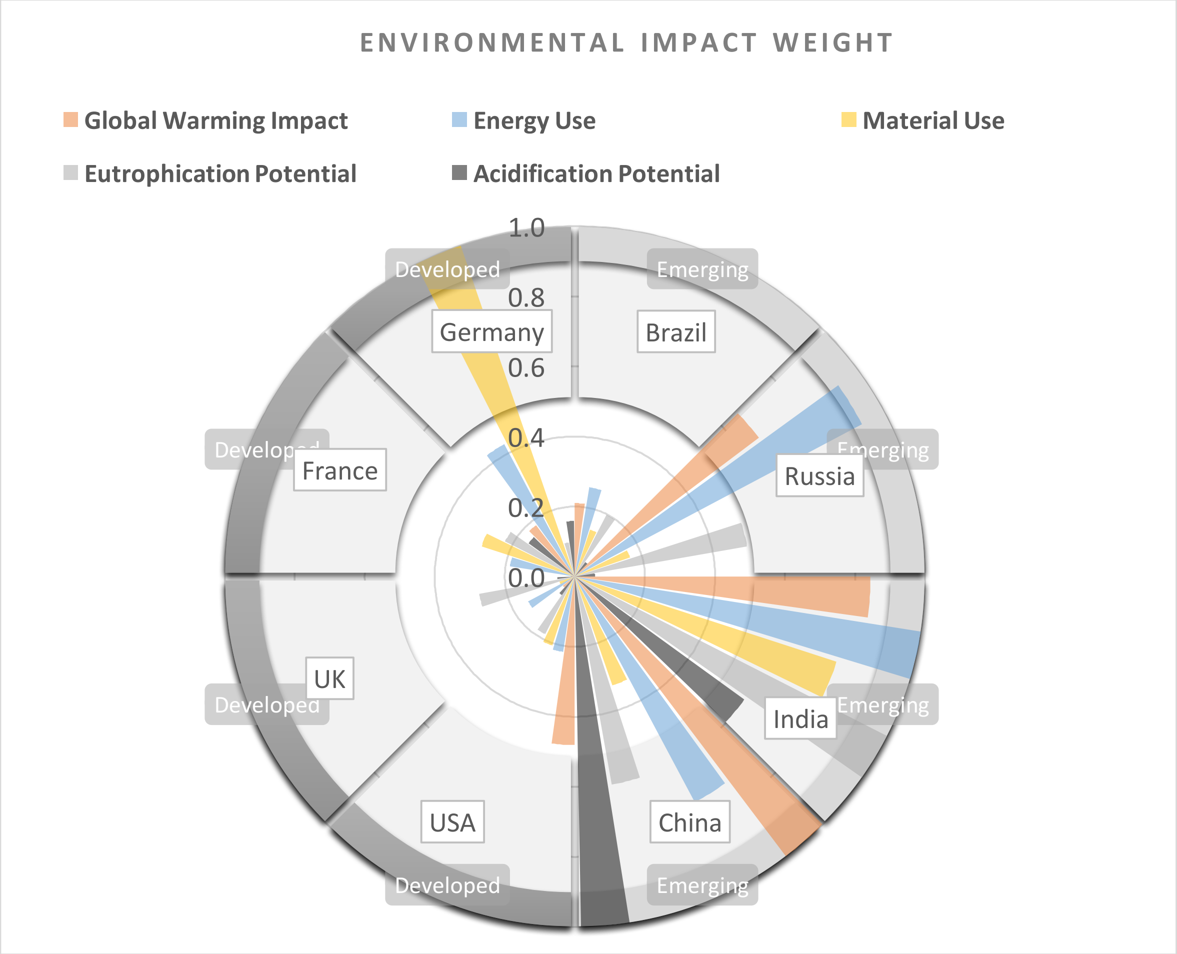


Fig 7.5 Environmental impact weight for developed and emerging economies

Figure 7.4 shows impacts based on a rank scale from 1 to 8, with 1 being the highest rank position and 8 being the lowest rank position. Since all the environmental impact categories are considered negative, therefore country ranking closer to 1(the inner circumference of the graph) depicts relatively good environmental performance in the specific impact. On the other hand, countries with ranking closer to 8 (that is the outer circumference of the graph) depict relatively poor environmental performance. It can be observed from Fig 7.4 emerging economies have rankings closer to 8 in most of the environmental impact categories.

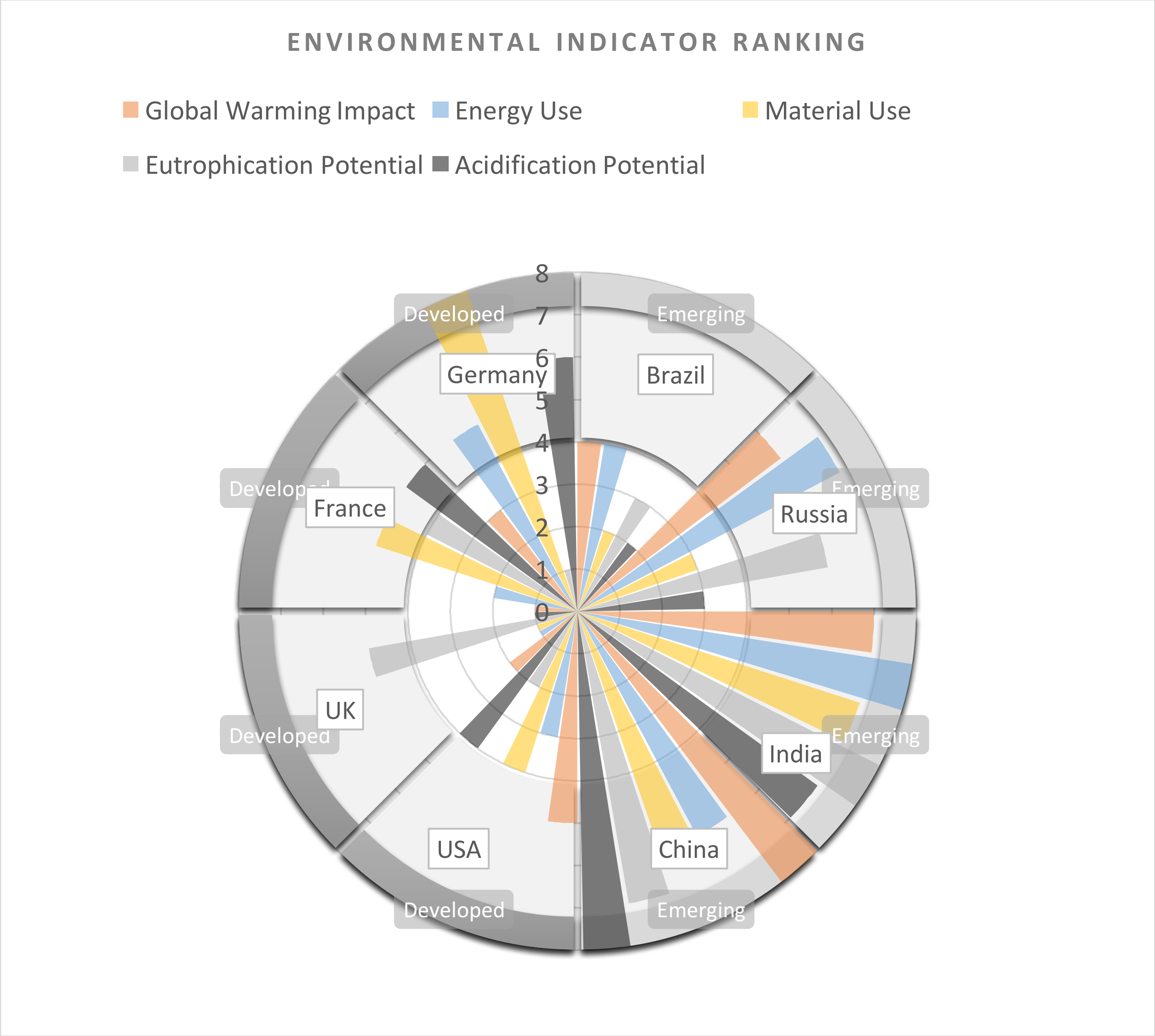


Fig 7.6 Environmental impact ranking between developed and emerging economies

With Global warming impact (GWP), China has the lowest rank position, followed by India as the second-lowest rank in terms of GWP. This means that in the production of silicates, China and India's economy potentially have a relatively higher negative environmental impact in terms of GWP compared to the other countries within the developed and emerging economies and therefore have poor environmental performance. France is the highest-ranked country for GWP depicting good environmental performance in the production of silicates.

For the energy use category, India has the lowest rank position depicting poor environmental performance in silicate production. Next to India, is Russia and China also having poor environmental performance in silicate production. Results suggest that Germany, although a developed economy appear to perform relatively poor compared to Brazil. In terms of energy use, the UK is the country with the highest environmental performance, followed by France and the USA.

For the material use category, Germany has the lowest rank position followed by India and China, which suggest that these countries have poor environmental performance in the silicate production with regards to material use. Similar to energy use, the UK has the highest environmental performance in terms of material use, followed by Brazil and Russia.

For the acidification potential category, China has the lowest rank position, followed by India and Germany. Highest ranked country for acidification potential is the UK followed by Brazil, Russia, and the USA. For the eutrophication potential category, India has the lowest rank position, followed by China, Russia, and the UK, respectively. Highest ranked country for eutrophication potential is Germany followed by the USA, Brazil, and France.

Social risk impact

In this section results on the social risk impact are presented.

Fig 7.7 Social indicator weight for emerging and developed economies

The results from social impacts weights shown in Fig 7.5 are similar to the environmental impacts (Fig 7.3) in that, the impacts are skewed towards emerging economies. This suggests that social impacts from the emerging economies are relatively very high compared to the developed economies. The only developed country with some noticeable social risk impacts is the USA, where Labour rights and decent work is a dominant social risk impact in the country. In China, human rights and Health & Safety have more weight contributing to the country's SR index compared to other social risk impacts categories. In India, labour rights and community infrastructure are the dominant social risk impact issue with significant contribution to the country's SR index. In Russia, socio-economic contribution and health & safety are the dominant social risk impacts. In the case of Brazil, the dominant social risk impact is from socio-economic contribution.

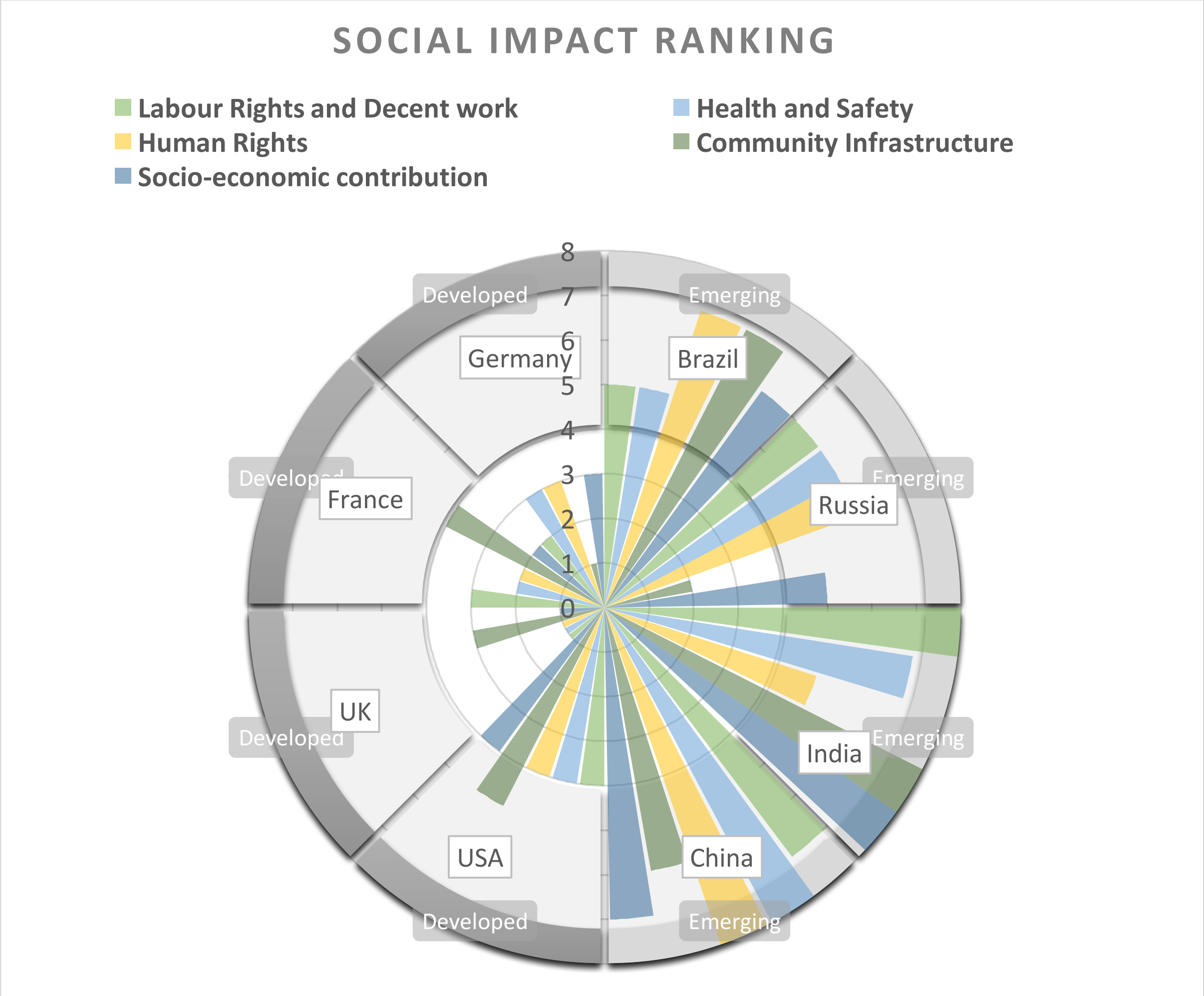


Fig 7.8 Social impact ranking between developed and emerging economies

With regards to social impact ranking (Fig 7.6), results indicate that the developed economies are ranked higher in most of the environmental impact categories compared to emerging economies which implies the latter have poor social sustainability performance in silicate production.

For the Labour Rights impact category, India has the lowest rank position, followed by China, Russia, and Brazil (in ascending order). Highest ranked country for Labour Rights is the UK, followed by Germany, France, and the USA (in descending order).

For the Health & Safety impact category, China has the lowest rank position, followed by India, Russia, and Brazil. On the other hand, the highest-ranked country for Health & Safety is the UK, followed by France, the USA, and Brazil.

For the Human Rights impact category, China has the lowest rank position, followed by Brazil, Russia, and India. Highest ranked country for Human Rights is the UK, followed by France, Germany, and the USA.

For the Community Infrastructure impact category, India has the lowest rank position, followed by Brazil, China, and the USA. Highest ranked country for Community Infrastructure is Germany, followed by Russia, UK, and France.

For the Socio-economic impact category, India has the highest rank position, followed by China, Brazil, and Russia. Lowest ranked country for Socio-economic is the UK, followed by France, Germany, and the USA.

7.3.2 Sustainability Index

This section presents results for all indices (EC index, EN index, SR index and LSCA index) for countries considered in this study. The relevance of these findings is to highlight how countries perform based on individual sustainability pillars in addition to overall sustainability with regards to basalt production.

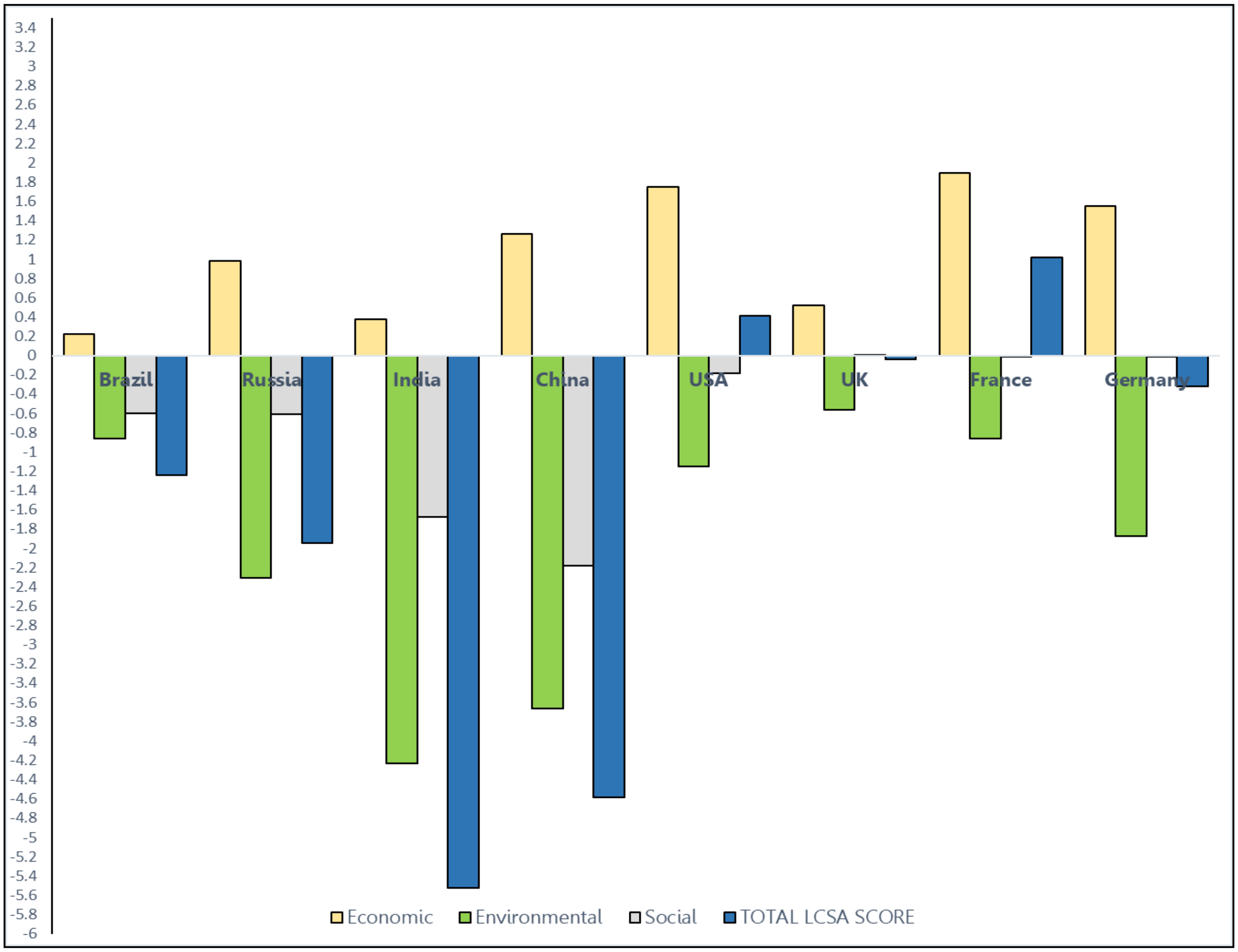


Fig 7.9 Results of TBL Sustainability indices

Economic Index Score (*EC index*)

A relatively high EC index score is interpreted as good economic sustainability performance. In contrast, relatively low EC index score is considered as poor economic sustainability performance with regards to basalt production. Among all selected countries, France has the highest *EC index* score of 1.9 followed by the USA and Germany with *EC index* score of 1.75 and 1.55, respectively which suggest that these countries perform better economically in the production of silicates for ERW. The high positive weighted impact of employee compensation in France (0.74), USA (0.71), and Germany (1.00) significantly contributes to the relatively high EC index score in these countries. The implication is that the USA, France, and Germany have better employee compensation in place for workers compared to the other countries.

The UK has the lowest EC index score among the developed economies. In addition, the result indicates that the UK's EC index score is far lower than China and Russia that have EC index score of 1.26 and 0.98, respectively. The reason for the UK's low EC index score is attributed to the relatively high negative weighted impact of imports involved in silicate production in the country. India and Brazil have the lowest EC index score among all the countries, that is 0.38 and 0.22, respectively.

Generally, the low EC index score in emerging economies compared to the developed economies can be attributed to the relatively high negative weighted impact of working hours in these countries compared to developed economies. The weighted impact of working hours, especially in India and China is very high that is 1.00 and 0.9, respectively compared for instance to developed economies like the USA and France which is 0.05 and 0.06 only. Subsequently, the results indicate that although India and China specifically have high EC index score among the emerging economies, the excessive working hours in these countries gives them an overall lower EC index compared to the USA and France.

Another reason why the developed economies potentially perform better economically in basalt production is attributed to the high positive weighted GDP impact in these countries compared to the emerging economies except for China. On average, GDP weighted impact in the developed economies ranges from 0.48 to 0.67, whereas for emerging economies, particularly Brazil, Russia and India, the average weighted GDP impact ranges from 0.30 to 0.41. China's weighted GDP impact of 1 is the highest among both developed and emerging economies which explains why among the emerging economies they perform better.

Environmental Index Score (*EN index*)

A relatively high EN index score is interpreted as good environmental sustainability performance while relatively low EN index score is considered as poor environmental sustainability performance.

The result shows that the developed economies have high EN index score and therefore generally perform better environmentally than the emerging economies with regards to basalt production. EN index for the UK (-0.57) and France (-0.87) are the highest among the developed economies compared to the low EN index in the USA (-1.15) and Germany (-1.87). India's EN index score of -4.23 is the lowest among the all the countries (both emerging and developed) indicating relatively abysmal environmental sustainability performance in this country associated with the production of silicates. China and Russia with relatively low EN index score of -3.66 and -2.31, respectively also have poor environmental sustainability performance. Brazil is EN index score (-0.86) indicates a relatively good environmental performance compared to the other emerging economies. In addition, the country's EN index is slightly higher than that of France (-0.87).

For the emerging economies, the weighted negative impact of GWP and energy use contributes to the low EN index scores in these countries. Therefore, improvements in EN index score for emerging economies especially must be centred on lowering global warming impact and energy use involved in the production of silicates. The weighted negative impact from acidification and eutrophication potential has a less significant contribution to EN index score for most of the countries except Russia where the weighted impact from acidification potential is at the same high level as GWP in the country.

Social Risk Impact Index Score (*SR index*)

The social risk impact index score (SR index) for a country is a combined weighted value of all social risk impact categories (Labour rights, health & safety, Human rights, community infrastructure, and socio-economic contribution) measured. It indicates the overall social sustainability performance of countries in producing silicates for ERW. A relatively high SR index score is interpreted as good social sustainability performance. In contrast, relatively low SR index score is considered as poor social sustainability performance in terms of basalt production.

Similar to results in EN index score, the SR index score results show that the developed economies have relatively high SR index score and therefore generally have an excellent social sustainability performance compared to the emerging economies which have low SR index score suggesting poor sustainability performance. Among the developed economies, SR index score for the UK, Germany and France are the highest compared to a relatively lower SR index for the USA. The negative weighted impact from Labour rights and decent work is a significant contributor to USA's relatively low SR index compared to the other developed economies. The implication here is that addressing adverse labour rights risk in the country can potentially lead to significant improvement in USA's social sustainability performance in basalt production.

China's SR index score of -2.18 is the lowest among the developed economies indicating relatively very poor social sustainability performance in this country with regards to basalt production. India also has a poor social sustainability performance shown by the country's low SR index score of -1.68. Brazil and Russia's SR index score indicates a relatively better social sustainability performance compared to China and India.

Improvements in SR index score for emerging economies, especially, must be centred on the social risk impacts that have a significant contribution to the country's SR index. For Brazil, community infrastructure and human rights have a significant impact on the low SR index scores in the country. For Russia and China, it is the health and safety and human rights risk impacts that contribute significantly to these country's low SR index score. For India, it the labour rights and decent work and community infrastructure that have the most significant contribution to the country's SR index. Although social sustainability performance in the developed countries is low, the positive weighted impact from socio-economic contribution from basalt production is relatively higher compared to the developing economies.

Lifecycle sustainability assessment index (*LCSA index*)

In this study, the lifecycle sustainability index score (LCSA index) for a country is an aggregated weighted value of the individual TBL impact index scores (EC index, EN index and SR index). It indicates the overall sustainability performance of countries in producing basalt for ERW. A high LCSA index score is interpreted as relatively good lifecycle sustainability performance while relatively low LCSA index score is considered as relatively poor lifecycle sustainability performance.

Generally, the results suggest that countries in the developed economies group have relatively good lifecycle sustainability performance compared to the emerging economies. This is indicated by the high LCSA index score in developed economies compared to emerging economies. The highest LCSA index is in France (1.04), followed by the USA (0.57). However, the LCSA score in the UK (-0.03) and Germany (-0.32) are the lowest among the developed economies. The lowest LCSA score of -3.88 is recorded in China. Like China, India also has poor lifecycle sustainability performance depicted by the country's low LCSA index score of -3.52. In comparison to the other emerging economies, Brazil has relatively high LCSA, although still significantly lower than the developed economies.

The significant contributor to the LCSA index scores of both developed and emerging economies is attributed to the environmental sustainability performance represented by the negative EN index score. The implication here is that improvement in a country's lifecycle sustainability performance associated with basalt production must be targeted at addressing environmental impacts. The second significant contributor which lowers a country's LCSA index score is social sustainability performance represented by the SR index. The high LCSA scores in the developed economies are attributed to high economic sustainability performance in these countries represented by the EC index score.

However, a closer look at the results reveals that the improved LCSA scores in LCSA for developed economies are attributed to the high imports in these countries compared to the emerging economies. Consequently, the developed economies rely more on imports in producing silicates, and therefore there is a high possibility that the negative environmental and social impacts are incurred in the countries they trade with. This assertion is also supported in the low working hours associated with silicate production in these countries.

Table 7.1 Summary of country rankings for sustainability indices

Ranking	LSCA Index	EC Index	EN Index	SR Index
1st	France	France	UK	UK
2nd	USA	USA	Brazil	Germany
3rd	UK	Germany	France	France
4th	Germany	China	USA	USA
5th	Brazil	Russia	Germany	Brazil
6th	Russia	UK	Russia	Russia
7th	China	India	China	India
8th	India	Brazil	India	China

In Table 7.1, a summary of country rankings for the various sustainability indices (LCSA, EC, EN and SR index) is shown. France is ranked first among all the countries in terms of LCSA index followed by the USA and UK. Among the four developed economies, Germany is the least ranked. India and China have very low ranking compared to Brazil and China in terms of the overall sustainability performance (that is LCSA index) in crushed silicate production. Similar to the LSCA index, France and USA are ranked first and second respectively in EC index. An interesting result highlighted by the EC index score ranking is that China and Russia has a relatively high ranking than the UK. The low ranking for the UK can be traced to the high imports involved in the production of crushed silicates. On the other hand, the high ranking for China especially can be attributed to the relatively high GDP generated in the country through the production of crushed silicates.

With regards to EN index, countries performing well depicted by their high rankings are the UK and Brazil, which is attributed to low energy and material use in these countries in the production of crushed silicates. Although classified as developed economies, the USA and Germany, in particular, have relatively low rankings in the EN index, ranked 4th and 5th. The worst performing countries in terms of EN index are China and India depicted by their low rankings. Again, similar to the EN index, the UK is also ranked 1st with regards to the SR index rankings followed by Germany. Among the four developed economies, the USA has the lowest ranking. Russia, India and China are the bottom three countries in terms of SR index.

The summary of country rankings presented in Table 7.1 also makes it easy to identify the trade-offs between the TBL factors for a given country. For example, in the case of Brazil, it can be observed that although there is a trade-off between economic performance (EC index) ranked low compared to EN and SR index where the country has relatively high rankings. This implies that to increase the LCSA index ranking of Brazil, the country's EC index must be targeted. Another example is China, where it can be seen that although the country has a high ranking for EC index, the low EN and SR index ranking leads to an overall low LSCA ranking. For Germany, the trade-off is seen between the country's relatively high EC and SR index on the one hand and the relatively low EN index on the other hand leading to relatively low LSCA ranking when compared to the other developed economies.

In addition to results shown so far, a sustainability dashboard is also presented in Fig 7.9, which shows for country profiles by providing a summarised snapshot of how a country fares in the various sustainability indices. This makes it easy for comparison between countries and also to narrow down on a country of interest.

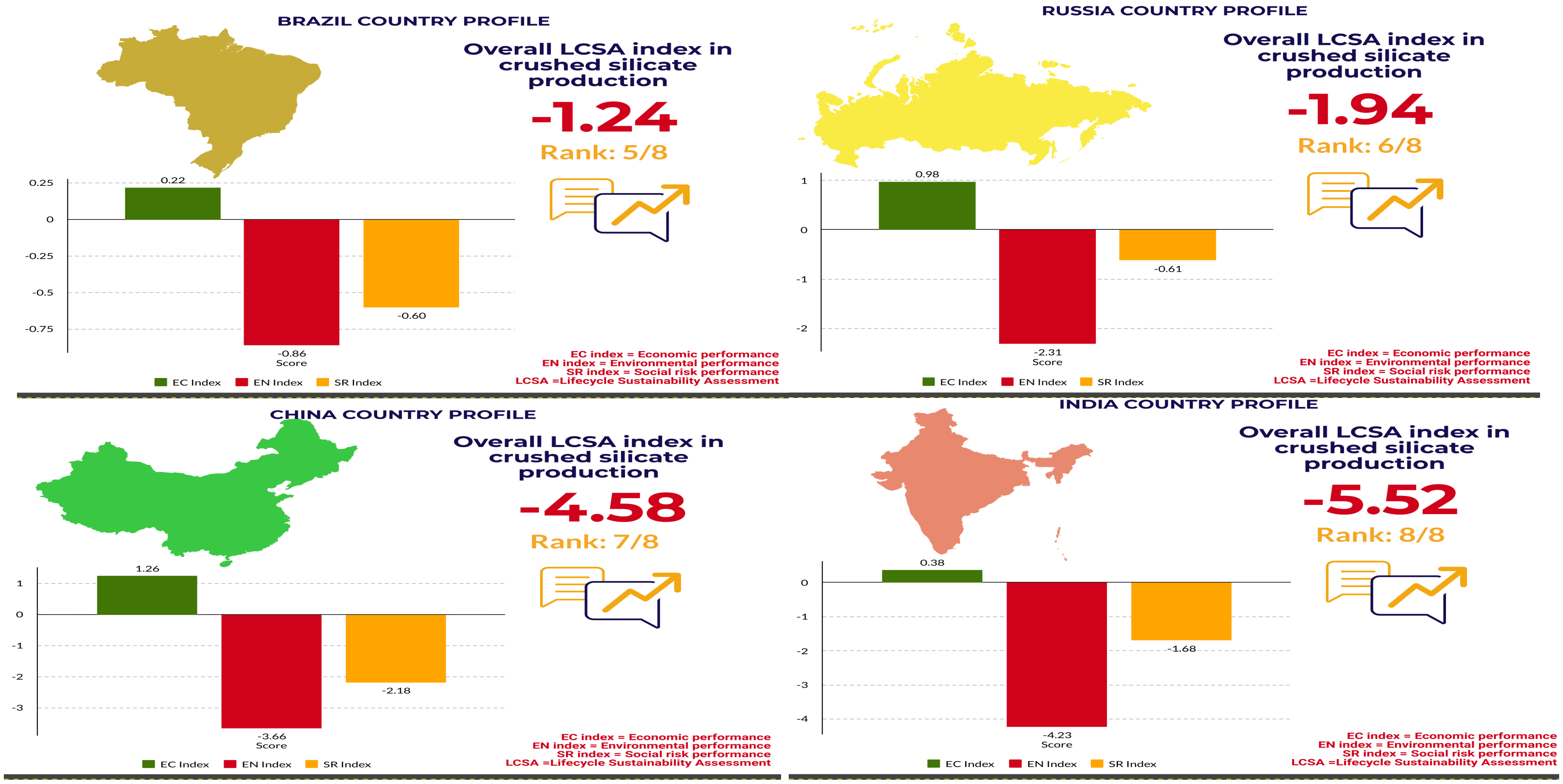


Figure 7.10a ERW Sustainability Index Dashboard for emerging economies

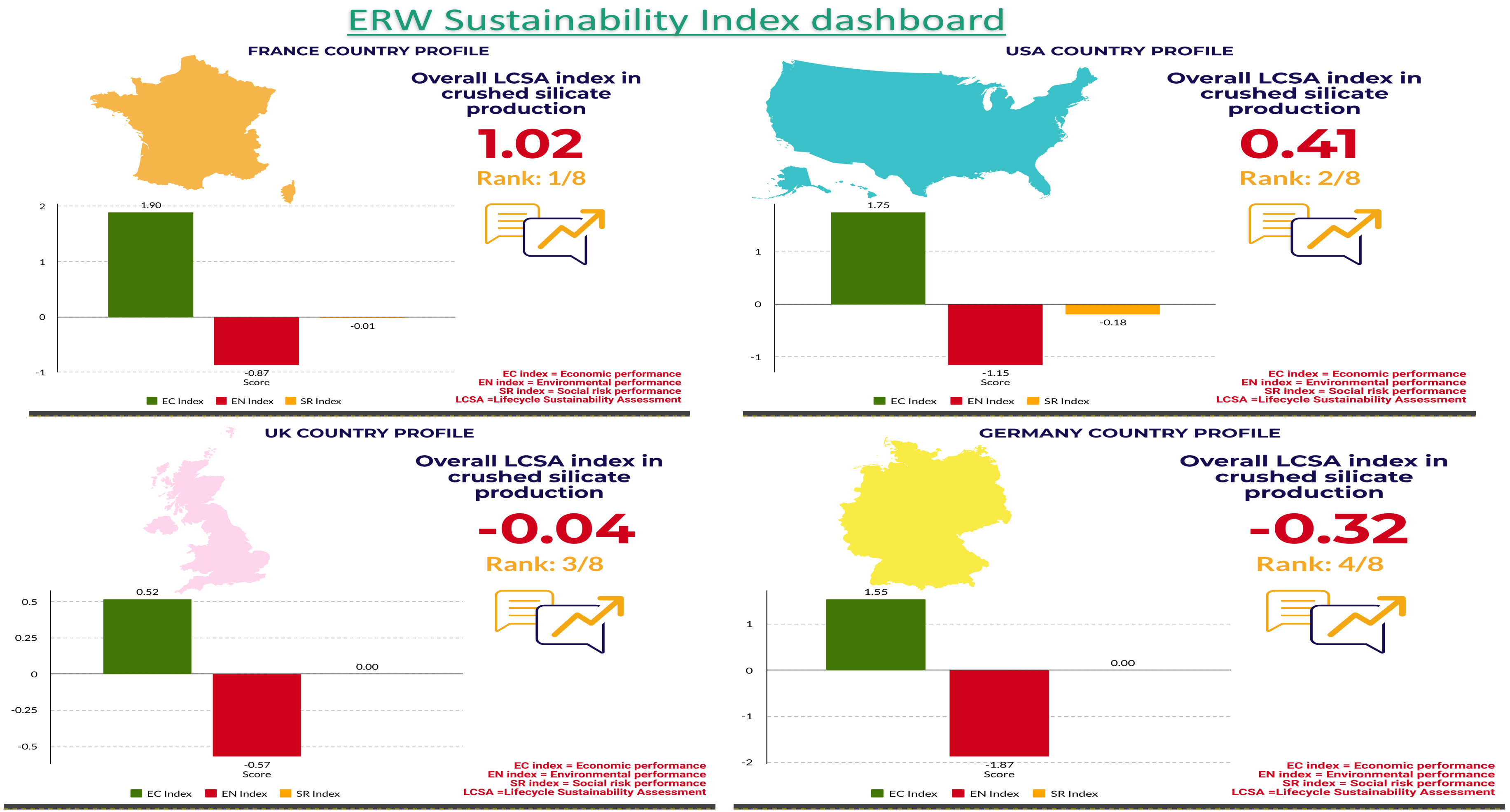


Figure 7.10b ERW Sustainability Index Dashboard for developed economies

7.3.3 Index Sensitivity Analysis

In line with the recommendation from the OECD Handbook, an index sensitivity analysis is carried out to the test the robustness of the results. Sensitivity analysis is carried out based on a different linear normalisation method than the distance to reference (DTR) method used in the analysis. Specifically, the Min-Max method, also known as vector normalisation, is employed to test the robustness of the indices. Normalised values based on the min-max method is calculated using the equation below:

Table 7.2 LCSA index comparison based on different normalisation methods

Country	DTR*	Min-Max	Country Rank
France	1.02	1.77	1st
USA	0.41	1.31	2nd
UK	-0.04	0.53	3rd
Germany	-0.32	0.41	4th
Brazil	-1.24	-0.96	5th
Russia	-1.94	-1.70	6th
China	-4.58	-3.82	7th
India	-5.52	-5.30	8th

*Distance to Reference normalisation

When the LCSA index based on DTR and Min-Max normalisation method are compared, it is observed that the rankings remain the same, which signals robustness of the results. The differences in values do not change the country performance in the overall performance in crushed silicate production. Using the min-max method, the index values for emerging economies improve slightly (depicted by an increase) although still negative, thereby depicting relatively poor overall sustainability performance in crushed silicate production compared to a developed economy. Another slight difference is noticeable in the LCSA index for the UK, wherein the min-max method increases beyond the zero marks and becomes positive.

7.4 Discussion

There is a number of insightful findings from the study in the current chapter that can serve as evidence for effective policy strategy for developing sustainable ERW agenda. At the country-level, the results highlight the specific areas of focus that must be addressed to improve sustainable production of silicates/basalt for ERW. It is assumed that not all impacts within the individual sustainability category carry equal weight (Tyrrell et al. 2013) and therefore, these must be captured within the analysis. By providing weights for the impacts, the study highlights the trade-offs in both the negative and positive areas that should be mitigated (in the case of negative impacts), and that can be explored (in the case of positive impacts) with regards to supply chain management of ERW.

For instance, in the case of developed countries, imports were a main economic impact that lowered their EC index while GDP increased their EC index, a similar conclusion in a study by (Wiedmann and Lenzen 2018). The EC index for emerging economies, on the other hand, were most affected by the excessive employee working hours. In terms of environmental performance represented by the EN index, the contributing factors differed from country to country as presented in the analysis and results section. However, impacts relating energy use, greenhouse gas emissions/GWP and material use were among some of the impacts with significant contribution low EN index.

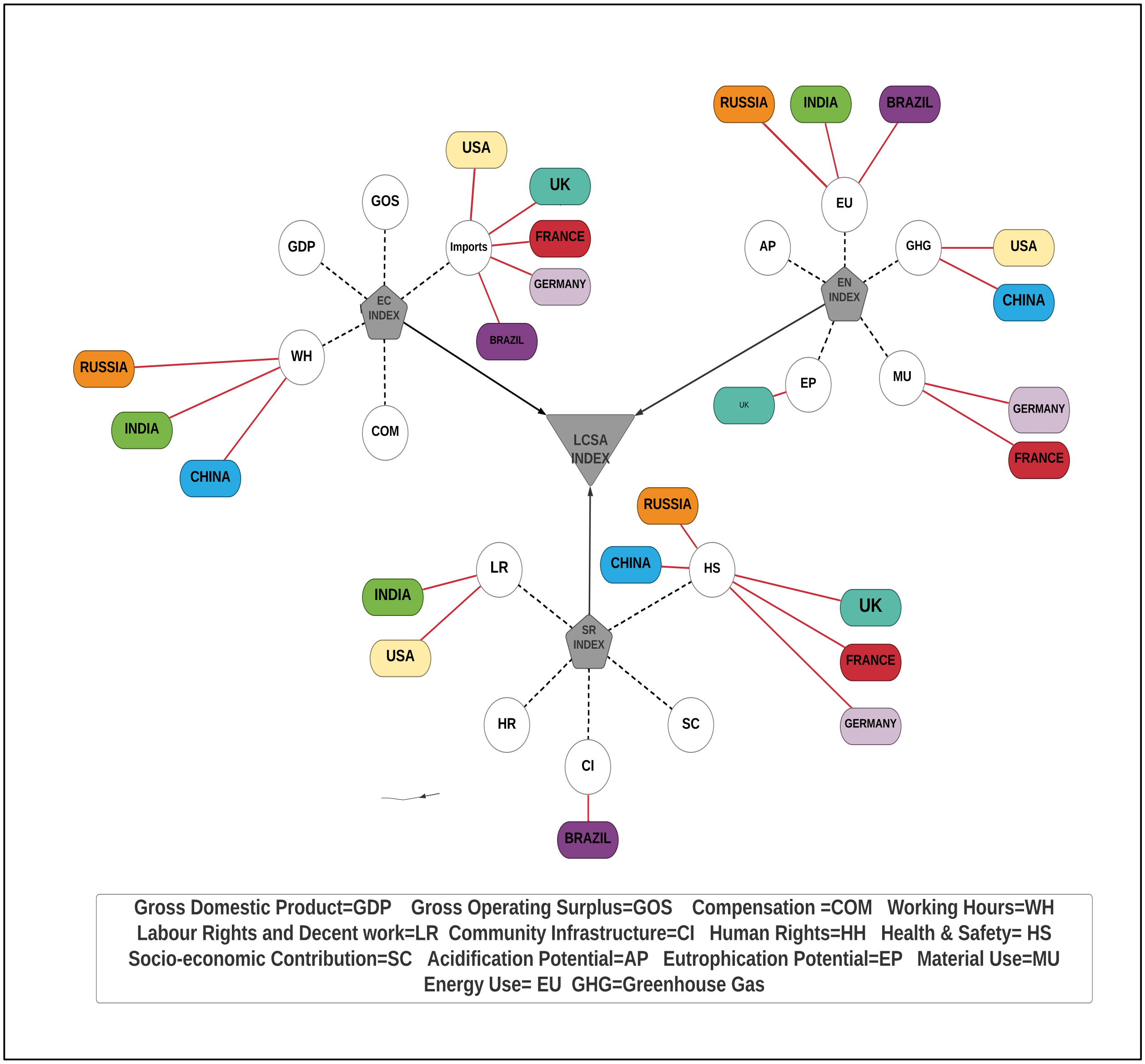


Figure 7.11: Network diagram showing critical TBL impacts

Based on the analysis conducted in the study, it is possible to trace the negative 'hotspot' that must be addressed to improve a country's sustainability in crushed silicates. Figure 7.11 illustrates this by showing a network diagram that shows the impacts that countries should focus on to address sustainability challenges. The significance of showing these results are mainly two, that is;

i. To identify or trace the critical impacts within an index.
ii. To identify the three most critical TBL impacts that policymakers in countries must focus on to address sustainability challenges in crushed silicate production.

The network diagram helps to identify the specific TBL impacts that are critical and must be addressed to improve sustainability in crushed silicates. Although a total of 15 TBL impacts were used in the integrated sustainability assessment of crushed silicate production, some impacts were more critical in affecting the sustainability indices for countries. Referring to the network diagram in Fig 7.10, we can identify the specific impacts that were critical in lowering countries' score in the three individual TBL index that is EC, EN and SR index. This can be observed by counting the number of countries (nodes) which extends from the impact. As a guiding rule, an impact is considered critical in an index if it has at least two extending nodes. For the EC index, the critical impacts are imports and working hours which has five and three nodes respectively. For the EN index, the critical impacts are energy use followed by material use and GHG emissions while for the SR index, the critical impacts are health and safety, followed by labour rights and decent work.

The diagram also is useful in producing insights for policymakers and other relevant stakeholders in countries to identify the three most crucial TBL impacts, one impact for each sustainability pillar (economic, environmental and social) that must be addressed to improve LCSA score. For Brazil, the impacts are imports(economic), energy use(environmental) and community infrastructure(social)*. In the case of Russia, the critical impacts are working hours, energy use and health and safety. China's critical TBL impacts are working hours, health and safety and GHG emissions. In the case of India, the country must focus on these impacts; working hours, labour rights and decent work and energy use. For the USA, the critical TBL impacts are imports, GHG emissions and labour rights and decent work. UK's critical TBL impacts are imports, eutrophication potential and health and safety. For France, the country must focus on imports, material use and health and safety. In the case of Germany, the critical TBL impacts are imports material use and health and safety.

The integration of TBL factors based on the index method used in the study allows for easy comparison between countries. This is made possible through the formulation of the LCSA index, which takes into account all individual sustainability assessment indices. Although countries LCSA index may vary depending on the component of the indices used, (that is the selected impacts for each TBL factor) its relevance remains valid and easy to use and interpret. The study also highlights important insights into the possible interactions and trade-off that exist between the TBL factors. One of such trade-offs highlighted in the paper is how developed economies through imports can achieve a better environmental sustainability performance in crushed silicate production within national boundaries. If the analysis is based on just economic performance without considering the environmental, then it could easily be concluded that developed economies perform better in the production of crushed silicates.

Beyond trade-offs between economic and environmental impacts, it may be difficult to establish such a direct link from the current study between economic and social sustainability in making assertions that economic sustainability in the developed country is achieved at the back end of negative social risk impacts in the other countries it imports from. However, such an assertion is not far off as study by (Wiedmann and Lenzen 2018) confirmed that a direct link exists between improved economic sustainability against negative environmental and social impacts via trade.

In conclusion, improvement in sustainability impacts associated with silicate production in countries depends on massive gains in environmental and social impacts. The input-output method employed for individual analysis of each sustainability pillar in Chapters 4, 5 & 6 is presented in a holistic perspective through the current chapter by integrating the TBL results. Although the overall results align with studies in the literature on relatively poor sustainability performance in emerging economies compared to developed economies, the study goes further by providing detailed analysis and discussion that gives explanatory context into how such a phenomenon exist by highlighting interactions between TBL sustainability factors.

7.5 Conclusion

The analysis and results of this chapter draw together the separate results from the previous studies on the individual TBL factors. The implication of the study in relation to contribution to knowledge and theory is summarised below:

Contribution to Knowledge**:** From the literature review conducted in Chapter 2, it was established that TBL sustainability considerations associated with silicate production for ERW were mostly focused on single quarry firm operations (Hangx and Spiers, 2009; Schuiling and Tickell, 2010; Lefebvre et al, 2019). In addition, from the extant literature, very little is known on the environmental and social considerations of ERW. Research by Lefebvre et al., (2019) measured environmental impacts of ERW but limited to firm level impacts on mining operations in a single country, Brazil. On the other hand, the current study extends knowledge on ERW in three distinctive ways. Firstly, the study quantifies potential impacts of ERW based on the three pillars of sustainability; environmental, economic and social. Secondly, the analysis is based on not just one country but eight countries carefully selected due to their major role in increasing global emissions. Thirdly, the analysis and measurement of these sustainability impacts is conducted from a system wide and macro-level perspective reflecting the inter-connections among sectors and firms I producing to meet demand for crushed silicate rocks.

Based on the analysis and results conducted in this chapter, it is now possible to know the potential reasons why a country engaging in the production of silicates rocks for ERW may perform better than another country. By analysing sustainability impact across a wide range of impacts (15 impacts) across economic, environmental and social impact, the study provides a comprehensive understanding of the underlying explanations for why a country outperforms another in terms of TBL sustainability performance. France for instance outperforms its counterpart developed country like the UK. From the results, we see that although the UK benefits from a relatively better environmental performance, France has a better ranking in economic and social impacts measured (depicted by a relatively high rank) compared to the UK. In studies like that of Renforth (2012) which considered the potential of ERW in the UK as 430billion tonnes CO_2 capture, this insight now provided by the current makes it possible to estimate the potential impacts associated with this CO_2 capture potential. Moosdorf et al., (2014) global analysis of the ERW, acknowledged the importance of considering sustainability issues such as extraction cost, carbon credits to minimize environmental impacts and social stigma of mining (as outlined in Table 2.2 in Chapter 2). Although these issues cuts across TBL impacts, the current study however, goes further by actually providing a baseline quantification of these TBL impacts.

Theoretical contribution: The study draws on the RBV theory on competitive advantage concept and uses the theory to explain the differences in TBL sustainability performance in countries producing silicate for ERW. This is based on the proposed integrated resource based view (IRBV), a modification of the RBV theory to include the environmental and social sustainability competitive advantage aside the economic advantage. Through IRBV theory and analysis based on the Input-Output methodological framework (Leontief, 1936), the study highlights the importance of capturing TBL knock-on effects due to interdependence between firms in producing to meet demand for crushed silicate rocks.

The results from the study show that generally, developed economies outperform emerging economies because they are able to produce silicates at a relative lower cost to their economy, environment and society. Drawing from the IRBV theory, the results suggest the competitive advantage that the selected developed economies have in terms of higher TBL supply chain performance, indicates that the industrial sectors in these countries manage their resources relatively better in silicate production. The IRBV theory therefore ensures that sustainability performance is measured from a wider macro-level perspective involving all affected firms within sectors and not at the micro-level (single quarry firm). Finally, beyond the application of the IRBV theory on ERW supply chain, the theoretical perspective can be extended in analysing sustainability of other negative emission technologies in future.

7.6 Chapter Summary

This chapter presents analysis, results, and discussion of integrated TBL impacts associated with the production of basalt for ERW. Based on data results from previous chapters on economic, environmental and social impact assessment of basalt production, the current study uses integrated indices that allow for comparison of the selected countries (emerging and developed economies) based on individual sustainability assessment and overall sustainability performance. The results highlight the impacts with significant contribution to both the individual and overall sustainability performance. In addition, a ranking of countries based on the sustainability performance in basalt production is also presented.

CHAPTER 8: COMPARATIVE LIFECYCLE ASSESSMENT OF BASALT ROCK AND INDUSTRIAL FERTILISERS

8.1 Introduction

Global demand for food is continually increasing, largely fueled by population growth. A recent report released by Food and Agriculture Organisation (FAO), World Food Programme and World Health Organisation (WHO) indicates that threat of food insecurity and hunger is on the ascendancy especially in the Africa and Latin America regions (WHO, 2018). At the same time, the constant cultivation and harvesting of food crops leads to the rapid depletion of soil nutrients at levels that cannot be considered sustainable for future production. As a solution, industrially produced chemical fertilisers, particularly Nitrogen-Phosphate-Potash (NPK) fertilisers have gained popularity to replenish lost nutrients and increase crop yields (Roberts 2009, Stewart and Roberts 2012).

The environmental and economic sustainability in the use of these fertilisers has, however, been questioned over the years. Fertiliser cost to local farmers especially in poor regions of the world is relatively high and yet such places have been known to have highly weathered soils in need of replenishment (Sanchez 2002, Chianu, Chianu et al. 2012). In addition to the high prices, evidence in previous research suggest the continuous production and use of these fertilisers present environmental challenges such as greenhouse gas emissions and eutrophication (Carpenter et al. 1998, Tilman et al. 2002, Wood and Cowie 2004, Atafar et al. 2010, Gan, Liang et al. 2014, Goucher et al. 2017, Pärn et al. 2018). In view of this, several studies have sought to compare the environmental performance of chemical fertilisers with other sources including human, plant, animal and food waste recovery and recirculation as substitutes for conventional fertilisers (Helsel 1992, Bøen and Haraldsen 2013, Franzosi et al. 2014, Brod et al. 2015).

This study investigates whether basalt rock dust fertiliser can serve as an environmentally sustainable close substitute to expensive conventional rock-derived P- and K- fertilisers (Van

Straaten 2002). The phrase ‘close substitute’ is used here to signify that basalt rock dust fertiliser cannot supply nitrogen (N) but can supply phosphorus (P) and potassium (K). Potential benefits of basalt dust for croplands include increased yields (Leonardos et al. 1987, Harley and Gilkes 2000, Theodoro and Leonardos 2006) possibly by reversing soil acidification, thereby increasing plant nutrient uptake, increasing root-associating mycorrhizal abundance and provision of trace elements to the crop plants, especially on highly weathered tropical soils (Gillman et al. 2001, Gillman et al. 2002, Anda et al. 2009).

Basalt also contains silica, which is not present in industrial fertilisers, released by weathering in a plant-available form (silicic acid). Although not an essential plant nutrient, silica can protect plants from abiotic stresses and pests and diseases(Beerling, Leake et al. 2018). Furthermore, basalt rock dust is one of the few fertilisers acceptable to the growing organic agricultural sector (Van Straaten 2006). In emerging economies such as Brazil, the government supports the use of silicate rocks such as basalt as soil remineralises for crop nutrition and has also been proposed to developing countries as a feasible solution aimed at reducing their reliance on expensive imported fertilisers (Manning and Theodoro 2018). Large-scale spreading of basalt rock dust on croplands may also represent a Carbon Dioxide Removal (CDR) strategy through the chemical breakdown of silicate rocks, a process known as enhanced weathering (Renforth 2012, Moosdorf et al. 2014, Taylor et al. 2016).

However, there is a need to understand the potential embodied environmental impacts during the production of milled basalt (also referred to here in the study as basalt rock dust fertiliser) and compare them with those of industrial fertilisers across a wide range of environmental indicators to provide a robust basis for decision-making. Previous studies, for instance, have highlighted the health challenges associated with the particle size distribution of basalt waste dust which may present different health challenge than those faced by industrial fertilisers (Dalmora et al. 2016). However, a full environmental impact assessment of both fertiliser types (in this case, basalt and industrial fertilisers) is required before a meaningful conclusion is reached on which option is environmentally sustainable.

The LCA method is used in estimating potential environmental impacts of products and processes. It has been applied in studies on fertilisers but mostly focused on impacts at their application or use stage (Brentrup et al. 2004, Skowroñska and Filipek 2014, Hasler et al. 2015, Quirós et al. 2015) with few studies assessing the environmental impacts from fertiliser production(Mirlean and Roisenberg 2006, Ledgard, Boyes et al. 2011, Hasler, Bröring et al. 2015). Against this backdrop, the current chapter presents a comparative lifecycle assessment (LCA) of basalt rock dust fertiliser and five rock-based industrially used P- and K- fertilisers: single superphosphate (SSP), triple superphosphate (TSP), potassium chloride (KCI), potassium carbonate (K2CO3) and potassium hydroxide (KOH). The study estimates and compares 15 potential environmental impact indicators including climate change impact (global warming potential), acidification potential, eutrophication potential, land use, ionising radiation, malodours air and six variants of toxicological footprints associated with basalt rock dust fertiliser production and the industrial P and K fertilisers. The specific objectives are to provide an assessment of the production side of the fertiliser supply chain, by tracing the impacts embodied in producing different fertiliser types from the start of the supply chain, i.e., production phase, to address the 'hidden' impacts. Such an assessment provides a holistic view of fertiliser production and allows for comparison on environmentally sustainable alternatives based on estimated environmental impacts.

8.2 Method and Data

The study deploys the Lifecycle Assessment (LCA) method which is carried out according to ISO 14040 standards. LCA is a widely-accepted method used in identifying and quantifying the environmental impacts of products and processes across its life cycle stages (Guinee 2002). The LCA method is used to calculate and compare the environmental profile of basalt rock dust fertiliser and five industrial Phosphorus (P) and Potassium (K) fertilisers using the

Supply Chain Environmental Analysis Tool (Koh et al., 2013), a lifecycle assessment software tool that captures lifecycle impacts along supply chains. In accordance with ISO 14040, process-based LCA has four phases.

Phase I: Goal and System boundary

Firstly, the LCA goal and system boundary of the product under study and setting an appropriate system boundary are outlined in Phase I. As stated earlier, the goal of this LCA is to estimate and compare the environmental impacts associated with the production of basalt rock dust fertiliser and industrial fertilisers.

A cradle-to-gate system boundary has been used, as such, raw material extraction and processing of product are included in the LCA system. The functional unit of the production of the fertilisers is set at 1kg of product. This is based on the assumption that 1kg of each fertiliser would provide the same soil nutritional value. The environmental impacts estimated are, therefore measured in relation to the functional unit. For example, for every 1kg produced, there is a climate change impact of 0.007kg CO_2-eq and ~1.4kg CO_2-eq for basalt rock dust and SSP fertiliser respectively. The same applies to all the other impact categories.

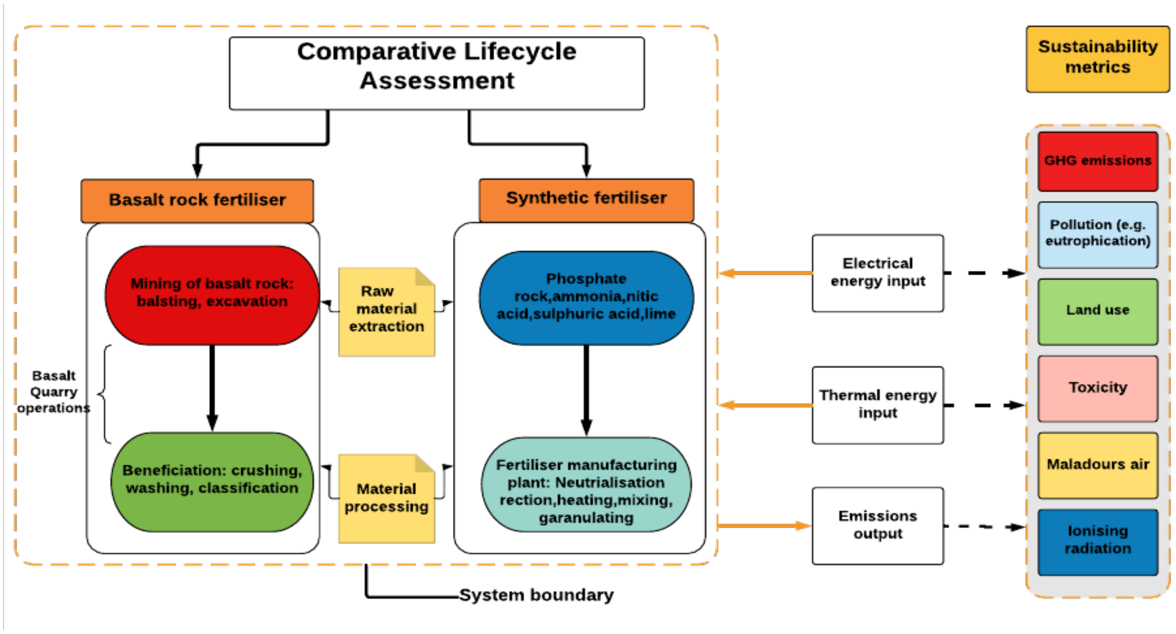


Figure 8.1: LCA System boundary, showing some relevant material and energy input inventory as well as processes involved in the production of basalt rock fertiliser and industrial fertilisers. See supplementary information for a detailed breakdown of actual quantities needed in producing 1kg of each fertiliser type. For simplicity, the specific production route or technique of each different industrial fertiliser is not shown in the diagram. The sustainability metric 'Toxicity" includes freshwater aquatic, freshwater sediment, marine aquatic, marine sediment, terrestrial and human toxicity.

Production routes for each fertiliser may differ, but there are fundamental similarities in their production. For instance, phosphate and potash rock are raw materials used in the production of most of the industrial fertilisers considered in this study. The system boundary of the LCA (Figure 8.1) in this research, therefore includes both the extraction of such raw materials and their processing at fertiliser plant to produce the different industrial fertiliser types. In the case of basalt rock fertiliser, the primary raw material needed is the basalt rock produced in basalt quarry operations which involves mining, crushing, grinding and classification.

Phase II: Lifecycle Inventory

In Phase II, the Life Cycle Inventory (LCI) phase, the inputs into the system (energy and raw material requirements) and system outputs are quantified. For each fertiliser product, we obtained data relating to the material and energy input needed per kilogram of output form Ecoinvent version 3.4 (See Appendix D). Some inputs, however, such as infrastructure was excluded since these are already set up. Therefore, the impacts focus on those associated with material and energy flow in producing both categories of fertilisers. Impacts from waste output were also excluded. The data used for the production of basalt rock fertiliser were from basalt quarry operations obtained from Ecoinvent database. Data pertaining to the production of each of the five industrial fertilisers are also from the Ecoinvent database.

Energy for mining used in the study is ~6 kWh per tonne (see Appendix D) which closely compares to ~5.23 kWh estimated by Hangx and Spiers (2009). During the crushing and grinding process, various particle sizes of the rocks are produced. The classification step allows for the varying grain sizes to be screened and grouped. Ideally, small grain sizes are more suitable for use as fertiliser as they have faster dissolution rate (Harley and Gilkes 2000, Anda, Shamshuddin et al. 2009).

High-energy input is required to grind rocks to small grain sizes (Moosdorf, Renforth et al. 2014). Renforth (2012) estimates 15-100kWh t^{-1} for grain sizes between 5 mm to 0.01 mm. Moosdorf et al. (2014) estimate optimistic and pessimistic energy requirements as 0.06 GJ t^{-1} and 2 GJ t^{-1} for grain sizes between 0.03mm and 0.001mm, respectively. Hangx and Spiers (2009) estimate production grain sizes of 100 μm and 37 μm, which correspond to the energy input of approximately 13 kWh t^{-1} and 24kWh $t^{-1,}$ respectively. In the current study, the total energy input for crushing and grinding is 0.04 MJ per kg from the Ecoinvent database (see Appendix D). This implies an energy input of approximately 11.1kWh per tonne of rock. Using grain size/energy calculations by Hangx and Spiers (2009) as the basis, we assume this energy input may correspond to potential grain sizes of 100 μm and 117 μm.

Phase III and IV: Lifecycle impact assessment and interpretation

In the impact assessment stage of the LCA (Phase III), the environmental impacts identified in the inventory analysis phase on human health and the environment across a range of indicators are evaluated before the results are presented and interpreted (Phase IV). The environmental profiles of the fertilisers are compared based on fifteen environmental impact categories which provide a broad assessment of impacts of their production supply chain on air, water, and land. There is an extensive range of LCA environmental indicators, but generally, these can be grouped as impacts under water emissions, air emissions and solid emissions (waste). The selection of indicators for the study, therefore took into account impact categories that reflect these general groups of environmental impacts. In addition, the selection of indicators for LCA must also reflect relevant implications to the study that are also closely associated with the product's sector (Chevalier, 2011). A complete description of selected impacts is shown in Appendix D.

The CML (2001) categorisation model available in Ecoinvent was used for all impact categories except those on ecosystem quality, human health, and resources. These are from Eco-indicator 99, which is also taken from the Ecoinvent database. Ecosystem quality includes effects on species such as vascular plants and lower organisms based on four indicators, namely ecotoxicity, acidification, eutrophication, and land use (Ibn-Mohammed et al 2016). Resources is a measure of the additional energy needed to extract minerals and fossil resources in the future. Human health includes the number and duration of diseases and life years lost. The other environmental impacts include acidification potential (kg SO_2e), climate change (kg CO_2e, GWP 100a) and eutrophication potential (kg NO_xe).

In addition, six variants of toxicological footprint with the reference unit, kg of 1, 4-dichlorobenzene equivalent (1, 4-DCB) are included; freshwater sediment ecotoxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, marine sediment ecotoxicity terrestrial ecotoxicity and human toxicity. These are a measure of the potential impact of toxic substances on the environment, mainly aquatic, sediment and terrestrial ecosystems. Malodours air (m^3 air), ionisation radiation (DALYs) and land use (m^2a) are also included. In total, 15 environmental impacts are estimated, and these forms the basis for comparison for 1kg each of basalt rock fertiliser and five industrial fertilisers produced. Full data on individual contributions of each input to each environmental impact indicator in the various fertilisers are shown as supplementary information in the appendix section.

8.3 Analysis and Results

Comparing environmental impacts

We find large differences in the environmental impacts associated with the production of basalt rock fertiliser compared with industrial fertilisers. The estimated value for each impact per kg produced for a given fertiliser type is shown in Table 8.1. We also show the relative percentage contribution of each fertiliser type to the total impact of all six fertilisers in a given environmental impact category (Figure 8.2). Triple superphosphate fertiliser production has the highest impact, followed by single superphosphate and potassium hydroxide. In climate change impact category, these three fertilisers (KOH, TSP and SSP) contribute over 80% to climate change impact per kg produced (Figure 2), the highest potential impact associated with KOH production, that is ~1.5kg CO_2-eq, followed by TSP and SSP which has ~1.4kg CO_2-eq each. On the other hand, the potash-based fertilisers KCl and K_2CO_3 have relatively lower impacts across all environmental impacts compared to the phosphorus-based fertilisers (TSP and SSP).

However, the toxicological footprint of KOH is very high with regards to marine sediment ecotoxicity, contributing to an average of 70%, which corresponds to 2.5kg 1-4-DCB-eq per kg produced. For freshwater aquatic, freshwater ecotoxicity and marine aquatic ecotoxicity, the dominant impacts come from SSP and TSP. In addition, the impacts of these phosphorus-based fertilisers in acidification potential, eutrophication potential, land use, ionising radiation, ecosystem quality, human health and resource is relatively very high with over 50% of the total impacts attributed to their production. On the other hand, the production of basalt fertiliser has minimal contribution to total impacts with less than an average of 1% contribution across all impacts estimated, largely due to the relatively low energy requirement in processing, which is discussed further in the study.

Table 8.1Environmental impact of different fertiliser types per kg produced

Impact categories	Unit	Basalt	SSP	TSP	KCl	K_2CO_3	KOH
Climate change impact (CC-I)	kg CO2-eq	7.00E-03	1.41	1.4	0.18	0.59	1.51
Acidification impact (A-I)	Kg Sox	7.00E-05	0.02	0	0	0	0.01
Eutrophication Impact (EU-I)	kg Nox	1.00E-04	0.01	0	0	0	0
Land use impact (LU-I)	m2a	4.00E-04	0.94	0.8	0.03	0.02	0.2
FAETP impact	kg 1,4- DCB	2.00E-03	1.98	1.7	0.09	0.19	0.66
FSETP impact	kg 1,4- DCB	4.00E-03	3.37	3.1	0.2	0.41	1.41
MAETP impact	kg 1,4- DCB	7.00E-03	3.51	3.3	0.33	0.7	2.4
MSETP impact	kg 1,4- DCB	8.00E-03	0	0	0.35	0.72	2.5
HTP impact	kg 1,4- DCB	3.00E-03	0.59	0.7	0.04	0.39	0.49
Terrestrial ecotoxicity (TE-I)	kg 1,4- DCB	3.00E-06	0	0	0	0	0
Ionising Radiation impact (IR-I)	DALYs	4.00E-11	14348.28	16355.4	0	0	0
Maladous air impact (MA-I)	m3a	4.00E+01	0.17	0.6	3298.53	4387.43	17865.2
Ecosystem quality impact (EQ-I)	points	1.00E-04	0.03	0	0	0	0.03
Human Health impact (HH-I)	points	3.00E-04	0.09	0.1	0	0.02	0.04
Resources impact (RE-I)	points	2.00E-04	0.07	0.1	0.01	0.02	0.05

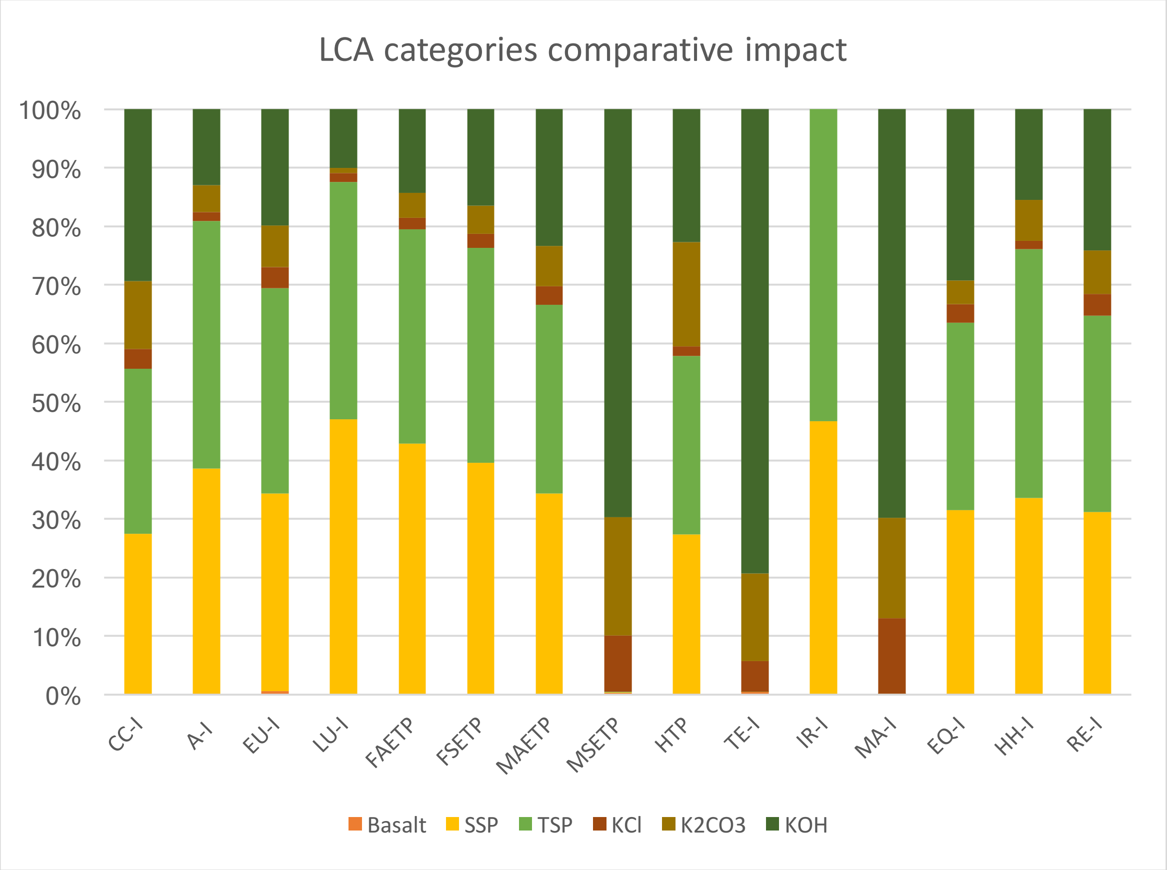


Figure 8.2: Comparison between basalt fertiliser and industrial PK fertilisers across 15 environmental sustainability metrics based on relative percentages. The potential sustainability metrics relate to the functional unit of producing 1kg each of fertiliser type. Breakdown of the contribution of individual material and energy input for each fertiliser to the total impact across indicators is provided in the appendix.

Comparing primary energy input

A key factor contributing to the massive difference in potential environmental impacts between basalt rock fertiliser and the industrial fertilisers is the high-primary energy inputs (electrical and thermal) in production of the latter. The production of SSP and KOH, in particular, has the highest electrical energy input of approximately 6.8MJ per kg produced each. Thermal energy is also very high in KOH production that is 4.8MJ per kg compared to

TSP, KCI and K_2CO_3, which require thermal energy input of 2.8MJ, 0.8MJ and 0.2MJ per kg produced respectively. Results show that overall basalt has very minimal energy input requirement per kg produced compared to the rest of the P- and K- fertilisers. The findings support the discourse that the production of industrial fertilisers is energy-intensive.

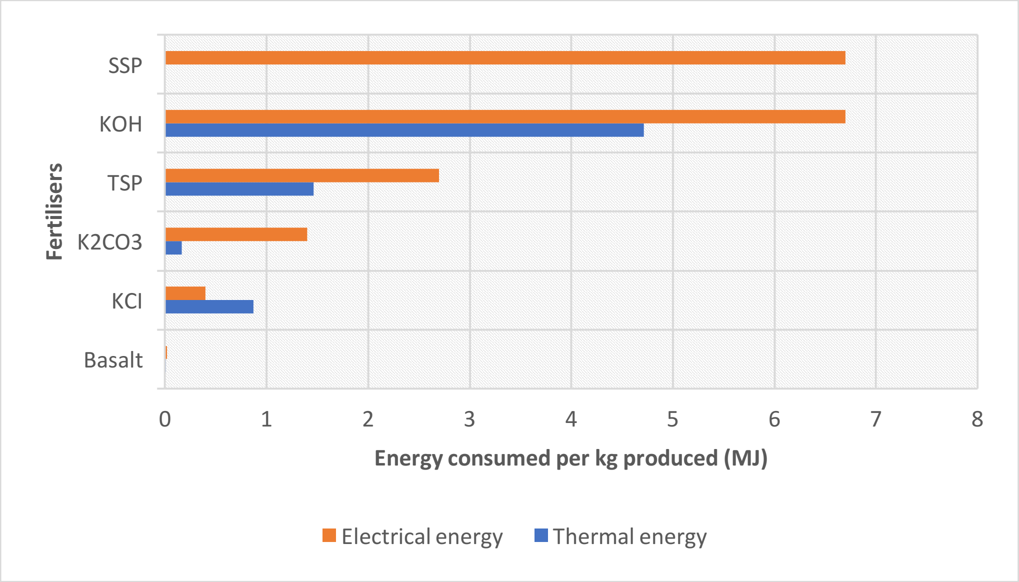


Figure 8.3: Thermal and Electrical energy input for fertiliser production. Data from Ecoinvent. Data on electrical energy consumption was not provided in Ecoinvent for SSP fertiliser. The assumption here is that electrical energy consumption for this fertiliser is similar to that of the other listed industrial fertiliser

8.4 Discussion and Conclusion

The study shows that accounting for embodied environmental impacts from the production phase is a critical missing element for sustainability assessment of fertilisers in the food production chain. The production-related impacts of fertilisers must be critically considered in global environmental discourses, agenda-setting, and negotiations. As population growth continues to drive increasing food production and consumption, it is crucial to ensure that fertiliser resources are efficiently sourced and with minimal environmental impacts to meet food security challenges. This may require broadening rock-based fertilisers to include basalt fertiliser, which, as analysed in the study, has relatively low production impacts on the environment. Thus, our paper's findings have policy relevance, particularly with regards to addressing a number of sustainable development goals (SDGs) as summarised in Table 8.2 below. We briefly and subsequently discuss the policy relevance of our findings to the SDGs.

Table 8.2: Policy relevance and contribution of Basalt fertiliser to achieving 2030 SDGs

Sustainable Development Goals	**Potential contribution from basalt dust fertiliser**
SDG 2 Zero hunger	Soil remineraliser to boost crop yields, increasing nutrient uptake, crop protection from abiotic stress
SDG 12 Responsible consumption and production	Reducing reliance on chemical fertiliser usage (P-K rock fertiliser); promoting circular economy through reuse of basalt mine waste
SDG 13 Climate change Action	Carbon dioxide sequestration through enhanced weathering
SDG 14 Life below water	Slows ocean acidification and associated impacts on marine organisms

Adapted from Smith et al. (2019)

Between 2016 and 2020, the International Fertiliser Association (IFA) projects that about US$130 billion will be invested into the fertiliser industry, increasing global capacity by over 150 million tonnes per annum (IFA,2001). The environmental impacts associated with such production growth in the fertiliser industry can be disastrous in the long term in terms of adverse climate and toxicological footprint. Transitioning to milled basalt as a natural geo-fertiliser to support food production may help address the UN SDG of 'Responsible consumption and production.' This can be achieved by reducing large quantities of PK fertiliser production, which this study shows can be possible through substituting PK fertiliser production with the more environmentally sustainable, basalt fertiliser production.

Our findings also have implications for the environmental costs of current and future global fertiliser production. Plans to expand fertiliser production to meet consumption without addressing emission intensities could end up being a significant driver in increasing toxicological footprints and climate change. The IFA (2001), for instance, projects global production of phosphoric acid used in fertiliser production could increase by 12% to 64.1 million tonnes in 2021. Potential environmental impacts of such an expansion in the fertiliser industry can be estimated by extrapolation of our results.

The results suggest that phosphate and potash-based fertilisers have relatively high potential production-related environmental impacts, beyond those associated with their application on croplands. These impacts mostly occur in the broader and upstream fertiliser supply chain and are related to the extraction of the material inputs, such as phosphate rock and potash, before their use in the fertiliser production. Furthermore, the production of phosphoric acid from phosphate rock involves the release of potentially harmful substances to air and water. An example is phosphogypsum, which is a radioactive gypsum generated as a by-product of the reaction of sulphuric acid and phosphate ore during the fertilizer production process (Pérez-López et al, 2007). Reports by IFA (2001) recognise the potentially harmful impacts of phosphate rock and potash mining.

Approximately 1.2% of the world's annual total energy is consumed by global fertiliser production (Swaminathan and Sukalac, 2004), and this percentage is proportional to the overall contribution of fertiliser industry to global GHG emissions. Energy-related impacts from industrial fertilisers, therefore, take into account all the energy inputs needed for producing the individual raw material inputs (such as phosphoric acid and potash salts) and thus gives the true picture of the relatively high production environmental footprint of the industrial fertilisers. Processing of basalt rock dust fertiliser, the grinding of rocks is considered as very energy-intensive (Moosdorf et al., 2014; Renforth., 2012), but in our analyses, this has the least consumption of both electrical and thermal energy per kg produced compared to all of the industrial fertilisers analysed (Figures 8.3).

Prices of conventional fertilisers produced from finite rock-derived phosphorus and potassium (potash) have doubled in the past decade (Amundson, Berhe et al. 2015). Potash prices were predicted in 2020 to double to $1500 compared to a decade ago where it was half the current price (Amundson et al., 2015). In regions with high prevalence of infertile soils, rock fertilisers presents a good opportunity as a relatively cheap and environmentally friendly fertilizer alternative for local farmers (Van Straaten 2006). In addition, the agricultural sector is identified as a critical sector in terms of its contribution to GHG emissions as well as where the adverse consequences of climate change are harshly felt. Approximately 25% of human-induced greenhouse emissions globally is attributed to agriculture (Smith et al. 2014).

It is vital to point out that in developing climate change mitigation options in this sector, the best solutions may not necessarily be to find entirely new technologies but to find ways to integrate existing practices with ‘green’ solutions such as crop farming with basalt rocks for carbon sequestration via the enhanced weathering process (Smith et al., 2019). In this regard, we identify that enhanced weathering with basalt can serve as credible carbon dioxide removal strategy to contribute to the UN sustainable development goal of Climate change action. As a co-benefit of enhanced weathering with basalt on croplands, the rate of ocean acidification can be slowed via run-off water of weathered by-products into the ocean. The IPCC predicts that as atmospheric CO_2 rises, ocean acidification could increase as much as 150% by 2100, resulting in pH reduction of nearly 0.4 (IPCC 2014).

Beyond the benefits of crop yield associated with industrial fertilisers, it is essential to find ways of achieving similar or comparable results, but with a fertiliser type, that has minimal impacts on ecology during production and application. From this perspective, sustainable fertiliser, such as basalt rock dust, could potentially be a suitable partial substitute for industrial P- and K- fertilisers. Increasing evidence on its positive impact on crop yield suggests a potential contribution to the Zero Hunger sustainable development goal (Smith et al. 2019). Due to the relatively fast reaction of conventional fertilisers to soil solution, in the short term, it may not be possible for multi-nutrient silicate rock fertilisers such as basalt to replace conventional fertilisers. Nevertheless, research suggests an immense potential of combining the application of rock and mineral fertilisers to extremely weathered and damaged soils (Garcia et al. 2020).

Questions remain, however, on the overall sustainability of basalt rock dust fertiliser which must be answered to increase it embedment in sustainable agriculture policies and global environment agenda. Further assessment on the economic and social risk or challenges associated with large scale adoption of basalt rock dust fertiliser must be investigated on national levels; research gaps which have been filled by previous studies in this thesis.

8.5 Limitations of the study

A limitation of the study is centred on the data type used. The use of primary data, in general, improves data precision compared to secondary data. However primary data collection for LCA modelling is a very time-consuming process and therefore the use of a widely accepted lifecycle inventory database such as the Ecoinvent was relied upon. This is deemed appropriate given the scale of the analyses in this study. The Ecoinvent database has been used extensively in most studies on environmental impact assessment using LCA. The transparency of the data makes it possible for results to be replicated.

It is possible that if actual site-specific primary data was collected from say quarry industries (in the case of basalt fertiliser) and fertiliser manufacturing plant (in the case of industrial fertiliser) results may slightly differ. However, we doubt the difference would be enough to change the outcome of the conclusions and results completely. We can come to this conclusion because the general conclusions of the study are linked with other similar studies especially of fertiliser production and these mostly confirms the narrative that high-energy use in production is a source of adverse environmental impacts such as GHGs emissions (Brentrup and Pallière 2008 , Jenssen and Kongshaug 2003 , Skowroñska and Filipek 2014).

The difference in the current study, however, is that a comparative environmental impact assessment is done based on a wide range of indicators, thereby our findings are robust and comprehensive. Likening the results with parallel studies increase reliability of the results. Having said that, the current study is the first that demonstrates the novel potential of sustainable fertiliser (basalt rock dust) in comparison with industrial fertilisers, giving thought-provoking insights into the embedded environmental impacts in their production and the consideration of natural alternative in the substitution of chemical fertilisers.

CHAPTER 9: COMPARATIVE LIFECYCLE ASSESSMENT OF NATURAL SILICATE (BASALT ROCK) AND ARTIFICIAL SILICATE WASTE ADDITIVE

9.1 Introduction

Meeting the 1.5^{0}c target of the Paris Agreement requires rapid and sustained emission phase down and Carbon Dioxide Removal (CDR) solutions, which could potentially capture global atmospheric CO_2 in large scale (IPCC 2014). The amendment of soils with crushed silicate rocks to capture CO_2, known as land-based enhanced rock weathering (ERW), is steadily receiving much attention (Edwards et al. 2017). In contrast to other CDR technologies such as biochar, Bio-Energy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC), ERW may represent a cost-effective method(Smith, Haszeldine et al. 2016).

ERW may entail mining, comminution (crushing and grinding), transportation and application of these silicate rock grains to specific target areas. The subsequent weathering of these silicate rock grains leads to the production of cations and bicarbonate solution that reaches the ocean via runoff where it is stored stably for >100,000 years (Hangx and Spiers 2009). In theory, ERW may represent an efficient option for CDR with significant ancillary benefits. Aside from reducing atmospheric CO_2, ERW has an added co-benefits of reducing ocean acidification resulting from the increase in total alkalinity levels in the ocean to improving the health of marine life (Schuiling and Krijgsman 2006). Undertaken on agricultural land, it may also increase food security by increasing crop yields through the release of plant and soil nutrients in the applied rock grains on agricultural croplands (Kantola et al. 2017, Beerling et al. 2018).

Different silicate source rocks can be used for ERW. Based on their silica content, these rocks can be classified as either ultramafic (<45% silica content) or mafic (between 45-53% silica content) (Bas et al. 1986). Previous study by Renforth (2012) identified and estimated the carbon capture potential of both ultramafic (e.g. dunite) and mafic (e.g., basalt) rocks in the UK as 430 $GtCO_2$. The bulk of this total according to the study, however, comes from mafic rocks including basalt while the ultramafic formations account for only 25.4 $GtCO_2$.

Aside from mining natural silicate bearing rocks such as basalt for ERW purpose, the use of artificial silicate waste can also serve as a complementary strategy. Artificial silicate waste refers to silicate bearing materials that are produced as by-products in human production activities such as cement kiln dust from cement production, steel slag from steel production in an electric furnace and coal ash produced from electricity generation in coal power plants (Pullin et al. 2019, Renforth 2019). A tonne of cement, for instance, produces at least 150kg of waste as kiln dust (Huntzinger et al. 2009). Large quantities of these by-product 'wastes' are produced globally with estimates between 7-17 billion tonnes annually (Renforth 2019). Several studies have explored the potential of using these cheap and easily available materials for large-scale CO_2 removal in line with policies promoting resource circularity and recycled waste use (Huntzinger et al. 2009, Ukwattage et al. 2013, Pullin et al. 2019, Renforth 2019).

Assessment of the feasibility of silicate bearing materials for EW, however, needs to account for the life cycle of their environmental sustainability. This LCA study aims to identify and measure the potential *embodied* environmental impacts related with the production of natural silicate mineral source rocks (basalt) and three artificial silicate waste additives (cement kiln dust, steel slag and coal ash) for ERW purposes. Assessing the lifecycle of CO_2 mitigation technologies and strategies are important because under certain scenarios, such technologies or strategies may not reduce CO_2 emissions as expected, and at worst could potentially be counterproductive.

Estimating the environmental impact of ERW across a range of environmental indicators will allow for ecological trade-off analysis, while guaranteeing that CO_2 emissions are not subsided at the cost of other environmental effects (Ibn-Mohammed et al, 2018). One study that comes close to such an assessment is the study by Moosdorf et al., (2014). Although from a lifecycle perspective, this is a carbon footprint analysis of the enhanced weathering process and therefore provides a narrow assessment of potential environmental impacts of ERW beyond carbon emissions. In addition, by measuring only the CO_2 efficiency of the ERW process, other greenhouse gases (GHGs) such as nitrous oxide and methane which all contribute to global warming impact are excluded from their study. Recent research by Lefebvre et al. (2019) on ERW and soil carbonation in Brazil consider broader environmental impacts similar to those estimated in this study. Their LCA work, however, is based on one silicate source material that is basalt. This study estimates and compares natural silicate mineral source rocks (basalt in this case) and three artificial silicate waste sources (cement kiln dust, steel slag and coal ash) used in ERW based on seven environmental impacts categories namely; climate change impact, acidification potential, freshwater aquatic ecotoxicity (FAETP), freshwater sediment ecotoxicity (FSETP), marine aquatic ecotoxicity (MAETP), marine sediment ecotoxicity (MSETP) and human toxicity (HTP). Collectively estimating these broad ranges of environmental impacts provides insight to support decision-making processes to a range of stakeholders including environmental scientists, policymakers and regulators.

9.2 Methods and Data

The paper utilizes process-based LCA, which is a extensively used method in quantifying the environmental footprint of products and services across lifecycle stages. Adopting the ISO LCA framework, the LCA objective, system boundary of the product systems to be studied, and setting an appropriate functional unit are outlined in Phase I. The functional unit of the entire ERW process is set at sequestration of a tonne of CO_2. Environmental impacts are measured in relation to the functional unit of tonnes of CO_2 captured using either basalt, cement kiln dust, steel slag or coal ash. For example, a global warming impact of $x$kg $CO_{2\text{-eq}}$ for basalt or cement kiln dust is the GHG emissions emitted for every tonne of CO_2 captured using basalt or cement kiln dust. Functional units for an LCA system highlight the service provided by the system in this instance sequestration of a tonne of CO_2.

The study aims to highlight and compare the embodied impacts from the production of basalt, cement kiln dust, steel slag and coal ash. The system boundary in the study focuses on the environmental impacts in the EW production supply chain, thus a cradle to gate LCA approach. The discourse on artificial silicate waste sources have been primarily focused on their feasibility for use in CO_2 sequestration but with little focus on the environmental impacts generated in producing them which stems from the original product produced. In view of this, a cradle to gate system boundary was chosen for this study, which includes raw material extraction to the processing at the manufacturing gate.

In Phase II, the Life Cycle Inventory (LCI) phase, the inputs into the system (specifically the energy and material requirements) and system outputs are quantified. Process data input into the basalt LCA system boundary was obtained from the Ecoinvent database and literature. These specifically relate to energy inputs into the categorised life cycle processes of mining and comminution (crushing and grinding). For each of the processes, we identified the energy input needed per tonne of basalt. The first process, mining entails drilling, blasting, excavation, and short distance haulage of a tonne of rock to the crusher site. Hangx and Spiers (2009) estimate the total energy required for these mining process as 5kWh t^{-1}. The rocks are then crushed and ground (comminution process) to small grain sizes that facilitate the weathering process on target areas.

The energy required mostly relies on the desired grain size so that the smaller the grain size, the higher the energy required. A review of the current literature on enhanced weathering shows many variations in energy input for comminution. The study by Moosdorf et al. (2014) estimates optimistic and pessimistic energy requirements as 0.06GJ t^{-1} and 2GJ t^{-1} for grain sizes ranging between 0.03mm and 0.001mm, respectively. In a UK study on ERW, the energy required is estimated as a range between 10kWh t^{-1} and 316kWh t^{-1}(Renforth,2012). In our study, we used Hangx and Spiers (2009) estimate of 10μm grain sizes, which corresponds to an energy input of 173kWh t^{-1} after primary and secondary crushing followed by tertiary grinding.

In the case of the artificial silicate wastes considered in the study, we use the unit process data obtained from Ecoinvent v3.4. In the case of the by-product cement kiln dust, we consider all unit process exchanges included in the production of Portland cement. For steel slag and coal ash, we consider the energy and material inputs from making of steel and electricity production from coal in power plant, respectively. A list of input and corresponding quantity for producing each silicate bearing materials are provided as supplementary information in the appendix.

In the impact assessment stage of the LCA (Phase III), the environmental impacts identified in the inventory analysis phase on human health and the environment across a range of indicators are evaluated after which the results are presented and interpreted (Phase IV). The study uses the CML lifecycle impact assessment method developed by the Centre of Environmental Science Leiden University, (Guinee et al. 2011) from Ecoinvent. The impacts selected relate to the seven environmental impact categories associated with the energy and material input for the production of basalt, cement kiln dust, steel slag and coal ash. The environmental impact categories considered in the study are climate change impact or global warming impact (GWP), acidification potential (AP), freshwater aquatic ecotoxicity (FAETP), freshwater sediment ecotoxicity (FSETP), marine aquatic ecotoxicity (MAETP), marine sediment ecotoxicity (MSETP) and human toxicity (HTP). Although these are not an exhaustive list of potential environmental impacts that can be estimated, these were chosen as due to the relative relevance of the production systems being studied. Unit of climate change impact is kg CO2-eq, Acidification potential (AP) is kg $SO_{x,}$ FAETP, FSETP, MAETP, MSETP and HTP is kg 1-4-DCB-eq.

The environmental impact of each silicate material is calculated as:

$$Impacts_{(i)} = \sum_{m=1}^{n} Q_m \times e_{i(m)} \qquad \text{Equation 1}$$

Where:

Impacts across indicator (i) (example: global warming impact, acidification potential freshwater aquatic, freshwater sediment, etc.) is calculated as the product-sum of all the supply chain inputs (or materials) (m) and the Impact Intensities (e) of environmental indicator (i) of material(m). The results and conclusions will inform scientists for future research and policymakers to design appropriate climate change mitigation strategies.

Aside from knowing the environmental impacts in the silicate source materials, we also compare enhanced weathering potential of each material based on the amount of carbon dioxide it can remove upon weathering. To do this, we need to estimate the CO_2 sequestration potential of the silicate source materials, that is the quantity of atmospheric CO_2 that a silicate material can capture. In the case of basalt, Renforth (2012) estimates a maximum potential of 0.3t CO_2 per tonne of rock and the same value is assumed in this study. For the artificial silicate-waste, he estimates the range of carbon sequestration potential based on total volume produced historically. Based on his work, CO_2 sequestration potential of artificial silicate waste was calculated as:

$$CO_2\,Sequestration\ Potential_{(i)} = \frac{Average\ TP}{Average\ RCO2} \qquad \text{Equation 2}$$

Where:

CO_2 sequestration potential of (i) (that is: cement kiln dust, steel slag, coal ash) is calculated as the average of total production volume that is $Average\ TP$ from Renforth's study divided by the average sequestration potential that is $Average\ RCO2$. Renforth estimates minimum and maximum range for silicate waste production and hence an average of the two is taken as $Average\ TP$. He estimates the CO_2 sequestration potential of artificial silicates based on some realistic assumptions on the cation content in the materials. Using these as references, we estimate the potential CO_2 sequestration potential of cement kiln dust, steel slag and coal ash. It must be noted that as these calculations are not based on actual field experiments, which would provide a more accurate figure, they must be considered at best as rough estimates of 'potential' CO_2 sequestration. The focus of the current study is a lifecycle assessment to highlight the environmental impacts of different silicate materials for ERW in relation to their CO_2 sequestration potential when used for enhanced weathering.

9.3 Analysis and Results

In Figure 9.1, we estimate and compare the maximum CO_2 sequestration potential of the silicate materials and the quantity required to sequester the functional unit of a tonne of CO_2. The results suggest an inverse relationship between CO_2 sequestration potential and quantity required such that the higher the CO_2 sequestration potential of the silicate material, the less quantity required to sequester a tonne of CO_2. In terms of sequestration potential, coal ash has the lowest that is 0.1t CO_2 $t^{-1,}$ and subsequently, a relatively large quantity (10 tonnes of material) would be potentially required to sequester a tonne of CO_2. Cement kiln dust has the highest sequestration potential of 0.5t CO_2 t^{-1} with 2 tonnes required to sequester a tonne of CO_2. Steel slag also has high sequestration potential of 0.4t CO_2 t^{-1} with ~2.5 tonnes required to sequester one tonne of CO_2. Basalt, on the other hand, has a maximum sequestration potential of 0.3t CO_2 t^{-1} with approximately 3 tonnes required to sequester a tonne of CO_2.

Figure 9.1: CO_2 sequestration potential and quantity required to sequester functional unit

Figure 9.2 shows the percentage contributions of the impacts in each of the life cycle stages of crushed basalt production. The mining process constitutes the most impact, especially concerning potential climate change impact, acidification impact and human toxicity. The toxicological impacts mostly emanate from the comminution stage where the crushing and grinding of the basalt rock takes place. Overall, the results in Figure 9.2 shows that the mining stage of the ERW process is where over 90% of all impacts measured occurs across all seven estimated environmental impact categories. This is despite the fact that the mining stage has the lowest energy input per tonne of CO_2 that is 5kWh/t (Hangx and Spiers,2009).

The implication here is that interventions meant to reduce negative environmental impacts of EW supply chain must be directed towards finding sustainable options for the mining of natural basalt rock. As a complementary strategy, natural thinking could also be to use artificial silicate by-products. These have relatively high CO_2 sequestration potential such as steel slag and cement kiln dust (shown in Fig 9.1) and may imply less mining of natural silicate rocks is required. At least 7 billion of these silicate wastes are produced each year globally, and maximum potential production could reach as high as 17 billion a year (Renforth., 2012). However, as iterated throughout the paper, the embodied impacts of these materials need to be considered as well to fully capture all associated environmental externalities.

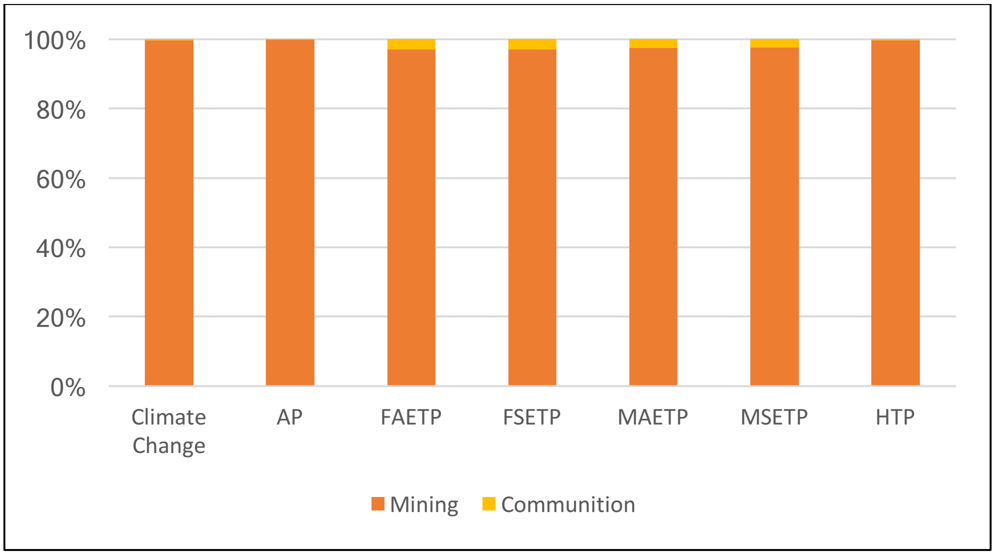


Figure 9.2: Environmental profile of 1kg basalt production process

In the case of cement kiln dust (Figure 9.3), the result shows that the presence of clinker in the production of portland cement has the highest impact averaging over 80% contribution to each impact category. The second-highest impact comes from electricity with an average of 20% contribution to freshwater, fresh sediment, marine water, and marine sediment ecotoxicity. Other inputs such as gypsum, limestone, ethylene glycol and steel have a relatively low contribution to environmental impacts.

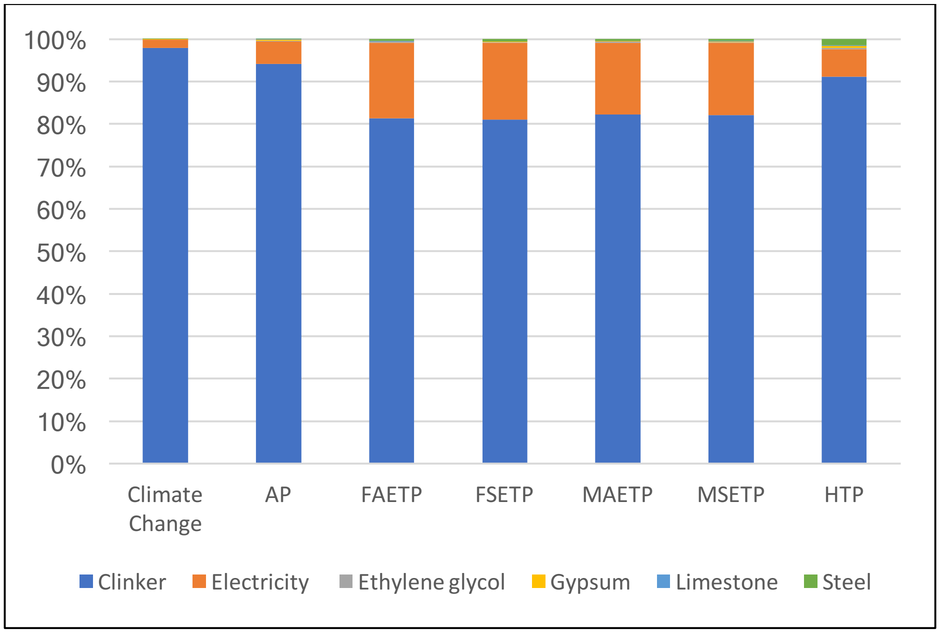


Figure 9.3: Environmental profile of 1kg cement kiln dust from cement production process

For steel slag (Figure 9.4), the presence of ferronickel in steel production constitutes high toxicological impacts particularly in freshwater, fresh sediment, marine water, and marine sediment ecotoxicity with an average contribution of 50% of total impacts followed by the presence of molybdenite with an average contribution of 30%. Concerning climate change and acidification potential, pig iron has a relatively high impact contribution of 70% and 60% respectively. The presence of ferrochromium contributes approximately 80% of total high human toxicity impacts in the production of steel.

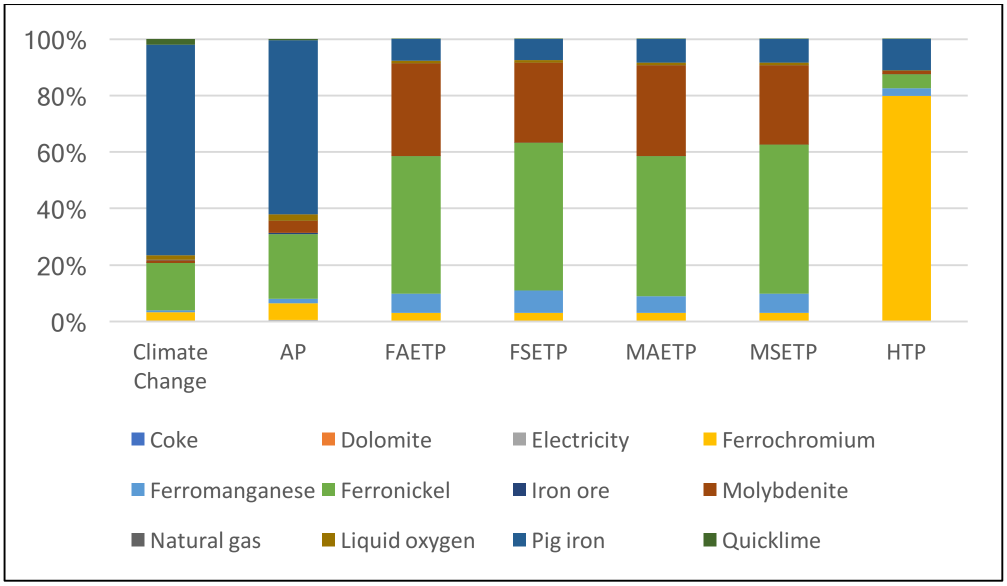


Figure 9.4 Environmental profile of 1kg steel slag from steel production process

For coal ash (Figure 9.5), the input with the dominant contribution to embodied environmental impacts is hard coal. Burning of hard coal in the generation of electricity contributes to approximately 98% of total impacts across all environmental impacts relating to ecotoxicity, climate change impact and acidification potential. The other inputs have relatively minimal environmental impacts.

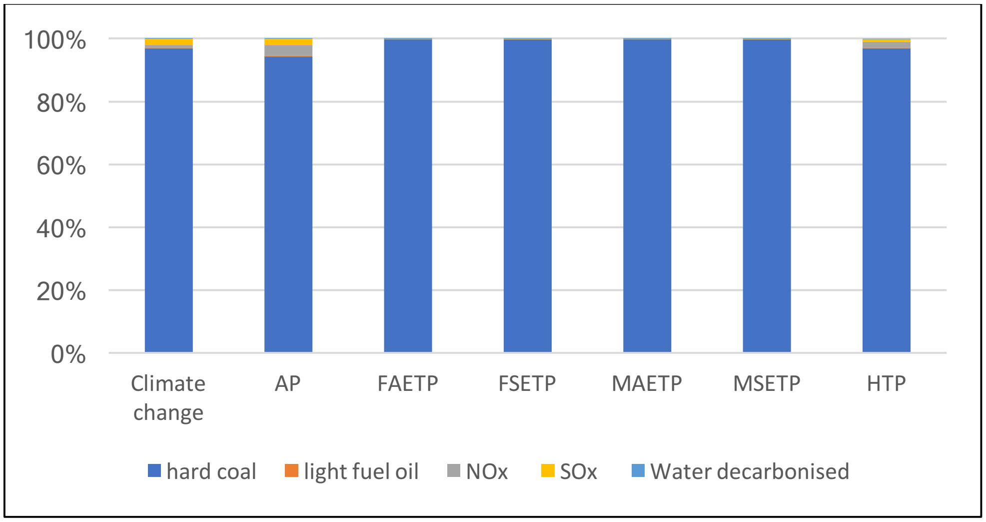
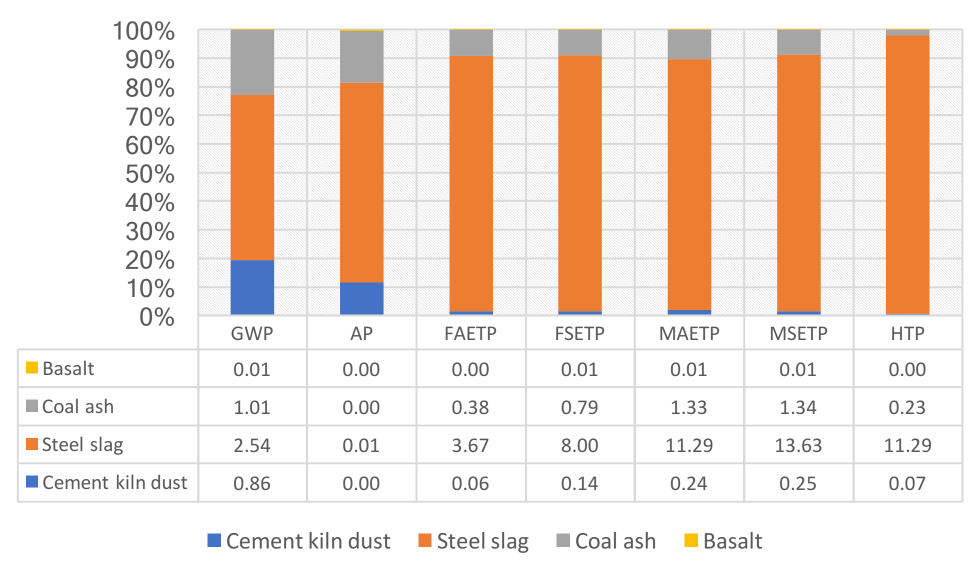


Figure 9.5: Environmental profile of 1kg coal ash produced from electricity production from coal

Figure 9.6 compares the environmental profile of all the four silicate source materials across the seven environmental impacts estimated. Results show that steel slag relatively has the highest contribution to environmental impacts for climate change, acidification potential and toxicological footprint (ecotoxicity). In comparison to the artificial waste silicate additive, the findings show that basalt may be considered as more environmentally sustainable as a silicate source for ERW purpose due to the relatively low embodied impacts associated with its production.



	GWP	AP	FAETP	FSETP	MAETP	MSETP	HTP
■ Basalt	0.01	0.00	0.00	0.01	0.01	0.01	0.00
■ Coal ash	1.01	0.00	0.38	0.79	1.33	1.34	0.23
■ Steel slag	2.54	0.01	3.67	8.00	11.29	13.63	11.29
■ Cement kiln dust	0.86	0.00	0.06	0.14	0.24	0.25	0.07

Figure 9.6 Comparing the environmental profile of silicate source materials. Unit of GWP is kg CO2-eq, Acidification potential (AP) is kg SO_x, FAETP,FSETP,MAETP,MSETP and HTP is kg 1-4-DCB-eq.

9.4 Discussion and conclusion

The above results of the study can be summarised as natural silicate material (basalt) has relatively minimal embodied environmental impact compared to artificial silicate wastes (cement kiln dust, steel slag and coal ash). The natural conclusion, therefore, is to assume that the best material for ERW implementation is to use virgin rock since it has less damaging ecological footprint during its production. However, there is a noticeable trade-off here; that is the carbon dioxide removal potential of these artificial silicate materials particularly steel slag and cement kiln dust (except for coal ash) is higher than that of natural silicate basalt. Therefore, in line with the overall aim of enhanced weathering as a CDR strategy, artificial silicates can be said to have more significant potential than basalt as a natural silicates source.

In addition, these artificial silicate-bearing waste materials are already available and, in some instance, has been stockpiled for years. In a recent study in the UK (Mayes, Riley et al. 2018) it is estimated that only ~3% of the carbon sequestration potential of steel slag from a historical blast furnace has been utilised. Using the UK as an example, Table 9.1 shows the annual production of these materials. A tonne of cement produces at least 150kg of waste as kiln dust(Van Oss and Padovani 2003). The UK produces an average of 8.2Mt of cement annually (Bide et al, 2013) and therefore based on a 65%CaO content (Renforth et al., 2011) an approximate production of 1.2Mt kiln dust waste is estimated. Coal ashes (fly ash and furnace bottom ash) are by-products of the combustion process at coal-fired power stations. Content of coal ash depends on the type of coal burnt, whether lignite, anthracite or bituminous. According to a recent report by the UK Quality Ash Association (2016), average 5Mt of fly ash are produced annually, and 70% are used for raw materials in the construction industry with the remaining spread on landfill site, which represents great potential for use in enhanced rock weathering. Overall, we estimate the UK annually generates approximately 7.2Mt of these artificial silicate wastes.

Table 9.1: Annual production estimate of artificial silicate wastes in the UK

Material	Cation content estimate	Annual production(Mt)
Cement kiln dust	65% CaO	1.2
Steel making slag	45% CaO and 7% MgO	1
Coal ash	3-20%CaO and 1%MgO	5
Total		7.2

*Estimates based on cation content from Renforth et al., 2011

The use of the artificial silicate fits perfectly into the growing interest in circular economy where waste in an industry or sector become a resource for another (Dora et al, 2016, Genovese et al, 2015). This ensures the move from a linear economy where finite resources are continually used for production and by-products become 'waste'. To promote the role of resource circularity and recycled waste use for ERW, we envisage the strategy can be complemented with artificial silicates waste such as those analysed in the study. This would most likely reduce the quantity of basalt needed to be mined, crushed and grinded and subsequently, the overall associated environmental impacts. Integrating artificial silicates into the basalt ERW supply chain will most likely require the implementation to be carried out on land not used for agriculture.

The results of the study highlight the potential embodied impacts of these artificial silicates and therefore considering their associated negative impacts, they must be a part of the solution in the fight against climate change. It must be noted however that, the use of these by-products does not necessarily absolve energy-intensive firms particularly steel producers, cement or coal-powered electricity industries from finding solutions to lower the negative environmental effects linked to their production supply chain. As shown in the study, the environmental impact in their production, which subsequently generates the silicate by-products is too high and therefore unsustainable to be solely relied on for carbon removal purposes.

In addition, further research is required into the environmental impacts in relation to the actual chemical weathering process and the effects of spreading both natural and artificial silicates on land. Furthermore, the use of these silicate waste would require treatment which might increase the embodied impacts. The scope of our LCA model, however, did not extend to this area. Such environmental impacts relate more to the actual characterization of the silicates and not the supply chain processes of their production, which has been the central aim of this study. Similarly, it is vital to emphasize that future research is required to examine socio-economic sustainability and recommend optimization of ERW supply chains that provide environmental-socio-economic sustainability to the natural and bio-physical eco-systems before their CO_2 sequestration.

9.5 Chapter Summary

While most studies suggest the use of natural silicate-bearing materials for ERW such as basalt rock, others propose artificial silicate bearing waste produced as by-products. The current chapter estimates and compares the environmental sustainability of four groups of silicate materials, namely basalt as a natural silicate and three artificial waste silicates: cement kiln dust, steel slag and coal ash. The Life Cycle Assessment (LCA) methodology is employed in the study to quantify seven environmental impact categories particularly global warming potential, acidification potential and five toxicological footprints related to the process of producing these silicate materials.

Results indicate that the artificial silicate waste materials, particularly cement kiln dust and steel slag have relatively higher CO_2 sequestration potential (0.5t CO_2 t^{-1} and 0.4t CO_2 t^{-1} respectively) than basalt (0.3 t CO_2 t^{-1}) except for coal ash which has relatively the lowest sequestration potential of 0.1t CO_2 t^{-1}. However, the embodied environmental impacts of the artificial silicates are found to be higher than basalt across all seven impacts estimated. For instance, whereas there is a global warming impact potential (GWP) of 0.01 t CO_2-eq per kg basalt produced, cement kiln dust, steel slag and coal ash all have relatively higher GWP of 0.86kg CO_2-eq, 2.25kg CO_2-eq and 1.01kg CO_2-eq CO_2-eq per kg produced. Nevertheless, since artificial silicate wastes are already available and, in most cases, have been stockpiled for long periods, their reuse in ERW implementation is still essential in industrial waste reduction and circular economy strategy.

CHAPTER 10: CONCLUSION AND FUTURE WORK

10.1 Introduction

This chapter presents the conclusion of the thesis. In this chapter, an overview and summary of key findings from the empirical studies conducted in line with the research aim and objectives presented in Chapter 1 (section 1.5) are discussed. In addition, the chapter presents an outline of the implications of the study and makes some policy recommendations in line with climate change mitigation. Finally, the limitations of the research are outlined and subsequently followed by suggestions for possible future research work. The central focus of this thesis has been centred on analysing the sustainability of enhanced rock weathering (ERW). As expounded in the introduction chapter of the thesis (section 1.2), ERW which involves the extensive application of crushed silicates on mainly croplands has been cited as one of the viable and growing CDR techniques to combat climate change globally. However, the viability of the ERW technique has focused mainly on the technical potential. This refers to previous studies that estimate the amount of carbon dioxide that can be potentially captured from the application of crushed silicate rocks such as basalt.

Conspicuously excluded from the viability assessment of ERW is the sustainability dimension from a triple bottom line perspective which includes economic, environmental, and social. This assertion is supported by Chapter 2, where a narrative literature review was used in exploring the relevant extant literature on ERW (section 2.3-2.10). In addition, the chapter presented a discussion on studies related to supply chain sustainability and the triple bottom line concept (section 2.11-2.12). One key highlight revealed through the review is that there is a lack of macro-level sustainability assessment on the production supply chain process of ERW, which involves the mining and quarrying of silicate rocks. In addition, little research on comparative sustainability assessment on different silicate materials has been carried out. The case for EW has been linked to fertiliser potential in terms of serving as a soil remineralizer (section 2.8). Yet, little is known on how the production of the crushed silicates environmentally compared to the production of existing and widely used rock-based fertilisers such as potassium and potash fertilisers. Against this backdrop, important research gaps in the literature on ERW supply chain sustainability were identified and subsequently, research questions were outlined.

To answer the research questions and fill the research gaps identified in Chapter 2, a methodological approach was designed in Chapter 3. The philosophical stance which informed the research approach used in the study was highlighted in the chapter (section 3.2). Based on a deductive approach, a quantitative method is used in the sustainability assessment of crushed silicates. In line with the quantitative approach, the main methodological principle applied is supply chain TBL (economic, environmental, and social) impact assessments. To capture macro-level TBL impacts a framework that encapsulates a lifecycle thinking was employed, that is the input-output model. The use of the input-output model especially fits in with the research aim of macro-level sustainability assessment and ensured that TBL impacts estimated reflect knock-on effects from both direct and indirect sectors involved in the production of the crushed silicates were included. The theoretical underpinning of the study was informed from the resource-based view, nature resource-based view, social resource-based view and a proposed integrated resource-based view theory (section 2.13). The bulk of the findings of the study is captured in the analysis sections, and these are summarised in the next section of the current chapter.

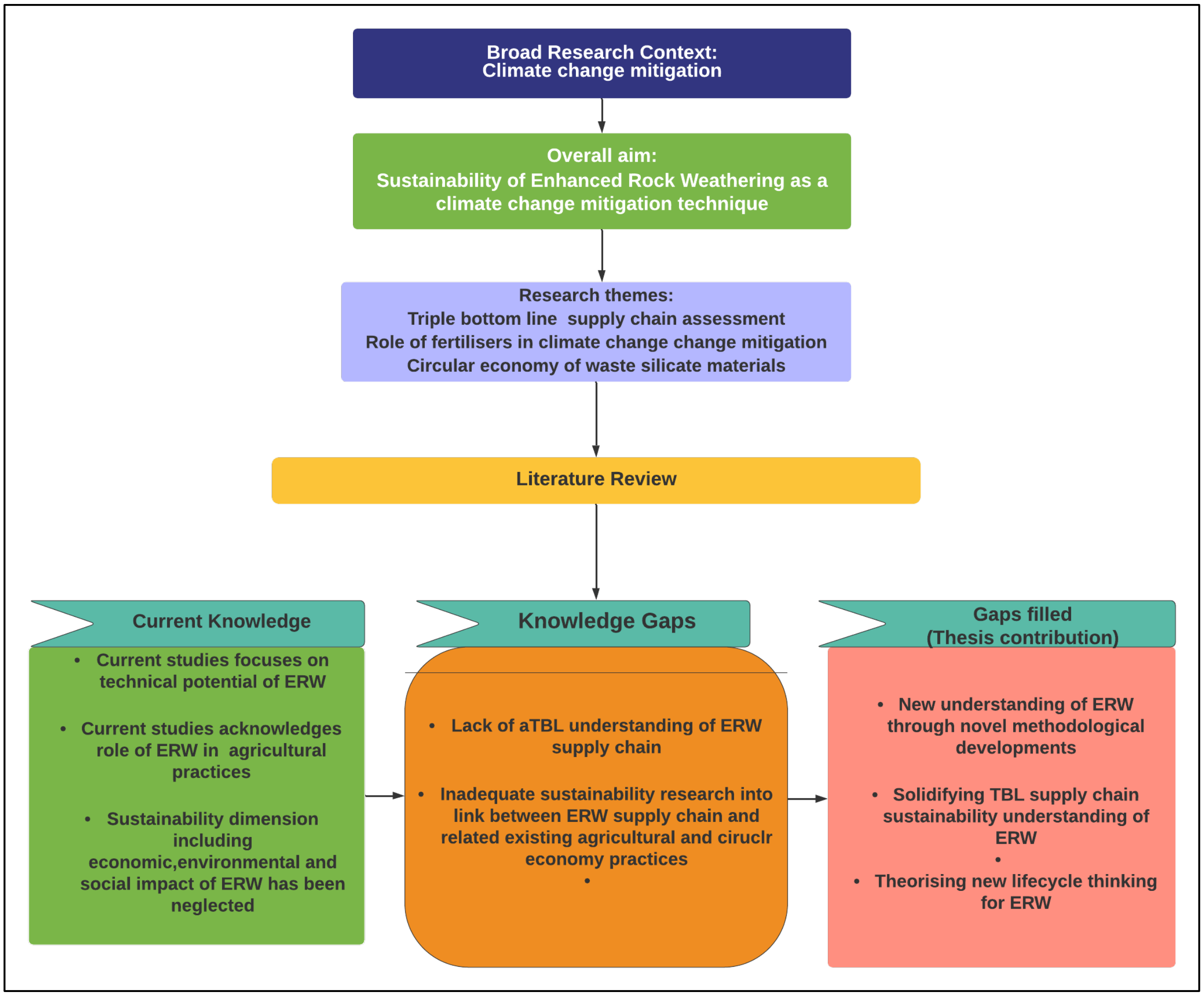


Figure 10.1: Summary of the research context, knowledge gaps and thesis contribution

10.2 Research Questions addressed and inter-connections between studies

This thesis contains six empirical studies on ERW. Although each study or chapter answers a distinct research question, overall the studies are all related. This section outlines the inter-connections between the studies carried out in each chapter.

To understand the context within which the studies were conducted, it is important to recall the specific research questions that the current thesis sought to address and link to the empirical studies presented and discussed. Overall there were three research questions addressed in the study.

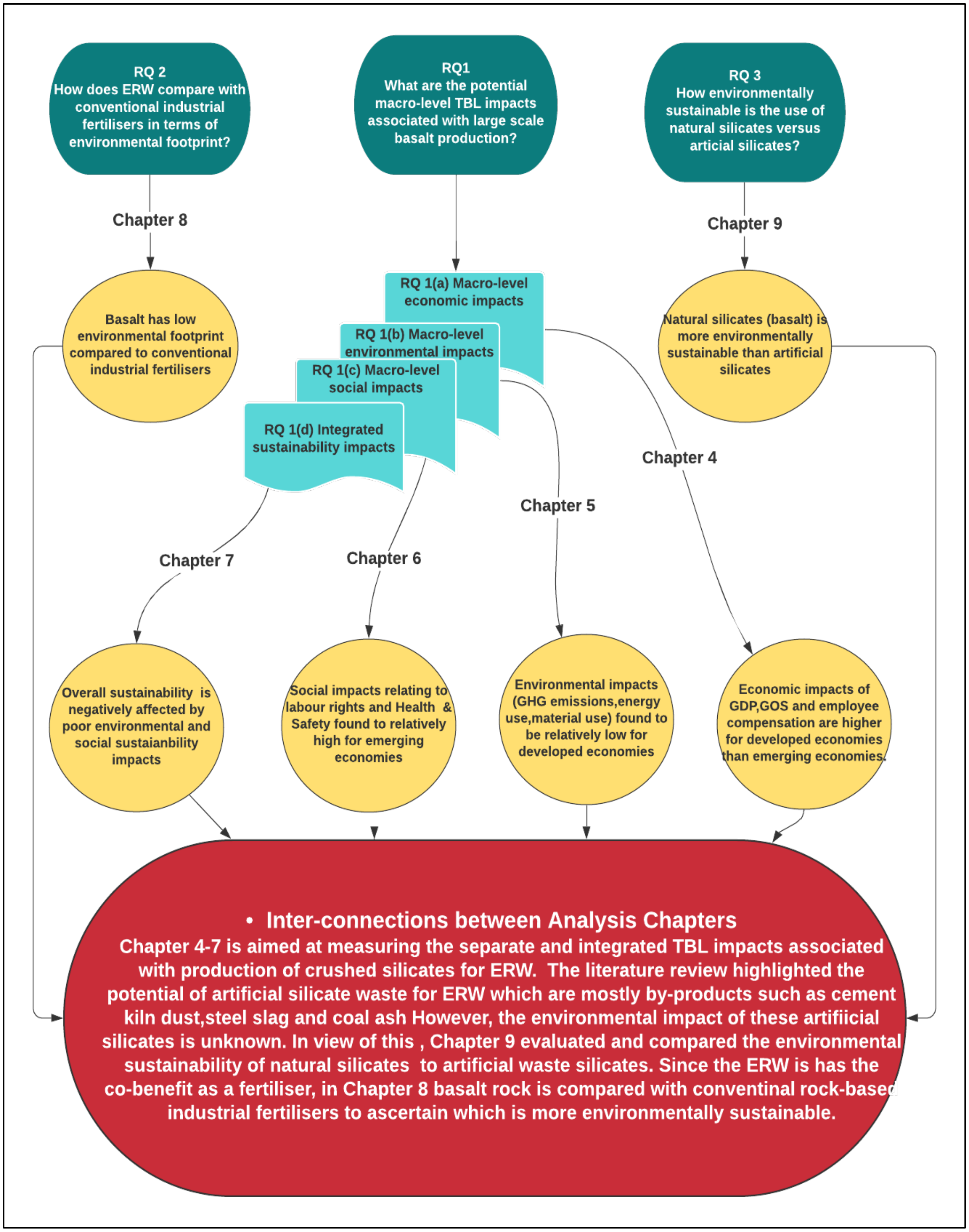
- RQ1: What are the potential macro-level TBL impacts associated with large-scale basalt production?
- RQ 2: How environmentally sustainable is the use of natural silicate versus artificial silicates?
- RQ 3: How does ERW compare with conventional industrial fertilisers in terms of environmental footprint?

To address RQ1, the economic, environmental and social impact of basalt production were assessed for different groups of countries; emerging and developed economies in chapters 4-6. Assessing the environmental and social impacts, puts the economic impacts into perspective by highlighting the environmental and social cost that comes alongside the economic gains from silicate production. Trade-off between the TBL impacts was further highlighted in Chapter 7 where countries were ranked based on their performance in indices across the TBL impacts. The results from this chapter provided possible explanations to a country's overall sustainability performance in ERW.

The analysis in chapters 4-7 however focused on the situation where rocks would have to be actually mined and crushed for use in ERW. Contrary to mining of rocks, the literature review also established the fact there are situations where, by-products that contains silicates could be used to capture CO_2. The question therefore remained that which option is more sustainable; mining fresh silicate rock or the use of silicate waste by-product which links to RQ2. To address this research question, a lifecycle assessment method was used to compare ERW with natural silicate(basalt) and three silicate waste by-products namely steel slag, cement kiln dust and coal ash. This finding complements the empirical chapters in 4-7 in that it helps decision makers to identify and evaluate their optimal ERW sustainability performance based on either fresh rock mining or use of artificial silicate sources.

Beyond the ERW production supply chain, it was important to note that the overall adoption of this CDR technique rest on whether the key stakeholders in this case, farmers participate. Aside the sustainability impacts of ERW based on fresh mining of rock or use of artificial silicates, it was established form the literature review that farmers play a vital role in the implementation since ERW is mainly carried out on croplands. From the perspective of farmers, the switch from their current use of industrial fertilisers to use of basalt rock fertilisers may depend on the benefits such as impact on crop yield of each fertiliser type. Although the several studies highlighted the impact of basalt rock on crop yield (Gilmann et al., 2002; Anda et al., 2009; Kantola et al., 2017; Beerling et al., 2018; Garcia et al, 2020), the environmental sustainability comparison of basalt rock dust fertiliser and industrial fertilisers had not been conducted. This led to the empirical study in Chapter 9 (addressing RQ3), where LCA method was used to compare the environmental profile of basalt and industrial rock based phosphorus and potassium fertilizers.

Figure 10.2, which is a modification of Fig 2.5 in Chapter 2, shows the research questions that have been answered by the thesis. It includes a highlight of some key findings for each chapter as well as a summary of the inter-connections between chapters.



- **Inter-connections between Analysis Chapters**

Chapter 4-7 is aimed at measuring the separate and integrated TBL impacts associated with production of crushed silicates for ERW. The literature review highlighted the potential of artificial silicate waste for ERW which are mostly by-products such as cement kiln dust,steel slag and coal ash However, the environmental impact of these artifiicial silicates is unknown. In view of this , Chapter 9 evaluated and compared the environmental sustainability of natural silicates to artificial waste silicates. Since the ERW is has the co-benefit as a fertiliser, in Chapter 8 basalt rock is compared with conventinal rock-based industrial fertilisers to ascertain which is more environmentally sustainable.

Figure 10.2: Research questions answered, key findings and inter-connections

10.3 Main Findings of the Thesis

In this section, a summary of the main findings of the research carried out in the analysis chapters of the thesis is presented.

Chapter 4: Following on from the literature review, it was determined that the economic assessment of the processes involved in ERW has primarily focused on the micro-level cost assessment. Various studies had been conducted that estimates the cost associated with mining, grinding, and crushing of rocks. It was determined that although such cost estimations are limiting as they fail to exclude the economic impacts arising from the inter-connections between sectors in an economy in producing the crushed silicates. To fill this gap, the economic assessment of ERW is done by way of performing macro-level lifecycle costing of silicate production. Using an economic input-output model, five economic impact categories, namely GDP, GOS, imports, employee compensation and working hours, are estimated. The analysis was conducted for eight countries grouped under emerging economies (Brazil, Russia, India, and China) and developed economies (USA, UK, France, and Germany). The main findings in this chapter are as follows:

- The production of silicates was found to be more favourable for developed economies than emerging economies, especially in indicators such as GDP, GOS and employee compensation. The exception, however, was China which had the highest GDP and GOS among all the countries.
- Emerging economies have abysmal economic performance in terms of employee compensation (section 4.3.4) and working hours (section 4.3.5). The findings suggest that while the production of crushed silicates will potentially require more working hours for developed economies than their counterparts in developed economies, the employee compensation received is relatively low and therefore appears not to commensurate the working hours involved.
- Imports are disproportionately high in developed economies, the highest being the UK than the emerging economies (section 4.3.3). This suggests that developed economies rely more on inputs from sectors outside their national boundaries in the production of crushed silicates. The high imports in developed economies will

prove critical in explaining why environmental impacts associated with the crushed silicates was found to be relatively low in these countries, which was covered in Chapter 5.

Chapter 5: The environmental pillar of TBL impacts was the focus of this chapter using the same group of countries for the economic assessment in Chapter 4. Although few studies including that of Moosdorf et al. (2014) and Lefebvre et al. (2019) had been conducted that attempts to map out some potential environmental impacts of ERW, these exclude the lifecycle macro-level impacts taking into account impacts from inter-connections between sectors in an economy in producing the crushed silicates. Towards filling this research gap, the input-output model is extended using environmental outputs including energy use, greenhouse gas emissions, material use, acidification potential and eutrophication potential. The main findings here are as follows:

- Generally, the emerging economies perform poorly in terms of environmental performance on the production of crushed silicates compared to developed economies especially in impacts relating to energy use, global warming impact and material use.
- The analysis revealed that one underlying reason for the low environmental impacts in developed economies is linked to the high import of inputs the countries engage in the production of crushed silicates (section 5.3.6). The finding aligns with other research work that supports the assertion of developing countries ‘cleaning up' their country at the expense of the countries they engage in trade with via imports.
- The environmental intensity (section 5.3.7) was one interesting finding in this chapter. It was determined that although a country's mining and quarrying sector may have a high total impact in a given impact category, the emission intensity which represents impact per unit output may be relatively higher. Therefore, in measuring the environmental impact associated with crushed silicates, it is the environmental intensity that determines the overall total impact. For instance, among the developed economies, the USA has the highest energy and material use in its mining and quarrying sector. However, in terms of energy and material use

intensity, Germany surpasses the USA. The material use intensity in Germany was found to be higher than that of India.

Chapter 6: It has been established in the literature that sustainability encompasses three pillars, that is economic, environmental, and social. However, social sustainability analysis is not as prevalent in the supply chain sustainability literature compared to the other two pillars, namely, economic and environmental. The assessment of social impacts must also be conducted with from a lifecycle perspective which led to the social lifecycle assessment. Nevertheless, there is no one widely accepted and standardised method for conducting SLCA. This, therefore, presented an opportunity for the current study to make a valuable methodological contribution to SLCA by proposing the Social Input-Output (SIO), which is an extension of the I-O model using social data. Using the social hotspot database (SHDB), the SIO model was used in Chapter 6 to estimate potential social risk impacts including labour rights and decent work, health and safety, human rights, community infrastructure and socio-economic contribution. Some of the key findings of the chapter are enumerated below:

- The general finding is similar to that of the environmental impact assessment in that the developed economies had relatively better social performance compared to the emerging economies. Among the emerging economies, China and India particularly had relatively the worst social performance in most of the social impact depicted by the relative high-risk hours for the social theme or impact category. In the case of the developed economies, it was the USA that had relatively the worst social performance compared to its counterparts such as France and Germany.
- However, beyond the overall social risk for a given social theme, results also highlighted the number of high and very high-risk indicators. This becomes relevant in explaining why a particular country had high or low social performance in crushed silicate production. The details

- The social risk that had high impacts were from the labour rights and decent work and health and safety which suggest that these are the social themes that need to be targeted for addressing social impacts associated with crushed silicate production in the countries. The socio-economic contribution was, however, more favourable to the emerging economies than the developed economies.

Chapter 7: To give an overall view of the sustainability performance of countries in the production of crushed silicates, indices were introduced in Chapter 7. Similar to the methodological challenges in SLCA, in estimating TBL impacts, there is no widely accepted method for integrating impacts. Therefore, indices were first developed for each TBL factor or sustainability pillar that is Economic Index (EC index score), Environmental index (EN index score) and Social Risk index (SR index score). Secondly, an overall index referred to as the Lifecycle Sustainability Assessment (LCSA) index was developed as the sum of all the three indices. In the estimation of the individual TBL indices, the weight of an impact category is considered, which makes it easy to identify the indicators with the highest contribution to a TBL factor. Therefore, it easy to identify the 'hotspot' in each country where policy measures must be targeted in addressing the impacts. The key finding in this chapter is as follows:

- Generally, the developed economies have better LCSA index than the emerging economies with France ranked as the top among all the countries followed by the USA. This is as a result of the relative high EC index in these countries attributed to their GDP, GOS and employee compensation per unit of crushed silicates. On the other hand, the developed economies Germany and the UK were found to relatively have lower LCSA index. India has relatively the worse sustainability performance among all the countries. The overall sustainability performance (LCSA index) of a country in the production of crushed silicates is affected negatively by the country's EN and SR index score. In other words, for a country to perform relatively better in terms of sustainability in silicate production, they would need to decrease the negative environmental and social impacts within the production supply chain. Among the emerging economies, Brazil performs well in all indices compared to Russia, India, and China.

- The hotspot for most countries and in their EN index is GHG, energy and material use. For the SR index, the labour rights and decent work and health and safety was the predominant indicator that affected their social sustainability performance.

Chapter 8: From the literature review, it was established that one of the reasons why ERW is gaining popularity among the CDR techniques is its role as a fertiliser and soil remineraliser aside its CO_2 sequestration potential. The silicate rock, especially basalt, is known to contain some important macronutrients, namely phosphorus and potassium needed by plants. This explains why the application of crushed silicates on croplands is mostly advocated. On the other hand, the massive use of industrial and conventional PK fertilisers has been questioned due to the expensive cost to local farmers and the link to environmental pollution. This has prompted many studies that seek to find alternatives to these fertilisers. The analysis in this chapter, therefore investigated whether basalt rock dust fertiliser can serve as an environmentally close substitute to expensive and conventional rock-based P and K fertilisers. Using the process-based LCA method, the chapter presented a comparative LCA of basalt rock dust fertiliser and five industrially produce P-K fertilisers namely single superphosphate (SSP), triple superphosphate (TSP), potassium chloride(KCl), potassium carbonate (K_2CO_3) and potassium hydroxide (KOH). Key findings of the study are summarised below:

- The environmental profile of basalt fertiliser production was found to be far less damaging compared to the industrial P-K fertilisers across all the 15 environmental impacts estimated. The production of basalt has less than 1% contribution to total impacts in a given impact category.
- The environmental profile of the phosphate-based fertilisers that is TSP and SSP were found to be relatively more damaging in 11 out of the 15 impact categories estimated including climate change impact, acidification potential, eutrophication potential and ecotoxicity. Potash based fertilisers KCl and K_2CO_3 had relatively lower impacts across all environmental impacts compared to the phosphate-based fertilisers.

- Primary energy input was the main source of differences in environmental impacts between basalt and the industrial fertilisers. The production of SSP and KOH, in particular, had relatively high electrical and thermal energy compared to the other fertilisers. The production of basalt had very low energy input.

Chapter 9: The CO_2 sequestration potential of ERW has been fundamentally linked to the mining and comminution of silicate rocks which is then applied on lands. However, other materials contain silicate that has also been cited as having CO_2 sequestration potential (Renforth 2019; Pullin et al., 2019; Renforth et al. 2013). Such materials, usually referred to as artificial silicates are mostly produced as by-products, and examples of these include cement kiln dust, steel slag and cold ash. A review of the literature reveals that comparative studies on these different artificial silicate types and natural silicate (in this case basalt) based on an environmental profile is missing from the discourse on ERW. To fill this gap, the study in Chapter 9 presented results on the comparative life cycle assessment off basalt as a natural silicate and three artificial silicates, namely cement kiln dust, steel slag and coal ash. Summary of the key findings are stated below:

- On the basis of CO_2 sequestration potential, two of the artificial silicates (steel slag and cement kiln dust) were found to have more significant CDR potential than natural silicates that is basalt in this case. Basalt has a CO_2 sequestration potential of 0.3t CO_2 t^{-1}. The results show that coal ash has the least CO_2 sequestration potential of 0.1t CO_2 t^{-1} compared to the other artificial silicates such as steel slag and cement kiln dust with CO_2 sequestration potential of 0.4t CO_2 t^{-1} and 0.5t CO_2 t^{-1}. The relatively low CO_2 sequestration potential of basalt relative to artificial silicates steel slag and cement kiln dust means the quantity of basalt is needed to sequester a functional unit of one tonne CO_2.
- Based on embodied environmental impacts, the artificial silicates were found to be more damaging than natural silicate(basalt). For instance, embodied GWP impact of basalt is 0.01kg CO_2-eq per kg whereas embodied GWP in steel slag, coal ash and cement kiln dust has ~2.5kg CO_2-eq, 1kg CO_2-eq and 0.86kg CO_2-eq. The findings suggest that for ERW purposes, natural silicate(basalt) may be considered as environmentally more sustainable than the artificial silicates based

on relatively low embodied impact although relatively it has lower CO_2 sequestration potential.

10.4 Contribution to Knowledge and theory

Contributions to knowledge resulting from this PhD research include:

d. ***New understanding for ERW supply chain through novel methodological developments:*** Sustainability assessment of ERW supply chain and in particular the social impact assessment of the production of crushed silicates has been made possible through the novel social input-output (SIO) method. Through the SIO model, insights into how society is impacted through the extended supply chain of mining and quarrying sectors are highlighted in the study. The development of the SIO model is based on an expansion of the traditional input-output LCA method. Beyond its application in ERW supply chain, it is envisaged that the SIO model can serve as valuable methodology for quantifying social impacts along extended supply chains for different products. In addition, the integrated sustainability indices method and presentation of results applied in Chapter 7 of the study serve as a valuable contribution to methodologies on sustainability composite index development which can be extended to other sustainability modelling studies in the future.

e. ***Solidifying the Triple Bottom Line supply chain understanding of ERW to support and complement the science of developing ERW as a truly credible and feasible climate change mitigation option.*** Before the current study, one significant gap in the literature and research on ERW has been a lack of understanding of the ERW supply chain impacts that covers the economic, environment and society. Some studies had acknowledged the importance and need for such TBL understanding of ERW, but no such study had been done. The current study, therefore in filling this gap, serves as a complementary study to these studies that had focused on the technical feasibility of ERW as a climate change mitigation option.

f. Theorising ***new lifecycle thinking for ERW supply chain based on the application of an extension of RBV theory to include TBL sustainability as a competitive advantage.*** The Resource based view(RBV) and other extensions of the theory that is Nature resource-based view (NRBV) and social resource-based view (SRBV) focused on the economic and environmental competitive advantage at the firm level. However, in the current study, contributions are made in highlighting the relevance of the proposed Integrated Resource Based-view (IRBV) theory, where competitive advantage is viewed from a supply chain level perspective that promotes an integrated TBL assessment. Prior to this study, competitive advantage of firms as stipulated in the RBV theory, was limited to individual firms' performance without recourse to the inter-linkages between firms which could also influence the level of competitive advantage. With the IRBV theory which is an expansion of the RBV theory, competitive advantage (in this case macro-level TBL sustainability performance) can be explained based on the inter-linkages among firms.

10.5 Research Implications and Recommendations

This section presents the wider implications of the study on climate change mitigation through CDR techniques and makes some policy recommendations in addition. Macro-level and economy-wide sustainability assessment of the production of crash silicates brings attention to how the role out of a CDR technique generates knock-on effects on other sectors of the economy. In providing solutions to addressing the growing climate change crisis, care must be taken to ensure that these solutions do not lead to negative externalities elsewhere. If such associated externalities do occur, the methodology presented in the study allows for tracing of where these impacts are located (example the results on sectoral contribution and direct and indirect impacts). In this way, it becomes easier to develop well-informed evidence base and targeted policies in addressing these externalities or in the very least in reducing the negative impacts in cases where they cannot be avoided. Through the extensions of the I-O model used in the analysis, decision-makers can trace the sectors impacted most by the production of crushed silicates aside the mining and quarrying sector.

The study relates TBL impacts to a functional unit of 1kg of crushed silicates. This makes it easy to scale up impacts associated with a given quantity of crushed silicates for ERW purposes. For instance, in the study by Moosdorf et al. (2014), the authors estimate that approximately 750,000 million tonnes of silicate are needed globally for enhanced rock weathering. However, the associated TBL sustainability impacts are unknown. By working out the impact per functional unit, this study fills the gap by making it possible to estimate impacts associated with large scale quantities of silicates.

The multi-country approach accounts for the fact that countries do differ in terms of sustainability impacts in adopting large scale implementation of CDR, including enhanced rock weathering. Parties to international climate agreements such as the Paris agreement will each have to assess the sustainability impacts of the CDR technique in the context of conditions unique to their country. The UNFCCC acknowledges this fact by dividing countries into Annex I and non-Annex II countries. However, in periodic climate change mitigation reports such as the IPCC annual reports, scenario analysis presented in these reports are usually based on the global context and does not represent the country-level context. The findings in the study, therefore serve as a good reference point that can be considered by policymakers in capturing the individual country impacts in adopting CDR techniques.

The study has also highlighted the role of ERW in the fertiliser industry. For years the growth in fertiliser use has come at an unsustainable cost to the environment. In the search for alternatives, it is recommended that crushed silicate should be favourably considered as the study findings show that, these have relatively far less damaging impact to the environment in their production compared to industrial P-K fertilisers. It is therefore recommended that rock-based fertilisers be extended to cover other rock such as basalt in this case which has the dual benefit of having low embodied environmental impacts and CO_2 sequestration via ERW. As noted in Chapter 9 of the study, the thinking here is not to suggest that ERW with silicate rocks such as basalt will completely replace industrial PK fertilisers. However relative to PK fertilisers, the basalt fertiliser has an additional comparative advantage, precisely, its CO_2 sequestration potential. In the very least, this warrants that ERW with basalt strategy is considered as supplementary to rock-based fertilisers. In which case, less of the P-K fertilisers will be produced and the reduction in quantity supplemented with basalt rock dust fertiliser.

Finally, the use of artificial silicates fits into the circular economy agenda, which aims to eliminate waste by converting waste to resource. Although the study findings show that the use of these artificial silicates has relatively high embodied impacts than natural silicates, the study also establishes that these have relatively high CO_2 sequestration potential. Furthermore, there are stockpiles of these materials in existence, and therefore it would be good to tap into these 'waste silicates' and reuse them for ERW purposes. Countries can minimize their impacts associated with mining and quarrying of crushed silicates by supplementing with already available stockpiles of artificial silicates.

The broader policy implications and contribution from the thesis can be summarised as follows:

i. ***Trade policy and sustainability:*** the current thesis contributes to knowledge on the role of trade policies on sustainability. The study, in particular, confirms that trade policies within a country can positively or negatively influence the country's ability to achieve TBL sustainability target in a given sector. Sustainability burdens, in particular, environmental and social impacts can be externalised to other countries through imports. International trade policies, therefore, must take into consideration fairness and equity on countries that are disproportionately affected by negative externalities.

ii. ***Climate change mitigation policy:*** The adoption of a climate change mitigation strategy is incomplete without consideration of the holistic sustainability implications that covers economic, environmental and social impacts. The study has implications is seen in how the implementation of a CDR in particular ERW can generate knock-on macro-level TBL impacts.

iii. ***Agricultural food policy:*** By adopting a comparative lifecycle assessment between fertilisers and ERW with basalt, the thesis highlights how climate change mitigation can be achieved alongside improvements in sustainable food production. The results of the study establish this link between agricultural food policy and climate change mitigation. The study results suggest that the agri-food policies need not be decoupled from climate change mitigation practices, but instead solutions such as ERW must be integrated into policy decision making.

10.6 Research Limitations

Although this thesis presents important results and fills the identified research gaps, there are some inherent limitations as well, which must be highlighted as well. These limitations are discussed below:

Single-country IO model: The I-O model used in the study is based on single country input-output tables. This defers from the multi-regional input-output (MRIO) model, which links the input-output table for different countries through international trade. For instance, whereas an IO model for UK inter-sectoral interactions within the country in addition to imports and exports, the MRIO model will show inter-sectorial between two specific countries such as the UK and China so that we can trace the particular country and sectors associated with imports and exports to the UK from China and vice versa. To some extent, the trade dimension is incorporated in the single I-O model used in the study by highlighting imports. However, the specific country that the imports come from is unknown and therefore it is impossible to estimate embodied import impacts since the technology of the exporting country is unknown.

Lack of trend analysis and forecast: Trend analysis based on time series data reveals industry patterns within economies and can help to make forecasts of how the sustainability impacts associated with silicate production could evolve in the future. However, the data source (WIOD, SHDB and GTAP) used for the macro-level sustainability assessment (chapter 4-6) is based on a single year that is 2011. Although WIOD has different years from 1999-2011, the decision to use the most the recent year

2011 was influenced by the SHDB and GTAP which does not have time-series data. Selecting the same reference, therefore allows for standardization of results and TBL sustainability integration performed in Chapter 7. The development of time series data for social impact would allow for a TBL-IO time series analysis.

Uncertainties due to aggregation: Within the input-output table, sector aggregation exists and therefore presents some embedded uncertainties in the results of the study. The Mining and Quarry sector where the crushed silicate production occurs also includes other economic activities. A detailed analysis requires disaggregation of the mining and quarrying sector into sub-sectors.

10.7 Suggestions for Future Research

This section outlines suggestions for future research that will be complementary to the findings of the current study on ERW sustainability and wider climate change mitigation strategies available.

Sustainability comparison of ERW with other Negative Emission Technologies (NETs). Solutions to climate change mostly involve the use of multi-approaches with different NETs. A study that looks at how the different NETs compare with each other in terms of TBL impacts will be essential in providing more evidence-based decisions on climate policies. There some previous studies exist in the literature where impacts of different NETs are compared, including ERW, BECCS, DAR, AR, SCS and Biochar. These however focused mainly on the environmental dimension of sustainability, excluding the economic and social dimensions. Based on a similar approach adopted in this study (that is integrated TBL assessment), future studies can be conducted to provide further evidence on sustainability concerns associated with the different NETs to guide policy formulation on climate change mitigation.

I***nter-linkages based on Multi-regional input analysis (MRIO).*** Following on from the single country IO model used in the current study, it would be useful to know the ERW sustainability impacts based on inter-linkages generated through international trade. As established in the study, some countries adopting ERW technology require that they import from other countries to produce crushed silicates. However, the use of the single IO does not allow to trace sustainability impacts to the specific countries where the imports originated. MRIO analysis can, in this instance, be used in analysing sustainability impacts based on origin-destination of crushed silicates. It is therefore recommended future research be considered in this area given the importance and relevance of imports to the TBL sustainability impacts of ERW as established in this thesis.

Primary field data. It is recommended that future studies incorporate the use of primary field data to validate results further. The LC3M centre for instance currently has started field trials in ERW with basalt in USA, UK, Australia, and Malaysia. Future fieldwork data can be used to validate further the index and sustainability assessment used in the study.

Time-series data for social impacts and forecast analysis. With the development of a comprehensive time-series data set on social data at country and sector level, it is hoped that the current thesis will form a basis for future work to be carried out in analysing TBL sustainability trends and forecast for enhanced rock weathering and another CDR techniques. This will assist policymakers in making the right decisions on a combination of CDR techniques or climate change mitigation solutions that will be sustainable years from now.

REFERENCES

1. Abbasi, M. and F. Nilsson (2012). "Themes and challenges in making supply chains environmentally sustainable." Supply Chain Management: An International Journal **17**(5): 517-530.

2. Acquaye, A. A., T. Wiedmann, K. Feng, R. H. Crawford, J. Barrett, J. Kuylenstierna, A. P. Duffy, S. C. L. Koh and S. McQueen-Mason (2011). "Identification of 'carbon hot-spots' and quantification of GHG intensities in the biodiesel supply chain using hybrid LCA and structural path analysis." Environmental science & technology **45**(6): 2471-2478.

3. Acquaye, A.A. and Duffy, A.P., 2010. Input–output analysis of Irish construction sector greenhouse gas emissions. *Building and Environment*, *45*(3), pp.784-791.

4. Ahi, P. and C. Searcy (2015). "An analysis of metrics used to measure performance in green and sustainable supply chains." Journal of Cleaner Production **86**: 360-377.

5. Allison, E. H., A. L. Perry, M. C. Badjeck, W. Neil Adger, K. Brown, D. Conway, A. S. Halls, G. M. Pilling, J. D. Reynolds and N. L. Andrew (2009). "Vulnerability of national economies to the impacts of climate change on fisheries." Fish and fisheries **10**(2): 173-196.

6. Amundson, R., A. A. Berhe, J. W. Hopmans, C. Olson, A. E. Sztein and D. L. Sparks (2015). "Soil and human security in the 21st century." Science **348**(6235): 1261071.

7. Anda, M., J. Shamshuddin, C. I. Fauziah and S. R. S. Omar (2009). "Dissolution of ground basalt and its effect on oxisol chemical properties and cocoa growth." Soil science **174**(5): 264-271.

8. Andrews, E. S. (2009). Guidelines for social life cycle assessment of products: social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development, UNEP/Earthprint.

9. Atafar, Z., A. Mesdaghinia, J. Nouri, M. Homaee, M. Yunesian, M. Ahmadimoghaddam and A. H. Mahvi (2010). "Effect of fertilizer application on soil heavy metal concentration." Environmental monitoring and assessment **160**(1-4): 83.

10. Azcue, J. M. (2012). Environmental impacts of mining activities: emphasis on mitigation and remedial measures, Springer Science & Business Media.

11. Bachu, S. (2000). "Sequestration of CO2 in geological media: criteria and approach for site selection in response to climate change." Energy conversion and management **41**(9): 953-970.

12. Bai, C. and Sarkis, J., 2010. Green supplier development: analytical evaluation using rough set theory. *Journal of cleaner production*, *18*(12), pp.1200-1210.

13. Baral, A. and Bakshi, B.R., 2010. Emergy analysis using US economic input–output models with applications to life cycles of gasoline and corn ethanol. *Ecological Modelling*, *221*(15), pp.1807-1818.

14. Barney, J. B. and D. N. Clark (2007). Resource-based theory: Creating and sustaining competitive advantage, Oxford University Press on Demand.

15. Barney, J.B., 1991. The resource based view of strategy: Origins, implications, and prospects. *Journal of management*, *17*(1), pp.97-211.

16. Barthel, M., J. A. Fava, C. A. Harnanan, P. Strothmann, S. Khan and S. Miller (2015). Hotspots analysis: Providing the focus for action. Life Cycle Management, Springer, Dordrecht**:** 149-167.

17. Bas, M. L., R. L. Maitre, A. Streckeisen, B. Zanettin and I. S. o. t. S. o. I. Rocks (1986). "A chemical classification of volcanic rocks based on the total alkali-silica diagram." Journal of petrology **27**(3): 745-750.

18. Beaulieu, E., Y. Goddéris, Y. Donnadieu, D. Labat and C. Roelandt (2012). "High sensitivity of the continental-weathering carbon dioxide sink to future climate change." Nature Climate Change **2**(5): 346-349.

19. Beerling, D. J., J. R. Leake, S. P. Long, J. D. Scholes, J. Ton, P. N. Nelson, M. Bird, E. Kantzas, L. L. Taylor, B. Sarkar, M. Kelland, E. DeLucia, I. Kantola, C. Müller, G. Rau and J. Hansen (2018). "Farming with crops and rocks to address global climate, food and soil security." Nature Plants **4**(3): 138-147.

20. Benoit-Norris, C., D. A. Cavan and G. Norris (2012). "Identifying Social Impacts in Product Supply Chains:Overview and Application of the Social Hotspot Database." Sustainability **4**(9).

21. Benoît-Norris, C., G. Vickery-Niederman, S. Valdivia, J. Franze, M. Traverso, A. Ciroth and B. Mazijn (2011). "Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA." The International Journal of Life Cycle Assessment **16**(7): 682-690.

22. Benoît, C., G. A. Norris, S. Valdivia, A. Ciroth, A. Moberg, U. Bos, S. Prakash, C. Ugaya and T. Beck (2010). "The guidelines for social life cycle assessment of products: just in time!" The international journal of life cycle assessment **15**(2): 156-163.

23. Benoît, C. and Mazijn, B., 2009. Guidelines for social life cycle assessment of products, UNEP/SETAC Life Cycle Initiative. *Sustainable Product and Consumption Branch Paris, France*.

24. Bide, T., Brown, T.J., Hobbs, S.F. and Idoine, N., 2014. United Kingdom Minerals Yearbook 2014: London. *UK, British Geological Survey, Open-Report OR/15/043*.

25. Bjørseth, A. (2016). "Rock Dust as a Sustainable Source of Fertiliser." Guidelines for Authors **6**: 40.

26. Blackford, J., H. Stahl, J. M. Bull, B. J. P. Bergès, M. Cevatoglu, A. Lichtschlag, D. Connelly, R. H. James, J. Kita and D. Long (2014). "Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage." Nature climate change **4**(11): 1011-1016.

27. Bode, C. and S. M. Wagner (2015). "Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions." Journal of Operations Management **36**: 215-228.

28. Bøen, A. and T. K. Haraldsen (2013). "Meat and bone meal and biosolids as slow-release phosphorus fertilizers." Agricultural and Food Science **22**(2): 235-246.

29. Brady, P. V. (1991). "The effect of silicate weathering on global temperature and atmospheric CO2." Journal of Geophysical Research: Solid Earth **96**(B11): 18101-18106.

30. Brammer, S.J. and Pavelin, S., 2006. Corporate reputation and social performance: The importance of fit. *Journal of management studies*, *43*(3), pp.435-455.

31. Brentrup, F. and Pallière, C., 2008. GHG emissions and energy efficiency in European nitrogen fertiliser production and use. In *Proceedings-International Fertiliser Society* (No. 639, pp. 1-25). International Fertiliser Society.

32. Brentrup, F., J. Küsters, J. Lammel, P. Barraclough and H. Kuhlmann (2004). "Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems." European Journal of Agronomy **20**(3): 265-279.

33. Brod, E., A. F. Øgaard, T. K. Haraldsen and T. Krogstad (2015). "Waste products as alternative phosphorus fertilisers part II: predicting P fertilisation effects by chemical extraction." Nutrient Cycling in Agroecosystems **103**(2): 187-199.

34. Brown, T., F. M. McEvoy, J. Mankelow, J. Ward, S. Bloomfield, T. Goussarova, N. Shah and L. Souron (2008). "The need for indigenous aggregates production in England."

35. Bruntland, G. H. (1987). "World commission on environment and development." Our common future **17**: 43-66.

36. Bryman, A. and E. Bell (2015). "Business research methods (Vol. 4th)." Glasgow: Bell & Bain Ltd.

37. Burniaux, J.M., Chateau, J., Dellink, R., Duval, R. and Jamet, S., 2009. The economics of climate change mitigation: How to build the necessary global action in a cost-effective manner.

38. Camanzi, L., A. Alikadic, L. Compagnoni and E. Merloni (2017). "The impact of greenhouse gas emissions in the EU food chain: A quantitative and economic assessment using an environmentally extended input-output approach." Journal of Cleaner Production **157**: 168-176.

39. Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley and V. H. Smith (1998). "Nonpoint pollution of surface waters with phosphorus and nitrogen." Ecological applications **8**(3): 559-568.

40. Carter, C. R. and D. S. Rogers (2008). "A framework of sustainable supply chain management: moving toward new theory." International journal of physical distribution & logistics management.

41. Chan, R. Y. K. (2005). "Does the natural-resource-based view of the firm apply in an emerging economy? A survey of foreign invested enterprises in China." Journal of management studies **42**(3): 625-672.

42. Chen, G., M. Hadjikakou and T. Wiedmann (2017). "Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis." Journal of cleaner production **163**: 224-240.

43. Chianu, J. N., J. N. Chianu and F. Mairura (2012). "Mineral fertilizers in the farming systems of sub-Saharan Africa. A review." Agronomy for sustainable development **32**(2): 545-566.

44. Ciroth, A. and J. Franze (2011). LCA of an ecolabeled notebook: consideration of social and environmental impacts along the entire life cycle, Lulu. com.

45. Cressey, D. (2014). Rock’s power to mop up carbon revisited, Macmillan Publishers Ltd., London, England.

46. Creswell, J. W. and J. D. Creswell (2017). Research design: Qualitative, quantitative, and mixed methods approaches, Sage publications.

47. Crotty, M. (1998). The foundations of social research: Meaning and perspective in the research process, Sage.

48. Cucchiella, F., L. Koh, C. Bai, J. Sarkis and X. Wei (2012). "Evaluating ecological sustainable performance measures for supply chain management." Supply Chain Management: An International Journal.

49. D'Hotman, D. V. O. and O. Villiers (1961). "Soil rejuvenation with crushed basalt in Mauritius." Int sugar J **63**: 363-364.

50. Dalmora, A. C., C. G. Ramos, M. L. S. Oliveira, E. C. Teixeira, R. M. Kautzmann, S. R. Taffarel, I. A. S. de Brum and L. F. O. Silva (2016). "Chemical characterization, nano-particle mineralogy and particle size distribution of basalt dust wastes." Science of the Total Environment **539**: 560-565.

51. Dan, V., 2017. Empirical and Non-empirical Methods. *The International Encyclopedia of Communication Research Methods*, pp.1-3.

52. de Haes, H. A. U., R. Heijungs, S. Suh and G. Huppes (2004). "Three strategies to overcome the limitations of life-cycle assessment." Journal of industrial ecology **8**(3): 19-32.

53. De Stefano, M. C., M. J. Montes-Sancho and T. Busch (2016). "A natural resource-based view of climate change: Innovation challenges in the automobile industry." Journal of Cleaner Production **139**: 1436-1448.

54. Delmas, M., 2001. Stakeholders and competitive advantage: the case of ISO 14001. *Production and Operations Management*, *10*(3), pp.343-358.

55. Delucchi, M. A. and T. E. Lipman (2001). "An analysis of the retail and lifecycle cost of battery-powered electric vehicles." Transportation Research Part D: Transport and Environment **6**(6): 371-404.

56. Dessert, C., B. Dupré, J. Gaillardet, L. M. François and C. J. Allegre (2003). "Basalt weathering laws and the impact of basalt weathering on the global carbon cycle." Chemical Geology **202**(3-4): 257-273.

57. Dora, M., Bhatia, M.S. and Gallear, D., 2016. Supply chain in a circular economy: a multidimensional research agenda.

58. Dreyer, L.C., Hauschild, M.Z. and Schierbeck, J., 2010. Characterisation of social impacts in LCA. *The International Journal of Life Cycle Assessment*, *15*(3), pp.247-259.

59. Dreyer, L., M. Hauschild and J. Schierbeck (2006). "A framework for social life cycle impact assessment (10 pp)." The International Journal of Life Cycle Assessment **11**(2): 88-97.

60. Edwards, D. P., F. Lim, R. H. James, C. R. Pearce, J. Scholes, R. P. Freckleton and D. J. Beerling (2017). "Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture." Biology letters **13**(4): 20160715.

61. Egilmez, G., M. Kucukvar and O. Tatari (2013). "Sustainability assessment of US manufacturing sectors: an economic input output-based frontier approach." Journal of Cleaner Production **53**: 91-102.

62. Ekener-Petersen, E., J. Höglund and G. Finnveden (2014). "Screening potential social impacts of fossil fuels and biofuels for vehicles." Energy Policy **73**: 416-426.

63. Ekener-Petersen, E. and Moberg, Å., 2013. Potential hotspots identified by social LCA–Part 2: Reflections on a study of a complex product. *The International Journal of Life Cycle Assessment*, *18*(1), pp.144-154.

64. Elkington, J. (1998). "Accounting for the triple bottom line." Measuring Business Excellence.

65. Epstein, M. J. and A. R. Buhovac (2014). Making sustainability work: Best practices in managing and measuring corporate social, environmental, and economic impacts, Berrett-Koehler Publishers.

66. Eskandarpour, M., P. Dejax, J. Miemczyk and O. Péton (2015). "Sustainable supply chain network design: An optimization-oriented review." Omega **54**: 11-32.

67. Eurostat, N. (2008). "Rev. 2–statistical classification of economic activities in the european community." Office for Official Publications of the European Communities, Luxemburg.

68. Fankhauser, S. and R. S. J. Tol (2005). "On climate change and economic growth." Resource and Energy Economics **27**(1): 1-17.

69. Finkbeiner, M., E. M. Schau, A. Lehmann and M. Traverso (2010). "Towards Life Cycle Sustainability Assessment." Sustainability **2**(10).

70. Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington and S. Suh (2009). "Recent developments in life cycle assessment." Journal of environmental management **91**(1): 1-21.

71. Fombrun, C. and Shanley, M., 1990. What's in a name? Reputation building and corporate strategy. *Academy of management Journal*, *33*(2), pp.233-258.

72. Foran, B., M. Lenzen, C. Dey and M. Bilek (2005). "Integrating sustainable chain management with triple bottom line accounting." Ecological economics **52**(2): 143-157.

73. Franzosi, C., L. N. Castro and A. M. Celeda (2014). "Technical evaluation of glauconies as alternative potassium fertilizer from the Salamanca Formation, Patagonia, Southwest Argentina." Natural Resources Research **23**(3): 311-320.

74. Freeman, R.E., 1984. Strategic management: A stakeholder theory. *Journal of Management Studies*, *39*(1), pp.1-21.

75. Fredline, L., M. Raybould, L. Jago and M. Deery Triple bottom line event evaluation: A proposed framework for holistic event evaluation.

76. Fuss, S., C. D. Jones, F. Kraxner, G. P. Peters, P. Smith, M. Tavoni, D. P. van Vuuren, J. G. Canadell, R. B. Jackson and J. Milne (2016). "Research priorities for negative emissions." Environmental Research Letters **11**(11): 115007.

77. Gallego, B. and M. Lenzen (2005). "A consistent input–output formulation of shared producer and consumer responsibility." Economic Systems Research **17**(4): 365-391.

78. Gan, Y., C. Liang, Q. Chai, R. L. Lemke, C. A. Campbell and R. P. Zentner (2014). "Improving farming practices reduces the carbon footprint of spring wheat production." Nature Communications **5**: 5012.

79. Garcia, W. d. O., T. Amann, J. Hartmann, K. Karstens, A. Popp, L. R. Boysen, P. Smith and D. Goll (2020). "Impacts of Enhanced Weathering on biomass production for negative emission technologies and soil hydrology." Biogeosciences.

80. Gauthier, C. (2005). "Measuring corporate social and environmental performance: the extended life-cycle assessment." Journal of business ethics **59**(1-2): 199-206.

81. Genovese, A., Acquaye, A.A., Figueroa, A. and Koh, S.L., 2017. Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, *66*, pp.344-357.

82. Ghertner, D. A. and M. Fripp (2007). "Trading away damage: quantifying environmental leakage through consumption-based, life-cycle analysis." Ecological Economics **63**(2-3): 563-577.

83. Gibbins, J. and H. Chalmers (2008). "Carbon capture and storage." Energy policy **36**(12): 4317-4322.

84. Gillman, G. P., D. C. Burkett and R. J. Coventry (2001). "A laboratory study of application of basalt dust to highly weathered soils: effect on soil cation chemistry." Soil Research **39**(4): 799-811.

85. Gillman, G. P., D. C. Burkett and R. J. Coventry (2002). "Amending highly weathered soils with finely ground basalt rock." Applied Geochemistry **17**(8): 987-1001.

86. Gluch, P. and H. Baumann (2004). "The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making." Building and environment **39**(5): 571-580.

87. Goldich, S. S. (1938). "A study in rock-weathering." The Journal of Geology **46**(1): 17-58.

88. Gollagher, M., Sarkis, J., Paloviita, A. and Luoma-aho, V., 2010. Recognizing definitive stakeholders in corporate environmental management. *Management Research Review*.

89. Goucher, L., R. Bruce, D. D. Cameron, S. C. L. Koh and P. Horton (2017). "The environmental impact of fertilizer embodied in a wheat-to-bread supply chain." Nature plants **3**(3): 17012.

90. Govindan, K., R. Khodaverdi and A. Jafarian (2013). "A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach." Journal of Cleaner production **47**: 345-354.

91. Govindan, K., J. Sarkis, C. J. C. Jabbour, Q. Zhu and Y. Geng (2014). "Eco-efficiency based green supply chain management: Current status and opportunities." European Journal of Operational Research **2**(233): 293-298.

92. Greene, J. A., R. Azevedo and J. Torney-Purta (2008). "Modeling epistemic and ontological cognition: Philosophical perspectives and methodological directions." Educational Psychologist **43**(3): 142-160.

93. Guan, D. and K. Hubacek (2007). "Assessment of regional trade and virtual water flows in China." Ecological economics **61**(1): 159-170.

94. Guinee, J. B. (2002). "Handbook on life cycle assessment operational guide to the ISO standards." The International Journal of Life Cycle Assessment **7**(5): 311.

95. Guinee, J. B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall and T. Rydberg (2011). Life cycle assessment: past, present, and future, ACS Publications.

96. Guo, M. and R. J. Murphy (2012). "LCA data quality: sensitivity and uncertainty analysis." Science of the total environment **435**: 230-243.

97. Halldorsson, A., H. Kotzab, J. H. Mikkola and T. Skjøtt-Larsen (2007). "Complementary theories to supply chain management." Supply chain management: An international journal.

98. Halog, A. and Y. Manik (2011). "Advancing integrated systems modelling framework for life cycle sustainability assessment." Sustainability **3**(2): 469-499.

99. Hangx, S. J. T. and C. J. Spiers (2009). "Coastal spreading of olivine to control atmospheric CO2 concentrations: A critical analysis of viability." International Journal of Greenhouse Gas Control **3**(6): 757-767.

100. Hardi, P. and Semple, P., 2000, October. The dashboard of sustainability: from a metaphor to an operational set of indices. In *Fifth International Conference on Social Science Methodology, Cologne*.

101. Harley, A. D. and R. J. Gilkes (2000). "Factors influencing the release of plant nutrient elements from silicate rock powders: a geochemical overview." Nutrient Cycling in Agroecosystems **56**(1): 11-36.

102. Hart, S. L. (1995). "A natural-resource-based view of the firm." Academy of management review **20**(4): 986-1014.

103. Hart, S. L. and G. Dowell (2011). "Invited editorial: A natural-resource-based view of the firm: Fifteen years after." Journal of management **37**(5): 1464-1479.

104. Hartmann, J., A. J. West, P. Renforth, P. Köhler, C. L. De La Rocha, D. A. Wolf-Gladrow, H. H. Dürr and J. Scheffran (2013). "Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification." Reviews of Geophysics **51**(2): 113-149.

105. Hasler, K., S. Bröring, S. W. F. Omta and H. W. Olfs (2015). "Life cycle assessment (LCA) of different fertilizer product types." European Journal of Agronomy **69**: 41-51.
106. Hauknes, J. and M. Knell (2009). "Embodied knowledge and sectoral linkages: An input–output approach to the interaction of high-and low-tech industries." Research Policy **38**(3): 459-469.
107. Hauschild, M.Z., Dreyer, L.C. and Jørgensen, A., 2008. Assessing social impacts in a life cycle perspective—Lessons learned. *CIRP annals*, *57*(1), pp.21-24.

108. Hayami, H., M. Nakamura and A. O. Nakamura (2015). "Economic performance and supply chains: The impact of upstream firms′ waste output on downstream firms′ performance in Japan." International Journal of Production Economics **160**: 47-65.

109. Heide, J.B., 1994. Interorganizational governance in marketing channels. *Journal of marketing*, *58*(1), pp.71-85.

110. Heijungs, R., G. Huppes and J. B. Guinée (2010). "Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis." Polymer degradation and stability **95**(3): 422-428.

111. Heijungs, R., E. Settanni and J. Guinée (2013). "Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC." The International Journal of Life Cycle Assessment **18**(9): 1722-1733.

112. Hellweg, S. and L. M. i Canals (2014). "Emerging approaches, challenges and opportunities in life cycle assessment." Science **344**(6188): 1109-1113.

113. Helsel, Z. R. (1992). "Energy and alternatives for fertilizer and pesticide use." Energy in farm production **6**: 177-201.

114. Hendrickson, C., Horvath, A., Joshi, S. and Lave, L., 1998. Peer reviewed: economic input–output models for environmental life-cycle assessment. *Environmental science & technology*, *32*(7), pp.184A-191A.

115. Heymann, J., 2010. *Profit at the bottom of the ladder: Creating value by investing in your workforce*. Harvard Business Press.

116. Hertel, T. W., N. Ramankutty and U. L. C. Baldos (2014). "Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions." Proceedings of the National Academy of Sciences **111**(38): 13799-13804.

117. Hillman, A.J., Cannella, A.A. and Paetzold, R.L., 2000. The resource dependence role of corporate directors: Strategic adaptation of board composition in response to environmental change. *Journal of Management studies*, *37*(2), pp.235-256.

118. Hinsinger, P., O. N. F. Barros, M. F. Benedetti, Y. Noack and G. Callot (2001). "Plant-induced weathering of a basaltic rock: experimental evidence." Geochimica et Cosmochimica Acta **65**(1): 137-152.

119. House, K. Z., C. H. House, D. P. Schrag and M. J. Aziz (2007). "Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change." Environmental Science & Technology **41**(24): 8464-8470.

120. Huang, Y.A., Weber, C.L. and Matthews, H.S., 2009. Categorization of scope 3 emissions for streamlined enterprise carbon footprinting.

121. Huntzinger, D. N., J. S. Gierke, S. K. Kawatra, T. C. Eisele and L. L. Sutter (2009). "Carbon dioxide sequestration in cement kiln dust through mineral carbonation." Environmental Science & Technology **43**(6): 1986-1992.

122. Holden, M.T. and Lynch, P., 2004. Choosing the appropriate methodology: Understanding research philosophy. *The marketing review*, *4*(4), pp.397-409.

123. Ibn-Mohammed, T., S. C. L. Koh, I. M. Reaney, A. Acquaye, D. Wang, S. Taylor and A. Genovese (2016). "Integrated hybrid life cycle assessment and supply chain environmental profile evaluations of lead-based (lead zirconate titanate) versus lead-free (potassium sodium niobate) piezoelectric ceramics." Energy & Environmental Science **9**(11): 3495-3520.

124. International Fertilizer Industry, A. (2001). Environmental aspects of phosphate and potash mining, UNEP.

125. International Resource, P., C. United Nations Environment Programme. Sustainable and B. Production (2011). Decoupling natural resource use and environmental impacts from economic growth, UNEP/Earthprint.

126. IPCC (2014). Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. , Cambridge, United Kingdom and New York, NY, USA.

127. Jason, C. and J. W. Clay (2004). World Agriculture and the Environment: a commodity-by-commodity guide to impacts and practices, Island Press.

128. Jennings, P. D. and P. A. Zandbergen (1995). "Ecologically sustainable organizations: An institutional approach." Academy of management review **20**(4): 1015-1052.

129. enssen, T.K. and Kongshaug, G., 2003, September. Energy Consumption and Greenhouse Gas Emmissions in Fertiliser Production. York (UK): International Fertiliser Society.

130. Johnsson, F., Kjärstad, J. and Rootzén, J., 2019. The threat to climate change mitigation posed by the abundance of fossil fuels. *Climate Policy*, *19*(2), pp.258-274.

131. Joint Research Centre-European Commission, 2008. *Handbook on constructing composite indicators: methodology and user guide*. OECD publishing.

132. Jørgensen, A., A. Le Bocq, L. Nazarkina and M. Hauschild (2008). "Methodologies for social life cycle assessment." The international journal of life cycle assessment **13**(2): 96.

133. Judkins, R. R., W. Fulkerson and M. K. Sanghvi (1993). "The dilemma of fossil fuel use and global climate change." Energy & fuels **7**(1): 14-22.

134. Kantola, I. B., M. D. Masters, D. J. Beerling, S. P. Long and E. H. DeLucia (2017). "Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering." Biology letters **13**(4): 20160714.

135. Kenyon, G.N., Meixell, M.J. and Westfall, P.H., 2016. Production outsourcing and operational performance: An empirical study using secondary data. *International Journal of Production Economics*, *171*, pp.336-349.

136. Kheshgi, H. S. (1995). "Sequestering atmospheric carbon dioxide by increasing ocean alkalinity." Energy **20**(9): 915-922.

137. Kitzes, J. (2013). "An introduction to environmentally-extended input-output analysis." Resources **2**(4): 489-503.

138. Kloepffer, W. (2008). "Life cycle sustainability assessment of products." The International Journal of Life Cycle Assessment **13**(2): 89.

139. Knight, K. W. and J. B. Schor (2014). "Economic growth and climate change: a cross-national analysis of territorial and consumption-based carbon emissions in high-income countries." Sustainability **6**(6): 3722-3731.

140. Koh, S. C. L., J. Morris, S. M. Ebrahimi and R. Obayi (2016). "Integrated resource efficiency: measurement and management." International Journal of Operations & Production Management.

141. Koh, S.L., Genovese, A., Acquaye, A.A., Barratt, P., Rana, N., Kuylenstierna, J. and Gibbs, D., 2013. Decarbonising product supply chains: design and development of an integrated evidence-based decision support system–the supply chain environmental analysis tool (SCEnAT). *International Journal of Production Research*, *51*(7), pp.2092-2109.

142. Köhler, P., J. Hartmann and D. A. Wolf-Gladrow (2010). "Geoengineering potential of artificially enhanced silicate weathering of olivine." Proceedings of the National Academy of Sciences **107**(47): 20228-20233.

143. Kraaijenbrink, J., J. C. Spender and A. J. Groen (2010). "The resource-based view: A review and assessment of its critiques." Journal of management **36**(1): 349-372.

144. Kucukvar, M., G. Egilmez and O. Tatari (2014). "Sustainability assessment of US final consumption and investments: triple-bottom-line input–output analysis." Journal of cleaner production **81**: 234-243.

145. Kumar, R. (2019). Research methodology: A step-by-step guide for beginners, Sage Publications Limited.

146. Lackner, K. S. (2003). "A guide to CO2 sequestration." Science **300**(5626): 1677-1678.

147. Lackner, K. S., C. H. Wendt, D. P. Butt, E. L. Joyce Jr and D. H. Sharp (1995). "Carbon dioxide disposal in carbonate minerals." Energy **20**(11): 1153-1170.

148. Larkin, A., J. Kuriakose, M. Sharmina and K. Anderson (2018). "What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations." Climate policy **18**(6): 690-714.

149. Ledgard, S. F., M. Boyes and F. Brentrup (2011). Life cycle assessment of local and imported fertilisers used on New Zealand farms, Ministry of Agriculture and Forestry.

150. Lefebvre, D., P. Goglio, A. Williams, D. A. C. Manning, A. C. de Azevedo, M. Bergmann, J. Meersmans and P. Smith (2019). "Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil." Journal of cleaner production **233**: 468-481.

151. Lenzen, M. (2000). "Errors in conventional and Input-Output—based Life—Cycle inventories." Journal of industrial ecology **4**(4): 127-148.

152. Lenzen, M. and R. Crawford (2009). "The path exchange method for hybrid LCA." Environmental science & technology **43**(21): 8251-8256.

153. Leonardos, O. H., W. S. Fyfe and B. I. Kronberg (1987). "The use of ground rocks in laterite systems: an improvement to the use of conventional soluble fertilizers?" Chemical Geology **60**(1-4): 361-370.

154. Leontief, W. (1986). Input-output economics, Oxford University Press.

155. Lindemann, C., Jahnke, U., Moi, M. and Koch, R., 2012, August. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. In *23th Annual International Solid Freeform Fabrication Symposium–An Additive Manufacturing Conference. Austin Texas USA 6th-8th August*.

156. Liu, L., G. Huang, B. Baetz and K. Zhang (2018). "Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies." Applied Energy **232**: 69-78.

157. López, M. V., A. Garcia and L. Rodriguez (2007). "Sustainable development and corporate performance: A study based on the Dow Jones sustainability index." Journal of Business Ethics **75**(3): 285-300.

158. Lowndes, I. and K. Jeffrey (2009). "Optimising the efficiency of primary aggregate production." Mineral Industry Research Organisation: 74.

159. Lu, Y. (2017). "China's electrical equipment manufacturing in the Global Value Chain: A GVC income analysis based on World Input-Output Database (WIOD)." International Review of Economics & Finance **52**: 289-301.

160. Macias, F. and W. Chesworth (1992). Weathering in humid regions, with emphasis on igneous rocks and their metamorphic equivalents. Developments in Earth Surface Processes, Elsevier. **2:** 283-306.

161. Macombe, C., P. Leskinen, P. Feschet and R. Antikainen (2013). "Social life cycle assessment of biodiesel production at three levels: a literature review and development needs." Journal of Cleaner Production **52**: 205-216.

162. Malik, A., M. Lenzen and A. Geschke (2014). "Triple bottom line analysis of a biofuel feedstock industry." GCB Bioenergy.

163. Maloni, M. J. and M. E. Brown (2006). "Corporate social responsibility in the supply chain: an application in the food industry." Journal of business ethics **68**(1): 35-52.

164. Mancini, L., Eynard, U., Eisfeldt, F., Ciroth, A., Blengini, G.A. and Pennington, D., 2018. Social Assessment of Raw Materials Supply Chains: A life-Cycle-Based Analysis. *Publications Office of the European Union: Luxembourg*.

165. Mani, D., S. N. Charan and B. Kumar (2008). "Assessment of carbon dioxide sequestration potential of ultramafic rocks in the greenstone belts of southern India." Current Science: 53-60.

166. Manik, Y., J. Leahy and A. Halog (2013). "Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia." The International Journal of Life Cycle Assessment **18**(7): 1386-1392.

167. Manning, D. A. C. and S. H. Theodoro (2018). "Enabling food security through use of local rocks and minerals." The Extractive Industries and Society.

168. Martínez-Blanco, J., Lehmann, A., Muñoz, P., Antón, A., Traverso, M., Rieradevall, J. and Finkbeiner, M., 2014. Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. *Journal of Cleaner Production*, *69*, pp.34-48.

169. Matter, J. M. and P. B. Kelemen (2009). "Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation." Nature Geoscience **2**(12): 837-841.

170. Mayer, A. L. (2008). "Strengths and weaknesses of common sustainability indices for multidimensional systems." Environment international **34**(2): 277-291.

171. Mayes, W. M., A. L. Riley, H. I. Gomes, P. Brabham, J. Hamlyn, H. Pullin and P. Renforth (2018). "Atmospheric CO2 sequestration in iron and steel slag: Consett, County Durham, United Kingdom." Environmental science & technology **52**(14): 7892-7900.

172. Maynard, M. (1994). "Methods, practice and epistemology: The debate about feminism and research." Researching women's lives from a feminist perspective **10**(26): 10-26.

173. McCusker, K. and S. Gunaydin (2015). "Research using qualitative, quantitative or mixed methods and choice based on the research." Perfusion **30**(7): 537-542.

174. McNerney, J., B. D. Fath and G. Silverberg (2013). "Network structure of inter-industry flows." Physica A: Statistical Mechanics and its Applications **392**(24): 6427-6441.

175. Mervine, E.M., Dipple, G.M., Power, I.M., Wilson, S.A., Southam, G., Southam, C., Matter, J.M., Kelemen, P.B., Stiefenhofer, J. and Miya, Z., 2017, September. Potential for offsetting diamond mine carbon emissions through mineral carbonation of processed kimberlite. In *International Kimberlite Conference: Extended Abstracts* (Vol. 11).

176. Mitchell, R.K., Agle, B.R. and Wood, D.J., 1997. Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. *Academy of management review*, *22*(4), pp.853-886.

177. Miller, R.E. and Blair, P.D., 2009. *Input-output analysis: foundations and extensions*. Cambridge university press.

178. Mirlean, N. and A. Roisenberg (2006). "The effect of emissions of fertilizer production on the environment contamination by cadmium and arsenic in southern Brazil." Environmental Pollution **143**(2): 335-340.

179. Mol, A. P. J. and D. A. Sonnenfeld (2000). Ecological modernisation around the world: persectives and critical debates, Psychology Press.

180. Mol, A. P. J. and G. Spaargaren (2000). "Ecological modernisation theory in debate: a review." Environmental politics **9**(1): 17-49.

181. Moosdorf, N., P. Renforth and J. Hartmann (2014). "Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering." Environmental Science & Technology **48**(9): 4809-4816.

182. Moran, D., D. McBain, K. Kanemoto, M. Lenzen and A. Geschke (2015). "Global supply chains of coltan: a hybrid life cycle assessment study using a social indicator." Journal of Industrial Ecology **19**(3): 357-365.

183. Morgan, D. L. (2007). "Paradigms lost and pragmatism regained: Methodological implications of combining qualitative and quantitative methods." Journal of mixed methods research **1**(1): 48-76.

184. Mori, K. and A. Christodoulou (2012). "Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI)." Environmental impact assessment review **32**(1): 94-106.

185. Muthu, S. S. (2014). Social life cycle assessment: an insight, Springer.

186. Nejat, P., F. Jomehzadeh, M. M. Taheri, M. Gohari and M. Z. A. Majid (2015). "A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries)." Renewable and sustainable energy reviews **43**: 843-862.

187. Nikolaou, I. E., K. I. Evangelinos and S. Allan (2013). "A reverse logistics social responsibility evaluation framework based on the triple bottom line approach." Journal of cleaner production **56**: 173-184.

188. Noori, M., M. Kucukvar and O. Tatari (2015). "A macro-level decision analysis of wind power as a solution for sustainable energy in the USA." International Journal of Sustainable Energy **34**(10): 629-644.

189. Norris, C.B., Norris, G.A. and Aulisio, D., 2014. Efficient assessment of social hotspots in the supply chains of 100 product categories using the social hotspots database. *Sustainability*, *6*(10), pp.6973-6984.

190. Norris, C. B., G. Norris and D. Aulisio (2013). "Social Hotspots Database." Online: http://socialhotspot. org.

191. Norris, G. A. (2001). "Integrating life cycle cost analysis and LCA." The international journal of life cycle assessment **6**(2): 118-120.

192. Onat, N. (2015). "A macro-level sustainability assessment framework for optimal distribution of alternative passenger vehicles."

193. Onat, N. C., M. Kucukvar and O. Tatari (2014). "Integrating triple bottom line input–output analysis into life cycle sustainability assessment framework: the case for US buildings." The International Journal of Life Cycle Assessment **19**(8): 1488-1505.

194. Oppon, E., A. Acquaye, T. Ibn-Mohammed and L. Koh (2018). "Modelling multi-regional ecological exchanges: The case of UK and Africa." Ecological Economics **147**: 422-435.

195. Pall, P., T. Aina, D. A. Stone, P. A. Stott, T. Nozawa, A. G. J. Hilberts, D. Lohmann and M. R. Allen (2011). "Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000." Nature **470**(7334): 382-385.

196. Pan, S.-Y., T.-C. Chung, C.-C. Ho, C.-J. Hou, Y.-H. Chen and P.-C. Chiang (2017). "CO 2 mineralization and utilization using steel slag for establishing a waste-to-resource supply chain." Scientific reports **7**(1): 1-11.

197. Pao, H.-T. and C.-M. Tsai (2010). "CO2 emissions, energy consumption and economic growth in BRIC countries." Energy policy **38**(12): 7850-7860.

198. Pärn, J., J. T. A. Verhoeven, K. Butterbach-Bahl, N. B. Dise, S. Ullah, A. Aasa, S. Egorov, M. Espenberg, J. Järveoja and J. Jauhiainen (2018). "Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots." Nature communications **9**(1): 1135.

199. Pelletier, N., Ustaoglu, E., Benoit, C., Norris, G., Rosenbaum, E., Vasta, A. and Sala, S., 2018. Social sustainability in trade and development policy. *The International Journal of Life Cycle Assessment*, *23*(3), pp.629-639.

200. Peters, G. P., C. L. Weber, D. Guan and K. Hubacek (2007). China's growing CO2 emissions a race between increasing consumption and efficiency gains, ACS Publications.

201. Petit, G., C. Sablayrolles and G. Yannou-Le Bris (2018). "Combining eco-social and environmental indicators to assess the sustainability performance of a food value chain: A case study." Journal of Cleaner Production **191**: 135-143.

202. Petti, L., M. Serreli and S. Di Cesare (2018). "Systematic literature review in social life cycle assessment." The International Journal of Life Cycle Assessment **23**(3): 422-431.

203. Petti, L., C. M. L. Ugaya and S. Di Cesare (2014). "Systematic review of social-life cycle assessment (S-LCA) case studies." Social LCA in progress. FruiTrop, Montpellier.

204. Pérez-López, R., Alvarez-Valero, A.M. and Nieto, J.M., 2007. Changes in mobility of toxic elements during the production of phosphoric acid in the fertilizer industry of Huelva (SW Spain) and environmental impact of phosphogypsum wastes. *Journal of Hazardous Materials*, *148*(3), pp.745-750.

205. Pieragostini, C., M. C. Mussati and P. Aguirre (2012). "On process optimization considering LCA methodology." Journal of environmental management **96**(1): 43-54.

206. Potter, P., N. Ramankutty, E. M. Bennett and S. D. Donner (2010). "Characterizing the spatial patterns of global fertilizer application and manure production." Earth interactions **14**(2): 1-22.

207. Power, I. M., G. M. Dipple, P. M. D. Bradshaw and A. L. Harrison (2020). "Prospects for CO2 mineralization and enhanced weathering of ultramafic mine tailings from the Baptiste nickel deposit in British Columbia, Canada." International Journal of Greenhouse Gas Control **94**: 102895.

208. Priyono, J. and R. J. Gilkes (2008). "High-energy milling improves the effectiveness of silicate rock fertilizers: a glasshouse assessment." Communications in soil science and plant analysis **39**(3-4): 358-369

209. Priyono, J. and Gilkes, R.J., 2004. Dissolution of milled-silicate rock fertilisers in the soil. *Soil Research*, *42*(4), pp.441-448.

210. Protocol, K. (1997). "United Nations framework convention on climate change." Kyoto Protocol, Kyoto **19**.

211. Pullin, H., A. W. Bray, I. T. Burke, D. D. Muir, D. J. Sapsford, W. M. Mayes and P. Renforth (2019). "Atmospheric Carbon Capture Performance of Legacy Iron and Steel Waste." Environmental science & technology **53**(16): 9502-9511.

212. Quirós, R., G. Villalba, X. Gabarrell and P. Muñoz (2015). "Life cycle assessment of organic and mineral fertilizers in a crop sequence of cauliflower and tomato." International journal of environmental science and technology **12**(10): 3299-3316.

213. Rebitzer, G. and D. Hunkeler (2003). "Life cycle costing in LCM: ambitions, opportunities, and limitations." The International Journal of Life Cycle Assessment **8**(ARTICLE): 253-256.

214. Rebitzer, G., D. Hunkeler and O. Jolliet (2003). "LCC—the economic pillar of sustainability: methodology and application to wastewater treatment." Environmental progress **22**(4): 241-249.

215. Remenyi, D., B. Williams, A. Money and E. Swartz (1998). Doing research in business and management: an introduction to process and method, Sage.

216. Renforth, P., von Strandmann, P.P. and Henderson, G.M., 2015. The dissolution of olivine added to soil: Implications for enhanced weathering. *Applied Geochemistry*, *61*, pp.109-118.

217. Renforth, P. (2012). "The potential of enhanced weathering in the UK." International Journal of Greenhouse Gas Control **10**: 229-243.

218. Renforth, P. (2019). "The negative emission potential of alkaline materials." Nature communications **10**(1): 1-8.

219. Renforth, P., D. A. C. Manning and E. Lopez-Capel (2009). "Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide." Applied Geochemistry **24**(9): 1757-1764.

220. Renforth, P., C. L. Washbourne, J. Taylder and D. A. C. Manning (2011). Silicate production and availability for mineral carbonation, ACS Publications.

221. Richardson, H. W. (1985). "Input-output and economic base multipliers: Looking backward and forward." Journal of Regional science **25**(4): 607-661.

222. Richter, J.S., Mendis, G.P., Nies, L. and Sutherland, J.W., 2019. A method for economic input-output social impact analysis with application to US advanced manufacturing. *Journal of Cleaner Production*, *212*, pp.302-312.

223. Roberts, T. L. (2009). "The role of fertilizer in growing the world’s food." Better crops **93**(2): 12-15.

224. Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke and H. J. Schellnhuber (2009). "A safe operating space for humanity." nature **461**(7263): 472-475.

225. Rogelj, J., M. Den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi and M. Meinshausen (2016). "Paris Agreement climate proposals need a boost to keep warming well below 2 C." Nature **534**(7609): 631-639.

226. Roy, R. N., A. Finck, G. J. Blair and H. L. S. Tandon (2006). "Plant nutrition for food security." A guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin **16**: 368.

227. Rungtusanatham, M., F. Salvador, C. Forza and T. Y. Choi (2003). "Supply-chain linkages and operational performance." International Journal of Operations & Production Management.

228. Saltelli, A., 2007. Composite indicators between analysis and advocacy. *Social indicators research*, *81*(1), pp.65-77.

229. Sánchez-Chóliz, J. and R. Duarte (2004). "CO2 emissions embodied in international trade: evidence for Spain." Energy Policy **32**(18): 1999-2005.

230. Sanchez, P. A. (2002). "Soil fertility and hunger in Africa." Science **295**(5562): 2019-2020.

231. Sarkis, J. and D. G. Dhavale (2015). "Supplier selection for sustainable operations: A triple-bottom-line approach using a Bayesian framework." International Journal of Production Economics **166**: 177-191.

232. Sarkis, J., Q. Zhu and K.-h. Lai (2011). "An organizational theoretic review of green supply chain management literature." International journal of production economics **130**(1): 1-15.

233. Saunders, M., P. Lewis and A. Thornhill (2003). "Research methods forbusiness students." Essex: Prentice Hall: Financial Times.

234. Savitz, A. (2013). The triple bottom line: how today's best-run companies are achieving economic, social and environmental success-and how you can too, John Wiley & Sons.

235. Schopka, H. H., L. A. Derry and C. A. Arcilla (2011). "Chemical weathering, river geochemistry and atmospheric carbon fluxes from volcanic and ultramafic regions on Luzon Island, the Philippines." Geochimica et Cosmochimica Acta **75**(4): 978-1002.

236. Schuiling, R. D. (2013). Carbon dioxide sequestration, Weathering approaches to. Geoengineering Responses to Climate Change, Springer**:** 141-167.

237. Schuiling, R. D. and P. L. De Boer (2010). "Coastal spreading of olivine to control atmospheric CO2 concentrations: A critical analysis of viability. Comment: Nature and laboratory models are different." International Journal of Greenhouse Gas Control **4**(5): 855.

238. Schuiling, R. D. and P. Krijgsman (2006). "Enhanced weathering: an effective and cheap tool to sequester CO 2." Climatic Change **74**(1-3): 349-354.

239. Schuiling, R. D. and O. Tickell (2010). "Enhanced weathering of olivine to capture CO2." Journal of Applied Geochemistry **12**(4): 510-519.

240. Schuiling, R. D. and S. A. Wilson (2011). "Enhanced silicate weathering is not limited by silicic acid saturation." Proceedings of the National Academy of Sciences **108**(12): E41-E41.

241. Shackley, S., C. McLachlan and C. Gough (2004). "The public perception of carbon dioxide capture and storage in the UK: results from focus groups and a survey." Climate Policy **4**(4): 377-398.

242. Shamshuddin, J., C. I. Fauziah, M. Anda, J. Kapok and M. Shazana (2011). "Using ground basalt and/or organic fertilizer to enhance productivity of acid soils in Malaysia for crop production." Malaysian Journal of Soil Science **15**(1): 127-146.

243. Sharifzadeh, M., G. Triulzi and C. L. Magee (2019). "Quantification of technological progress in greenhouse gas (GHG) capture and mitigation using patent data." Energy & Environmental Science **12**(9): 2789-2805.

244. Shemfe, M.B., Gadkari, S. and Sadhukhan, J., 2018. Social hotspot analysis and trade policy implications of the use of bioelectrochemical systems for resource recovery from wastewater. *Sustainability*, *10*(9), p.3193.

245. Siche, J. R., F. Agostinho, E. Ortega and A. Romeiro (2008). "Sustainability of nations by indices: Comparative study between environmental sustainability index, ecological footprint and the emergy performance indices." Ecological economics **66**(4): 628-637.

246. Singh, R. K., H. R. Murty, S. K. Gupta and A. K. Dikshit (2009). "An overview of sustainability assessment methodologies." Ecological indicators **9**(2): 189-212.

247. Skowroñska, M. and T. Filipek (2014). "Life cycle assessment of fertilizers: a review." International Agrophysics **28**(1).

248. Slaper, T. F. and T. J. Hall (2011). "The triple bottom line: What is it and how does it work." Indiana business review **86**(1): 4-8.

249. Smeeding, T., 1983. The size distribution of wage and nonwage compensation: employer cost versus employee value. In *The measurement of labor cost* (pp. 237-286). University of Chicago Press.

250. Smith, P. (2016). "Soil carbon sequestration and biochar as negative emission technologies." Global change biology **22**(3): 1315-1324.

251. Smith, P., J. Adams, D. J. Beerling, T. Beringer, K. V. Calvin, S. Fuss, B. Griscom, N. Hagemann, C. Kammann and F. Kraxner (2019). "Impacts of land-based greenhouse gas removal options on ecosystem services and the United Nations Sustainable Development Goals." Annual Review of Environment and Resources **44**.

252. Smith, P., H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera and C. Mbow (2014). "Agriculture, forestry and other land use (AFOLU)."

253. Smith, P., S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R. B. Jackson, A. Cowie and E. Kriegler (2016). "Biophysical and economic limits to negative CO 2 emissions." Nature climate change **6**(1): 42-50.

254. Smith, P., R. S. Haszeldine and S. M. Smith (2016). "Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK." Environmental Science: Processes & Impacts **18**(11): 1400-1405.

255. Stallard, R. F. (1998). "Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial." Global biogeochemical cycles **12**(2): 231-257.

256. Starik, M. and G. P. Rands (1995). "Weaving an integrated web: Multilevel and multisystem perspectives of ecologically sustainable organizations." Academy of Management Review **20**(4): 908-935.

257. Stern, N. and Stern, N.H., 2007. *The economics of climate change: the Stern review*. cambridge University press.

258. Stewart, W. M. and T. L. Roberts (2012). "Food security and the role of fertilizer in supporting it." Procedia Engineering **46**: 76-82.

259. Strefler, J., T. Amann, N. Bauer, E. Kriegler and J. Hartmann (2018). "Potential and costs of carbon dioxide removal by enhanced weathering of rocks." Environmental Research Letters **13**(3): 034010.

260. Strefler, J., N. Bauer, T. Amann, E. Kriegler and J. Hartmann (2015). "Enhanced weathering and BECCS-are carbon dioxide removal technologies complements or substitutes." Abu Dhabi **10**.

261. Suh, S. and S. Nakamura (2007). "Five years in the area of input-output and hybrid LCA." The International Journal of Life Cycle Assessment **12**(6): 351.

262. Sukamolson, S. (2007). "Fundamentals of quantitative research." Language Institute Chulalongkorn University **1**: 2-3.

263. Svensson, G. and B. Wagner (2015). "Implementing and managing economic, social and environmental efforts of business sustainability." Management of Environmental Quality: An International Journal.

264. Swaminathan, B. and Sukalac, K.E., 2004, September. Technology transfer and mitigation of climate change: The fertilizer industry perspective. In *IPCC Expert Meeting on Industrial Technology Development, Transfer and Diffusion, Tokyo, Japan* (Vol. 2123).

265. Swarr, T. E., D. Hunkeler, W. Klöpffer, H.-L. Pesonen, A. Ciroth, A. C. Brent and R. Pagan (2011). Environmental life-cycle costing: a code of practice, Springer.

266. Tamazian, A., J. P. Chousa and K. C. Vadlamannati (2009). "Does higher economic and financial development lead to environmental degradation: evidence from BRIC countries." Energy policy **37**(1): 246-253.

267. Tate, W.L. and Bals, L., 2018. Achieving shared triple bottom line (TBL) value creation: toward a social resource-based view (SRBV) of the firm. *Journal of Business Ethics*, *152*(3), pp.803-826.

268. Taylor, L. L., J. Quirk, R. M. S. Thorley, P. A. Kharecha, J. Hansen, A. Ridgwell, M. R. Lomas, S. A. Banwart and D. J. Beerling (2016). "Enhanced weathering strategies for stabilizing climate and averting ocean acidification." Nature Climate Change **6**(4): 402-406.

269. Ten Berge, H. F. M., H. G. Van der Meer, J. W. Steenhuizen, P. W. Goedhart, P. Knops and J. Verhagen (2012). "Olivine weathering in soil, and its effects on growth and nutrient uptake in ryegrass (Lolium perenne L.): a pot experiment." PloS one **7**(8).

270. Theodoro, S. H. and O. H. Leonardos (2006). "The use of rocks to improve family agriculture in Brazil." Anais da Academia Brasileira de Ciências **78**(4): 721-730.

271. Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor and S. Polasky (2002). "Agricultural sustainability and intensive production practices." Nature **418**(6898): 671.

272. Timmer, M., A. A. Erumban, R. Gouma, B. Los, U. Temurshoev, G. J. de Vries, I. a. Arto, V. A. A. Genty, F. Neuwahl and J. Francois (2012). The world input-output database (WIOD): contents, sources and methods, Institue for International and Development Economics.

273. Traverso, M., L. Bell, P. Saling and J. Fontes (2018). "Towards social life cycle assessment: a quantitative product social impact assessment." The International Journal of Life Cycle Assessment **23**(3): 597-606.

274. Traverso, M., Finkbeiner, M., Jørgensen, A. and Schneider, L., 2012. Life cycle sustainability dashboard. *Journal of industrial ecology*, *16*(5), pp.680-688.

275. Trochim, W. M. K. and J. P. Donnelly (2001). Research methods knowledge base, Atomic Dog Publishing Cincinnati, OH.

276. Tukker, A. and Dietzenbacher, E., 2013. Global multiregional input–output frameworks: an introduction and outlook. *Economic Systems Research*, *25*(1), pp.1-19.

277. Tuli, F. (2010). "The basis of distinction between qualitative and quantitative research in social science: Reflection on ontological, epistemological and methodological perspectives." Ethiopian Journal of Education and Sciences **6**(1).

278. Tyrrell, T., C. M. Paris and V. Biaett (2013). "A quantified triple bottom line for tourism: Experimental results." Journal of Travel Research **52**(3): 279-293.

279. Ukwattage, N. L., P. G. Ranjith and M. Bouazza (2013). "The use of coal combustion fly ash as a soil amendment in agricultural lands (with comments on its potential to improve food security and sequester carbon)." Fuel **109**: 400-408.

280. Ulrich, D. and Barney, J.B., 1984. Perspectives in organizations: resource dependence, efficiency, and population. *Academy of Management Review*, *9*(3), pp.471-481.

281. Umair, S., Björklund, A. and Petersen, E.E., 2015. Social impact assessment of informal recycling of electronic ICT waste in Pakistan using UNEP SETAC guidelines. *Resources, Conservation and Recycling*, *95*, pp.46-57.

282. Vachon, S. and R. D. Klassen (2006). "Extending green practices across the supply chain: the impact of upstream and downstream integration." International Journal of Operations & Production Management **26**(7): 795-821.

283. Valente, C., A. Brekke and I. S. Modahl (2018). "Testing environmental and social indicators for biorefineries: Bioethanol and biochemical production." The International Journal of Life Cycle Assessment **23**(3): 581-596.

284. Van Haaster, B., Ciroth, A., Fontes, J., Wood, R. and Ramirez, A., 2017. Development of a methodological framework for social life-cycle assessment of novel technologies. *The International Journal of Life Cycle Assessment*, *22*(3), pp.423-440.

285. Van Oss, H. G. and A. C. Padovani (2003). "Cement manufacture and the environment part II: environmental challenges and opportunities." Journal of Industrial ecology **7**(1): 93-126.

286. Van Straaten, P. (2002). "Rocks for crops: agrominerals of sub-Saharan Africa."

287. Van Straaten, P. (2006). "Farming with rocks and minerals: challenges and opportunities." Anais da Academia Brasileira de Ciências **78**(4): 731-747.

288. Van Vliet, N., O. Mertz, A. Heinimann, T. Langanke, U. Pascual, B. Schmook, C. Adams, D. Schmidt-Vogt, P. Messerli and S. Leisz (2012). "Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment." Global Environmental Change **22**(2): 418-429.

289. Vergragt, P. J., N. Markusson and H. Karlsson (2011). "Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in." Global Environmental Change **21**(2): 282-292.

290. Waddock, S.A. and Graves, S.B., 1997. The corporate social performance–financial performance link. *Strategic management journal*, *18*(4), pp.303-319.

291. Wang, L. and L. Lin (2007). "A methodological framework for the triple bottom line accounting and management of industry enterprises." International Journal of Production Research **45**(5): 1063-1088.

292. Watkin, M. K. (1999). The Suitability of Corndale Quarry Basalt" blue-metal" Dust as a Slow-release Fertiliser, Southern Cross University.

293. Wernerfelt, B. (1984). "A resource-based view of the firm." Strategic management journal **5**(2): 171-180.

294. White, A. F. and S. L. Brantley (1995). "Weathering rates of silicate minerals." Chemical Weathering Rates of Silicate Minerals, Reviews in Mineralogy **31**: 1-22.

295. Wiedmann, T. (2009). "A review of recent multi-region input–output models used for consumption-based emission and resource accounting." Ecological economics **69**(2): 211-222.

296. Wiedmann, T. and M. Lenzen (2008). Unravelling the impacts of supply chains—a new triple-bottom-line accounting approach and software tool. Environmental management accounting for cleaner production, Springer**:** 65-90.

297. Wiedmann, T. and M. Lenzen (2018). "Environmental and social footprints of international trade." Nature Geoscience **11**(5): 314-321.

298. Wiedmann, T., M. Lenzen, K. Turner and J. Barrett (2007). "Examining the global environmental impact of regional consumption activities—Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade." Ecological economics **61**(1): 15-26.

299. Willard, B. (2012). The new sustainability advantage: seven business case benefits of a triple bottom line, New Society Publishers.

300. Williams, C. (2007). "Research methods." Journal of Business & Economics Research (JBER) **5**(3).

301. Wilson, J. P. (2015). "The triple bottom line Undertaking an economic, social, and environmental retail sustainability strategy." International Journal of Retail & Distribution Management **43**(4-5): 432-+.

302. Wilson, S. A., G. M. Dipple, I. M. Power, J. M. Thom, R. G. Anderson, M. Raudsepp, J. E. Gabites and G. Southam (2009). "Carbon dioxide fixation within mine wastes of ultramafic-hosted ore deposits: Examples from the Clinton Creek and Cassiar chrysotile deposits, Canada." Economic geology **104**(1): 95-112.

303. Wilson, S. A., A. L. Harrison, G. M. Dipple, I. M. Power, S. L. L. Barker, K. U. Mayer, S. J. Fallon, M. Raudsepp and G. Southam (2014). "Offsetting of CO2 emissions by air capture in mine tailings at the Mount Keith Nickel Mine, Western Australia: Rates, controls and prospects for carbon neutral mining." International Journal of Greenhouse Gas Control **25**: 121-140.

304. Winkler, H., B. Brouns and S. Kartha (2006). "Future mitigation commitments: Differentiating among non-Annex I countries." Climate Policy **5**(5): 469-486.

305. Wood, S. W. and A. Cowie (2004). "A review of greenhouse gas emission factors for fertiliser production."

306. World Health Organization, 2018. *The state of food security and nutrition in the world 2018: building climate resilience for food security and nutrition*. Food & Agriculture Org.

307. Wu, F., S. Yeniyurt, D. Kim and S. T. Cavusgil (2006). "The impact of information technology on supply chain capabilities and firm performance: A resource-based view." Industrial Marketing Management **35**(4): 493-504.

308. Xu, X., J.-Q. Chen and S. Q. Xie (2006). "Framework of a product lifecycle costing system."

309. Yang, Y., W. W. Ingwersen, T. R. Hawkins, M. Srocka and D. E. Meyer (2017). "USEEIO: A new and transparent United States environmentally-extended input-output model." Journal of cleaner production **158**: 308-318.

310. Yang, Q.Z. and Song, B., 2006, August. Eco-design for product lifecycle sustainability. In *2006 4th IEEE International Conference on Industrial Informatics* (pp. 548-553). IEEE.

311. Yawar, S.A. and Seuring, S., 2017. Management of social issues in supply chains: a literature review exploring social issues, actions and performance outcomes. *Journal of Business Ethics*, *141*(3), pp.621-643.

312. York, R., E. A. Rosa and T. Dietz (2004). "The ecological footprint intensity of national economies." Journal of Industrial Ecology **8**(4): 139-154.

313. Zamagni, A. (2012). "Life cycle sustainability assessment." The International Journal of Life Cycle Assessment **17**(4): 373-376.

314. Zamani, B., Sandin, G., Svanström, M. and Peters, G.M., 2018. Hotspot identification in the clothing industry using social life cycle assessment—opportunities and challenges of input-output modelling. *The International Journal of Life Cycle Assessment*, *23*(3), pp.536-546.

315. Zamagni, A., O. Amerighi and P. Buttol (2011). Strengths or bias in social LCA?, Springer.

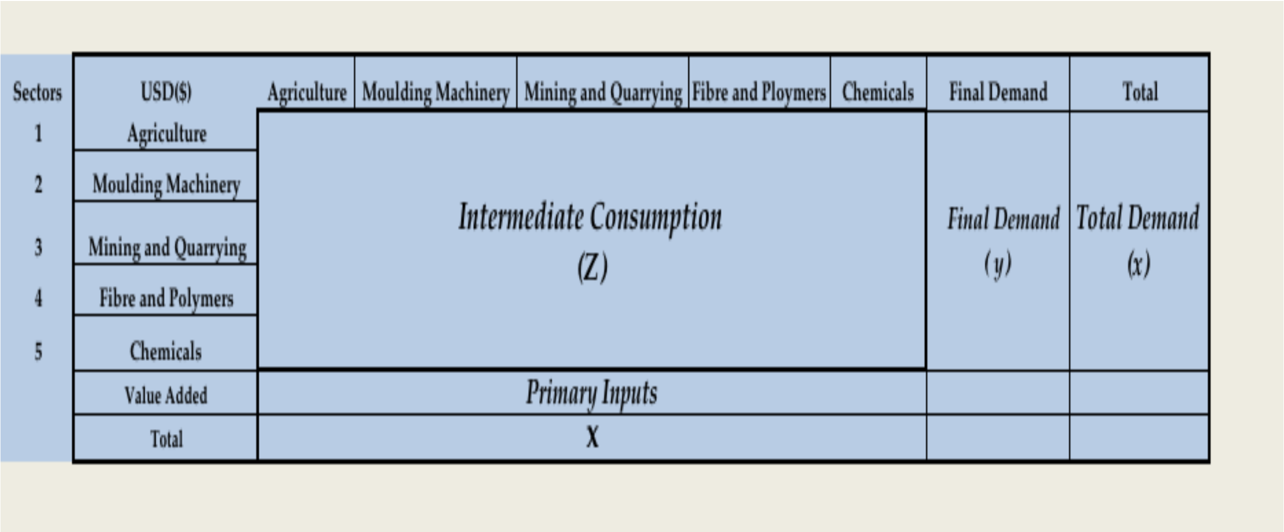
316. Zhou, L., H. Tokos, D. Krajnc and Y. Yang (2012). "Sustainability performance evaluation in industry by composite sustainability index." Clean Technologies and Environmental Policy **14**(5): 789-803.

317. Zimdars, C., Haas, A. and Pfister, S., 2018. Enhancing comprehensive measurement of social impacts in S-LCA by including environmental and economic aspects. *The International Journal of Life Cycle Assessment*, *23*(1), pp.133-146.

APPENDIX

Appendix A: Supplementary Information for Chapter 4 & 5 (Economic and Environmental assessment)

Table S1: An illustrative Input-Output Table



Sectors	USD($)	Agriculture	Moulding Machinery	Mining and Quarrying	Fibre and Ploymers	Chemicals	Final Demand	Total
1	Agriculture	*Intermediate Consumption (Z)*					*Final Demand (y)*	*Total Demand (x)*
2	Moulding Machinery							
3	Mining and Quarrying							
4	Fibre and Polymers							
5	Chemicals							
	Value Added	*Primary Inputs*						
	Total	X						

Table S1 is an illustrative Input-Output (I-O) Table. The framework is based on the structure of the economy in which flow of resources (products and services) recorded as monetary transaction usually in US dollars or other national currencies depending on the source of data. Industries use the products of other industries to produce their products. These inter-connections are captured in I-O tables which are national accounting data usually compiled by statistical agencies in a country. In the I-O table, this inter-industry relationship is known as Intermediate consumption (Z). Other parts of the I-O table show the Final demand(Y) of commodities by households, governments, investment, or exports and the Total Output(X) of a sector.

The relationship between Intermediate consumption (Z), Final demand (Y) and Total output (X) is given by:

$$\mathbf{Z + Y = X}$$

Table S2: 9-Sector Aggregation for World Input-Output Database (WIOD)

No./Code	**WIOD 35 Economic Sectors**	**9 Aggregated Sectors**
1	Agriculture, Hunting, Forestry and Fishing	Food and Agriculture
2	Food Beverages and Tobacco	
3	Coke, Refined Petroleum and Nuclear Fuel	Mining Fossil fuels
4	Mining and Quarrying	uarrying, Metals and Minerals
5	Basic Metals and Fabricated Metal	
6	Textiles and Textiles products	Textiles and Leather
7	Leather and footwear	
8	Wood and Products of wood and cork	onstruction and Non-Metallic
9	Pulp, Paper, Printing and Publishing	
10	Chemical and chemical products	
11	Rubber and Plastics	
12	Other Non-Metallic Mineral	
13	Construction	
14	Electricity, Gas and Water supply	lectricity, Gas and Petroleum
15	aintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	Machinery and Equipment
16	Transport Equipment	
17	Electrical and Optical equipment	
18	Machinery nec	
19	Manufacturing and Recycling	
20	Inland Transport	Transport
21	Water transport	
22	Air transport	
23	ale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	Services
24	rade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	
25	Hotels and Restaurants	
26	r Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	
27	Post and Telecommunications	
28	Financial Intermediation	
29	Real Estate Activities	
30	Renting of M&Eq and Other Business Activities	
31	Public Admin and Defence; Compulsory Social Security	
32	Education	
33	Health and Social Work	
34	Other Community, Social and Personal Services	
35	Private Households with Employed Persons	

Appendix B: Supplementary Information for Chapter 6 (Social risk impact assessment)

Table S3: 9- Sector Aggregation for GTAP

No./Co	**57 Economic Sectors**	**9 Aggregated Sectors**
1 pdr	Paddy rice	Food and Agriculture
2 wht	Wheat	
3 gro	Cereal grains nec	
4 v_f	Vegetables; fruit; nuts	
5 osd	Oil seeds	
6 c_b	Sugar cane; sugar beet	
7 pfb	Plant-based fibers	
8 ocr	Crops nec	
9 ctl	Bovine cattle; sheep and goats; horses	
10 oap	Animal products nec	
11 rmk	Raw milk	
12 wol	Wool; silk-worm cocoons	
13 frs	Forestry	
14 fsh	Fishing	
15 cmt	Bovine meat products	
16 omt	Meat products nec	
17 vol	Vegetable oils and fats	
18 mil	Dairy products	
19 pcr	Processed rice	
20 sgr	Sugar	
21 ofd	Food products nec	
22 b_t	Beverages and tobacco products	
23 wtr	Water	
24 coa	Coal	Mining
25 oil	Oil	
26 gas	Gas	
27 nmm	Minerals nec	Metals and Minerals
28 omn	Mineral products nec	
29 i_s	Ferrous metals	
30 nfm	Non-Ferrous Metals nec	
31fmp	Fabricated Metal products	
32 tex	Textiles	Textiles and Leather
33 wap	Wearing apparel	
34 lea	Leather products	
35 lum	Wood products	Construction and Non-Metallic
36 ppp	Paper products; publishing	
37 crp	Chemical; rubber; plastic products	
38 cns	Construction	
39 p_c	Petroleum; coal products	Electricity, Gas and Petroleum
40 ely	Electricity	
41 gdt	Gas distribution	
42 mvh	Motor vehicles and parts	Machinery and Equipment
43 otn	Other Transport equipment nec	
44 ele	Electronic equipment	
45 ome	Machinery and equipment nec	
46 omf	Other Manufactures nec	
47 otp	Other Transport(road, rail, pipelines,etc)	Transport
48 wtp	Water transport	
49 atp	Air transport	
50 trd	Trade	Services
51 cmn	Communication	
52 ofi	Other Financial intermediation	
53 isr	Insurance	
54 obs	Other Business services	
55 ros	Recreational and other services	
56 osg	Other services government(Public Administration; Defense; Education; Health)	
57 dwe	Dwellings	

Table S4: Example of Data Sources on social issues included in SHDB

World Health Organisation
World Bank, World development indicators
International Trade Union Confederation
International Labour Organisation (ILOSTAT)
US Department of Labour
Global Slavery Index
Organisation for Economic Co-operation and Development (OECD)
International Organisation for Migration
The Office of the High Commissioner on Human Rights (OHCHR)
Human Rights Watch
World Legal Rights Data
US Department of State
International Monetary Fund
EuroStat
UNDP Human Development Indicator
Cingranelli-Richards Human Rights Dataset (CIRI)
Heidelberg Institute for International Conflict Research
The UN Refugee Agency
Center for Systemic Peace
Minority Rights Group International

Table S5: High (H) and Very-High (VH) Risk in Labour and Decent Work for Brazil

Sub-category indicators	Risk level
Risk that Sector Average Wage is below Sweat-free Wage	HR
Percent of population living under the relevant poverty line	HR
Risk of Male Child Labor in Country	HR
Risk of child labor by sector (qualitative)	HR
Percent Total Child Labor in Sector (quantitative)	HR
Percent Total Child Labor in Sector (quantitative)	VH
Forced labor by sector	VH
Percent of Population working >X hrs per week, >60 hrs per week	HR
Percent of Population working >X hrs per week, >60 hrs per week	VH
Freedom of Association Rights, Collective Bargaining Rights, Right to Strike	HR
Risk that a country has not ratified international conventions or set up policies for immigrants	HR
Evidence of Risk to Migrant Workers	HR
Child education leave	HR
Child health leave	HR
Maternity leave pay	HR
Parental leave duration	HR
Wage replacement of paid parental leave	VH
Ratification of Conventions by Sector	HR

Table S6: High (H) and Very-High (VH) Risk in Labour and Decent Work for Russia

Sub-category indicators	Risk Level
Risk that Sector Average Wage is below Sweat-free Wage	HR
U.S. Dept of Labor Trafficking in Persons Report Tiers	VH
Forced Labor in Country - Qualitative Global Slavery Index	VH
Overall Forced Labor in Country	VH
Percent of Population working >X hrs per week, >60 hrs per week	HR
Percent of Population working >X hrs per week, >60 hrs per week	VH
Freedom of Association Rights, Collective Bargaining Rights, Right to Strike – Qualitative	HR
Overall risk of Freedom of Association	HR
Net Migration Rate (NMR) per 1,000 Population	HR
Total Immigrants to Destination Country 2017	VH
Immigrants as a Percentage of the Population, 2017	HR
Workers' Remittances and Compensation Received per Emigrant (USD) - calculated using Total R&C/#Emigrants	HR
Risk that a country has not ratified international conventions or set up policies for immigrants	HR
Evidence of Risk to Migrant Workers – Qualitative	VH
Paternity leave pay	HR
Wage replacement of paid parental leave	HR
Unemployment percentage at sector level	HR

Table S7: High (H) and Very-High (VH) Risk in Labour and Decent Work for India

Sub-category indicators	Risk Level
Risk that Sector Average Wage is below Sweat-free Wage	HR
Risk that Avg Wage is Below Country Minimum Wage	VH
Percent of population living under the relevant poverty line	VH
Risk of Male Child Labor in Country	HR
Risk of Female Child Labor in Country	HR
Risk of Total Child Labor in Country	HR
Risk of child labor by sector	VH
Percent Total Child Labor in Sector	VH
Percent Total Child Labor in Sector	HR
Forced Labor in Country - Qualitative Global Slavery Index	VH
Overall Forced Labor in Country	VH
Forced labor by sector	VH
Percent of Population working >X hrs per week, >60 hrs per week	HR
Freedom of Association Rights, Collective Bargaining Rights, Right to Strike	VH
Overall risk of Freedom of Association	VH
Total Immigrants to Destination Country 2017	VH
Evidence of Risk to Migrant Workers – Qualitative	VH
Paid sick leave coverage begins on first day of incapacity	HR
Sick leave duration	VH
Sick leave pay	VH
Child education leave	HR
Child health leave	HR
Adult need leave	HR
Maternity leave pay	VH
Parental leave duration	VH
Wage replacement of paid parental leave	VH
Overall risk of inadequate social benefits	HR
Total Number of Labor Laws in Country	HR
Number of ILO Conventions Ratified, Abstained, Denounced	VH
Prevalence of discrimination in the workplace	HR

Table S8: High (H) and Very-High (VH) Risk in Labour and Decent Work for China

Sub-category indicators	Risk Level
Risk that Sector Average Wage is below Sweat-free Wage	HR
Percent of population living under the relevant poverty line	HR
Risk of child labor by sector	VH
U.S. Dept of Labor Trafficking in Persons Report Tiers	VH
Percent of Population working >X hrs per week, >60 hrs per week	HR
Freedom of Association Rights, Collective Bargaining Rights, Right to Strike – Qualitative	VH
Overall risk of Freedom of Association	VH
Workers' Remittances and Compensation Paid per Immigrant (USD) - calculated using Total R&C/#Immigrants	VH
Risk that a country has not ratified international conventions or set up policies for immigrants	HR
Evidence of Risk to Migrant Workers	HR
Paid annual leave	HR
Child education leave	HR
Child health leave	HR
Maternity leave pay	VH
Paternity leave pay	VH
Parental leave duration	HR
Wage replacement of paid parental leave	VH
Overall risk of inadequate social benefits	HR
Number of ILO Conventions Ratified, Abstained, Denounced	VH
Prevalence of discrimination in the workplace (qualitative)	HR

Table S9: High (H) and Very-High (VH) Risk in Labour and Decent Work for USA

Sub-category indicators	Risk Level
Freedom of Association Rights, Collective Bargaining Rights, Right to Strike	HR
Collective bargaining coverage	VH
Overall risk of Freedom of Association	HR
Net Migration Rate (NMR) per 1,000 Population	HR
Total Immigrants to Destination Country 2017	VH
Immigrants as a Percentage of the Population, 2017	VH
Risk that a country has not ratified international conventions or set up policies for immigrants	HR
Evidence of Risk to Migrant Workers	HR
Paid annual leave	VH
Paid sick leave coverage begins on first day of incapacity	HR
Sick leave duration	VH
Sick leave pay	VH
Adult need leave	VH
Maternity leave duration	VH
Maternity leave pay	VH
Paternity leave pay	VH
Parental leave duration	VH
Wage replacement of paid parental leave	VH
Overall risk of inadequate social benefits	VH
Number of ILO Conventions Ratified, Abstained, Denounced	VH

Table S10: High (H) and Very-High (VH) Risk in Labour and Decent Work for UK

Sub-category Indicators	Risk lev
Freedom of Association Rights, Collective Bargaining Rights, Right to Strike	HR
Collective bargaining coverage	HR
Overall risk of Freedom of Association	HR
Net Migration Rate (NMR) per 1,000 Population	HR
Total Immigrants to Destination Country 2017	VH
Immigrants as a Percentage of the Population, 2017	HR
Risk that a country has not ratified international conventions or set up policies for immigrants	HR
Evidence of Risk to Migrant Workers	HR
Wage replacement of paid parental leave	VH
Number of ILO Conventions Ratified, Abstained, Denounced	HR

Table S11: High (H) and Very-High (VH) Risk in Labour and Decent Work for France

Sub-category indicators	Risk Level
Percent of Population working >X hrs per week, >60 hrs per week	HR
Percent of Population working >X hrs per week, >60 hrs per week	VH
Total Immigrants to Destination Country 2017	VH
Immigrants as a Percentage of the Population, 2017	HR
Risk that a country has not ratified international conventions or set up policies for immigrants	HR
Average of Unemployment Percentage at the country level	HR

Table S12: High (H) and Very-High (VH)Risk in Labour and Decent Work for Germany

Sub-category indicators	Risk Level
Percent of Population working >X hrs per week, >60 hrs per week	HR
Percent of Population working >X hrs per week, >60 hrs per week	VH
Total Immigrants to Destination Country 2017	VH
Immigrants as a Percentage of the Population, 2017	HR
Risk that a country has not ratified international conventions or set up policies for immigrants	HR

2. Health and Safety

Table S12: High (H) and Very-High (VH) Risk in Health and safety for Brazil

Sub-category indicators	Risk level
Disability-adjusted life years due to occupational-related Mesothelioma	HR
Asthma DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Chronic Obstructive Pulmonary Disease DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Silicosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Heart disease Due to Particulate Matters (DALYs)	HR
Non-Fatal Work Related injuries by sector	HR
Non-fatal injuries by country	HR

Table S14: High (H) and Very-High (VH) Risk Health and Safety for Russia

Sub-category indicators	Risk Level
Occupational Noise Exposure to Males (85-90 dBA)	HR
Occupational Noise Exposure to Males (>90 dBA)	VH
Occupational Noise Exposure to Females (85-90 dBA)	HR
Occupational Noise Exposure to Females (>90 dBA)	HR
Overall Occupational Noise Exposure Risk	VH
Deaths due to occupational-related Lung Cancer	HR
Deaths due to occupational-related Mesothelioma	HR
Disability-adjusted life years due to occupational-related Lung Cancer	HR
Disability-adjusted life years due to occupational-related Mesothelioma	HR
Overall Occupational Cancer Risk - loss of life (DALYs)	HR
Overall Occupational Cancer Risk – Deaths	HR
Chronic Obstructive Pulmonary Disease DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Asbestosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Silicosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Heart disease Due to Particulate Matters (DALYs)	HR
Miners’ pneumoconiosis DALYs as a result of Workplace Exposure to airborne particulates	HR
Fatal injuries by sector	VH
Fatality Rate of injuries by country	HR

Table S15: High (H) and Very-High (VH) Risk Health and Safety for India

Sub-category indicators	**Risk level**
Deaths due to occupational-related Lung Cancer	HR
Deaths due to occupational-related Leukemia	HR
Deaths due to occupational-related Mesothelioma	HR
Disability-adjusted life years due to occupational-related Lung Cancer	HR
Disability-adjusted life years due to occupational-related Leukemia	HR
Disability-adjusted life years due to occupational-related Mesothelioma	VH
Overall Occupational Cancer Risk - loss of life (DALYs)	VH
Overall Occupational Cancer Risk – Deaths	HR
Asthma DALYs as a result of Workplace Exposure to airborne particulates, both genders	VH
Chronic Obstructive Pulmonary Disease DALYs as a result of Workplace Exposure to airborne particulates, both genders	VH
Asbestosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Silicosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Heart disease Due to Particulate Matters (DALYs)	VH

Table S16: High (H) and Very-High (VH) Risk Health and Safety for China

Sub-category indicators	**Risk Level**
Occupational Noise Exposure to Males (85-90 dBA)	HR
Occupational Noise Exposure to Males (>90 dBA)	HR
Occupational Noise Exposure to Females (85-90 dBA)	HR
Occupational Noise Exposure to Females (>90 dBA)	HR
Overall Occupational Noise Exposure Risk	HR
Deaths due to occupational-related Lung Cancer	VH
Deaths due to occupational-related Leukemia	VH
Deaths due to occupational-related Mesothelioma	VH
Disability-adjusted life years due to occupational-related Lung Cancer	VH
Disability-adjusted life years due to occupational-related Leukemia	VH
Disability-adjusted life years due to occupational-related Mesothelioma	VH
Overall Occupational Cancer Risk - loss of life (DALYs)	VH
Overall Occupational Cancer Risk – Deaths	VH
Asthma DALYs as a result of Workplace Exposure to airborne particulates, both genders	VH
Chronic Obstructive Pulmonary Disease DALYs as a result of Workplace Exposure to airborne particulates, both genders	VH
Asbestosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	VH
Silicosis DALYs as a result of Workplace Exposure to airborne particulates, both genders	VH
Heart disease Due to Particulate Matters (DALYs)	VH
Miners' pneumoconiosis DALYs as a result of Workplace Exposure to airborne particulates	VH

Table S17: High (H) and Very-High (VH) Risk Health and Safety for USA

Sub-category indicators	Risk Level
Deaths due to occupational-related Leukemia	HR
Asthma DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Heart disease Due to Particulate Matters (DALYs)	HR
Non Fatal Work Related injuries by sector	HR
Non Fatal Work Related injuries by sector	VH
Fatal injuries by sector	HR
Fatal injuries by sector	VH

Table S18: High (H) and Very-High (VH) Risk Health and Safety for UK

Sub-category indicators	Risk Level
Deaths due to occupational-related Lung Cancer	HR
Deaths due to occupational-related Leukemia	HR
Disability-adjusted life years due to occupational-related Lung Cancer	HR
Disability-adjusted life years due to occupational-related Leukemia	HR
Overall Occupational Cancer Risk - loss of life (DALYs)	HR
Overall Occupational Cancer Risk – Deaths	HR
Asthma DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Heart disease Due to Particulate Matters (DALYs)	HR
Miners’ pneumoconiosis DALYs as a result of Workplace Exposure to airborne particulates	HR
Non Fatal Work Related injuries by sector	HR
Non Fatal Work Related injuries by sector	VH
Fatal injuries by sector	HR
Non-fatal injuries by country	HR

Table S19: High (H) and Very-High (VH) Risk Health and Safety for France

Sub-category indicators	Risk Level
Deaths due to occupational-related Lung Cancer	HR
Deaths due to occupational-related Leukemia	HR
Disability-adjusted life years due to occupational-related Lung Cancer	HR
Disability-adjusted life years due to occupational-related Leukemia	HR
Overall Occupational Cancer Risk - loss of life (DALYs)	HR
Overall Occupational Cancer Risk – Deaths	HR
Asthma DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Heart disease Due to Particulate Matters (DALYs)	HR
Miners’ pneumoconiosis DALYs as a result of Workplace Exposure to airborne particulates	HR
Non Fatal Work Related injuries by sector	VH
Fatal injuries by sector	HR
Non-fatal injuries by country	VH

Table S20: High (H) and Very-High (VH) Health and Safety for Germany

Subcategory indicators	Risk Level
Deaths due to occupational-related Lung Cancer	HR
Deaths due to occupational-related Leukemia	HR
Disability-adjusted life years due to occupational-related Lung Cancer	HR
Disability-adjusted life years due to occupational-related Leukemia	HR
Overall Occupational Cancer Risk - loss of life (DALYs)	HR
Overall Occupational Cancer Risk – Deaths	HR
Asthma DALYs as a result of Workplace Exposure to airborne particulates, both genders	HR
Heart disease Due to Particulate Matters (DALYs)	HR
Miners’ pneumoconiosis DALYs as a result of Workplace Exposure to airborne particulates	HR
Non Fatal Work Related injuries by sector	VH
Non-fatal injuries by country	VH

3. Human Rights

Table S21: High (H) and Very-High (VH) Risk Human Rights for Brazil

Sub-category indicators	Risk Level
The Global Gender Gap Index, Global Gender Gap Report, World Economic Forum	HR
Gender Inequality Index (GII), UNDP Human Development Indicators Report	HR
High Conflict Heidelberg Institute – overall	HR
High Conflict UNDP	HR
Overall High Conflict	HR
Estimated Obesity (BMI = 30 kg/m^2) Prevalence, Aged 15+, Females	HR
Cases of HIV (per 1000 adults 15-49 years)	HR
Notified cases of Malaria (per 100,000 population)	HR
Dengue Fever, Incidence rate (per 100,000 population)	HR

Table S22: High (H) and Very-High (VH) Risk Human Rights for Russia

Sub-category indicators	Risk Level
Percent of Population that is Indigenous	HR
Indigenous Sector Issues Identified	HR
The Cingranelli-Richards Human Rights Dataset (CIRI), Women's Rights	HR
High Conflict UNDP	HR
Overall High Conflict	HR
Cerebrovascular disease, Estimated Age Standardized Death Rate (per 100,000)	VH
Malignant neoplasms, Estimated Age Standardized Death Rate (per 100,000)	VH
Estimated Obesity (BMI = 30 kg/m^2) Prevalence, Aged 15+, Females	HR
Cases of HIV (per 1000 adults 15-49 years)	VH
Cases of Tuberculosis (per 100,000 population)	HR

Table S23: High (H) and Very-High (VH) Risk Human Rights for India

Sub-category indicators	Risk Level
Percent of Population that is Indigenous	HR
Indigenous Sector Issues Identified	HR
Social Institutions and Gender Index (SIGI)	HR
The Global Gender Gap Index, Global Gender Gap Report, World Economic Forum	HR
Gender Inequality Index (GII), UNDP Human Development Indicators Report	HR
Overall Gender Inequity in Country	HR
High Conflict Heidelberg Institute – overall	VH
High Conflict UNDP	HR
Minority Rights Group International - People under Threat, Total Score based on several indicators	HR
Overall High Conflict	VH
Under-five mortality rate (probability of death before age 5 per 1000 live births)	VH
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	HR
Cerebrovascular disease, Estimated Age Standardized Death Rate (per 100,000)	HR
Respiratory diseases, Estimated Age Standardized Death Rate (per 100,000)	VH
Mortality rate attributed to household and ambient air pollution and exposure to unsafe WASH services (per 100 000 population)	HR
Population affected by natural disasters, average per year per million people	HR
Cases of Tuberculosis (per 100,000 population)	HR
Notified cases of Malaria (per 100,000 population)	VH
Age-standardized mortality rates from communicable diseases (per 100,000 population)	HR

Table S24: High (H) and Very-High (VH) Risk Human Rights for China

Sub-category indicators	Risk level
Percent of Population that is Indigenous	HR
Indigenous Sector Issues Identified	HR
The Global Gender Gap Index, Global Gender Gap Report, World Economic Forum	HR
The Cingranelli-Richards Human Rights Dataset (CIRI), Women's Rights	VH
High Conflict Heidelberg Institute – overall	VH
High Conflict UNDP	VH
Minority Rights Group International - People under Threat, Total Score based on several indicators	HR
Overall High Conflict	HR
Under-five mortality rate (probability of death before age 5 per 1000 live births)	VH
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	VH
Cerebrovascular disease, Estimated Age Standardized Death Rate (per 100,000)	VH
Malignant neoplasms, Estimated Age Standardized Death Rate (per 100,000)	HR
Population affected by natural disasters, average per year per million people	VH
Cases of Tuberculosis (per 100,000 population)	HR

Table S25: High (H) and Very-High (VH) Risk Human Rights for USA

Sub-category indicators	Risk Level
Risk of a country not adopting Intl Conventions to Protect Indigenous	HR
High Conflict UNDP	VH
Overall High Conflict	HR
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	HR
Estimated Obesity (BMI = 30 kg/m^2) Prevalence, Aged 15+, Males	HR
Estimated Obesity (BMI = 30 kg/m^2) Prevalence, Aged 15+, Females	HR
Cases of HIV (per 1000 adults 15-49 years)	HR

Table S26: High (H) and Very-High (VH) -Risk Human Rights for UK

Sub-category indicators	Risk Level
High Conflict UNDP	HR
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	HR
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	VH
Estimated Obesity (BMI = 30 kg/m^2) Prevalence, Aged 15+, Females	HR

Table S27: High (H) and Very-High (VH) Risk Human Rights for France

Sub-category indicators	Risk Level
High Conflict UNDP	VH
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	HR

Table S28: High (H) and Very-High (VH) Risk Human Rights for Germany

Sub-category indicators	Risk Level
High Conflict UNDP	VH
Overall High Conflict	HR
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	HR
Cardiovascular diseases, Estimated Age Standardized Death Rate (per 100,000)	VH
Estimated Obesity (BMI = 30 kg/m^2) Prevalence, Aged 15+, Females	HR

Community Infrastructure

Table S29: High (H) and Very-High (VH) Risk Community Infrastucture for Brazil

Sub-category indicators	Risk Level
% Urban Access to an Improved Source of Drinking Water	HR
Percent of Children Out of Primary School, male	HR
Percent of Children Out of Primary School, total	HR
Number of Hospital Beds per 1000 population	HR
Large holdings Land % < x hectares	HR

Table S30: High (H) and Very-High (VH) Risk Community Infrastucture for Russia

Sub-category indicators	Risk Level
Percentage of commercially-owned farms in country	HR
Smallholdings Land % < x hectares	VH

Table S31: High (H) and Very-High (VH) Risk Community Infrastucture for India

Sub-category indicators	Risk Level
% Urban Access to an Improved Source of Drinking Water	HR
% Total Access to an Improved Source of Drinking Water	HR
% Rural Access to an Improved source of Sanitation	HR
% Total Access to an Improved source of Sanitation	HR
Number of Hospital Beds per 1000 population	HR
Smallholdings Land % < x hectares	VH

Table S32: High (H) and Very-High (VH)-Risk Community Infrastucture for China

Sub-category indicators	Risk level
Percent of Children Out of Primary School, male	HR
Percent of Children Out of Primary School, female	HR
Percent of Children Out of Primary School, total	HR
Smallholdings Land % < x hectares	VH

Table S33: High (H) and Very-High (VH) Risk Community Infrastucture for USA

Sub-category indicators	Risk Level
Number of Hospital Beds per 1000 population	HR
Largeholdings Land % < x hectares	VH

Table S34: High (H) and Very-High (VH) Risk Community Infrastucture for UK

Sub-category indicators	Risk Level
Number of Hospital Beds per 1000 population	HR
Large holdings Land % < x hectares	VH

Table S35: High (H) and Very-High (VH) Risk Community Infrastucture for France

Sub-category indicators	Risk Level
5.E.d Largeholdings Land % < x hectares	HR

Table S36: High (H) and Very-High (VH) Community Infrastucture for Germany

Sub-category indicators	Risk Level
Percentage of commercially-owned farms in country	VH
Large holdings Land % < x hectares	VH

Table S37: Indicators used in estimating socio-economic impact

Socio-economic impact	**Code**
Total value added	TVA
Total wage payments	TWP
Payments to technically skilled professionals	PSP
Payments to clerks	PC
Payments to service and shop floor workers	PSFW
Payments to officers and managerial professionals	POMP
Payments to agricultural and other low-skilled workers	PALW
Payments to capital	PC
Payments for land	PL
Payments for natural resources	PNR
Total economic output	TEO

Appendix C Supplementary Information for Chapter 7 (Integrated TBL Assessment)

Table S38: TBL impacts for emerging and developed economies

			Emerging Economies				**Developed Economies**			
	Impact category	*Unit*	**Brazil**	**Russia**	**India**	**China**	**USA**	**UK**	**France**	**Germany**
Economic	GDP	$	4.6	4.8	6.3	15.3	10.0	7.4	10.3	9.0
	Gross Operating Surplus(GOS)	$	2.1	2.8	4.1	5.9	6.5	4.9	4.1	4.2
	Imports	$	0.118	0.014	0.009	0.132	0.187	0.328	0.028	0.201
	Employee Compensation	$	0.8	1.4	1.1	2.1	2.2	1.0	2.3	3.1
	Working hours	hours	0.342	0.197	1.187	1.079	0.060	0.028	0.073	0.093
Environmental	Global Warming Impact	kg CO2-eq	113.1	354.9	455.1	539.0	259.0	23.1	6.5	99.2
	Energy Use	MJ	73.7	264.7	285.1	207.8	62.0	43.1	53.6	122.0
	Material Use	MJ	173.8	205.8	968.9	405.6	255.1	57.0	345.0	1232.9
	Eutrophication Potential	kg Nox	8.7	21.9	43.8	26.4	8.1	12.2	9.8	4.4
	Acidification Potential	kg Sox	2.7	3.0	31.3	52.4	3.4	2.6	8.5	8.3
Social	Labour Rights and Decent work	risk hours	36.8	51.9	193.7	93.2	28.8	0.2	1.3	1.1
	Health and Safety	risk hours	19.6	52.1	65.0	119.2	4.1	2.0	2.9	3.2
	Human Rights	risk hours	25.2	27.2	9.6	73.4	6.0	0.5	0.7	1.1
	Community Infrastructure	risk hours	14.0	0.0	33.5	11.8	2.5	0.2	0.2	0.0
	Socio-economic contribution	$	4.3	3.9	8.4	5.5	1.3	0.3	0.3	0.4

Table S39: Results from Sensitivity Analysis Scenario 1

DTR Normalisation method								
Additive Aggregation method								
	Brazil	Russia	India	China	USA	UK	France	Germany
GDP	0.30	0.32	0.41	1.00	0.66	0.48	0.67	0.59
Gross Operating Surplus(GOS)	0.32	0.43	0.63	0.91	1.00	0.75	0.63	0.65
Imports	-0.36	-0.04	-0.03	-0.40	-0.57	-1.00	-0.09	-0.61
Employee Compensation	0.26	0.44	0.36	0.66	0.71	0.32	0.74	1.00
Working hours	-0.29	-0.17	-1.00	-0.91	-0.05	-0.02	-0.06	-0.08
EC Index	**0.22**	**0.98**	**0.38**	**1.26**	**1.75**	**0.52**	**1.90**	**1.55**
Global Warming Impact	-0.21	-0.66	-0.84	-1.00	-0.48	-0.04	-0.01	-0.18
Energy Use	-0.26	-0.93	-1.00	-0.73	-0.22	-0.15	-0.19	-0.43
Material Use	-0.14	-0.17	-0.79	-0.33	-0.21	-0.05	-0.28	-1.00
Eutrophication Potential	-0.20	-0.50	-1.00	-0.60	-0.18	-0.28	-0.22	-0.10
Acidification Potential	-0.05	-0.06	-0.60	-1.00	-0.06	-0.05	-0.16	-0.16
EN Index	**-0.86**	**-2.31**	**-4.23**	**-3.66**	**-1.15**	**-0.57**	**-0.87**	**-1.87**
Labour Rights and Decent work	-0.19	-0.27	-1.00	-0.48	-0.15	0.00	-0.01	-0.01
Health and Safety	-0.16	-0.44	-0.55	-1.00	-0.03	-0.02	-0.02	-0.03
Human Rights	-0.34	-0.37	-0.13	-1.00	-0.08	-0.01	-0.01	-0.02
Community Infrastructure	-0.42	0.00	-1.00	-0.35	-0.08	-0.01	-0.01	0.00
Socio-economic contribution	0.51	0.47	1.00	0.65	0.16	0.03	0.04	0.05
SR Index	**-0.60**	**-0.61**	**-1.68**	**-2.18**	**-0.18**	**0.00**	**-0.01**	**0.00**

Table S40: Results from Sensitivity Analysis Scenario 1

Max-Min Normalisation Method								
Additive Aggregation method								
	Brazil	Russia	India	China	USA	UK	France	Germany
GDP	0.43	0.45	0.59	1.43	0.94	0.69	0.96	0.85
Gross Operating Surplus(GOS)	0.46	0.63	0.93	1.33	1.46	1.09	0.93	0.95
Imports	-0.37	-0.04	-0.03	-0.42	-0.59	-1.03	-0.09	-0.63
Employee Compensation	0.34	0.59	0.49	0.89	0.96	0.43	0.99	1.34
Working hours	-0.29	-0.17	-1.02	-0.93	-0.05	-0.02	-0.06	-0.08
EC Index	**0.57**	**1.46**	**0.95**	**2.31**	**2.72**	**1.16**	**2.73**	**2.43**
Global Warming Impact	-0.2	-0.7	-0.9	-1.0	-0.5	0.0	0.0	-0.2
Energy Use	-0.3	-1.1	-1.2	-0.9	-0.3	-0.2	-0.2	-0.5
Material Use	-0.1	-0.2	-0.8	-0.3	-0.2	0.0	-0.3	-1.0
Eutrophication Potential	-0.2	-0.6	-1.1	-0.7	-0.2	-0.3	-0.2	-0.1
Acidification Potential	-0.1	-0.1	-0.6	-1.1	-0.1	-0.1	-0.2	-0.2
EN Index	**-0.94**	**-2.55**	**-4.60**	**-3.94**	**-1.23**	**-0.63**	**-0.95**	**-2.02**
Labour Rights and Decent work	-0.2	-0.3	-1.0	-0.5	-0.1	0.0	0.0	0.0
Health and Safety	-0.2	-0.4	-0.6	-1.0	0.0	0.0	0.0	0.0
Human Rights	-0.3	-0.4	-0.1	-1.0	-0.1	0.0	0.0	0.0
Community Infrastructure	-0.4	0.0	-1.0	-0.4	-0.1	0.0	0.0	0.0
Socio-economic contribution	0.5	0.5	1.0	0.7	0.2	0.0	0.0	0.0
SR Index	**-0.59**	**-0.61**	**-1.65**	**-2.18**	**-0.18**	**0.00**	**-0.01**	**0.00**

Appendix D: Supplementary Information for Chapter 8 (Comparative LCA of basalt versus industrial fertilisers)

Table S41: Description of selected environmental impact categories

Global warming potential	Measure of greenhouse gas emissions over 100 years
Acidification Potential	Measures of potential release of acid into surface waters and soils
Eutrophication Potential	Measures of water pollution caused by increased nutrients
Land use	Measures of land occupation and loss of biodiversity
Fresh water aquatic ecotoxicity (FAETP 100a)	Measures of fresh water ecosystems impact from toxic emissions to water within 100-year period
Fresh water sediment ecotoxicity (FSETP 100a)	Measures of fresh water sediment ecosystem impact from toxic emissions to water within a 100-year period
Marine water sediment ecotoxicity (MAETP 100a)	Measures of toxic substances released on marine aquatic ecosystem
Marine water sediment ecotoxicity (MSETP 100a)	Measures of toxic substance release on marine sediment ecosystem
Human Toxicity Impact (HTP 100a)	Measures of harmful toxic substances release to humans within a 100-year period
TAETP 100a	Measures of toxic substances release to terrestrial ecosystem within a 100-year period
Ionising radiation	Measures of exposure to harmful rays (gamma, alpha, etc) to humans
Malodous air	Measures of air pollution
Ecosystem Quality	Effects on species such as vascular plants and lower organisms based on four indicators namely ecotoxicity, acidification, eutrophication and land use
Human Health	Effects on human health includes the number and duration of diseases and life years lost.
Resources	Effects on resources is a measure of the surplus or extra energy required in the future to extract minerals and fossil resources that are of lower quality.

MATERIAL AND ENERGY INVENTORY

Table S42: Material and energy inventory for 1kg of basalt fertilizer

Inputs	Quantity	Unit
alkyd paint, white, without solvent, in 60% solution state	2.9996E-06	Kg
Blasting	0.00007729	Kg
Chemical	3.5995E-07	Kg
Diesel (Crushing and grinding)	0.041394	MJ
Electricity(Mining)	0.0062092	kWh
Thermal energy (Heat)	0.00029731	MJ
lubricating oil	0.000053993	Kg

Table S43: Material and energy inventory for 1kg of Single Superphosphate (SSP) fertilizer

Inputs	Quantity	Unit
Sulfuric acid	1.75	kg
Electricity	1.85	kWh
Phosphate rock	1	kg

Table S44: Material and energy inventory for 1kg of Triple Superphosphate (TSP) fertilizer

Inputs	Quantity	Unit
Electricity	0.752	kg
Thermal energy(Heat)	1.46	kWh
Phosphoric acid	0.966	MJ
Phosphate rock	0.3	kg

Table S45: Material and energy inventory for 1kg of Potassium Chloride (KCI) fertilizer

Inputs	Quantity	Unit
diesel, burned in building machine	0.040298	MJ
electricity, medium voltage	0.11999	kWh
salt tailing from potash mine	4.5798	kg
heat, district or industrial, natural gas	0.87095	MJ

Table S46: Material and energy inventory for 1kg of Potassium Carbonate (K_2CO_3) fertilizer

Inputs	Quantity	Unit
carbon dioxide, liquid	0.27726	Kg
electricity, medium voltage	0.416	kWh
heat, from steam, in chemical industry	0.167	MJ
nitrogen, liquid	0.014909	Kg

Table S47: Material and energy inventory for 1kg of Potassium Hydroxide (KHO) fertilizer

Inputs	Quantity	Unit
electricity, medium voltage	1.8601	kWh
heat, district or industrial, natural gas	4.712	MJ
heat, district or industrial, other than natural gas	2.63	MJ
potassium chloride, as K2O	0.493	Kg
salt tailing from potash mine	0.023	Kg

LIFECYLE IMPACTS ASSESSMENT (LCIA) RESULTS

The following tables (from Table S48-S54) show the breakdown of the contributions of each individual input (material and energy) to the total lifecycle impacts shown in Figure 8.2 of main document. It makes it easy to therefore identify and trace the source of inputs in a fertiliser and how it contributes to overall total impacts in a given sustainability metric.

Table S48: LCIA results of Basalt fertilizer across environmental sustainability metrics

	Alkyd paint	Blasting	Chemical	Diesel	Electricity	Thermal energy	lubricating oil	Total
Climate change (kg CO_2-eq)	2.0E-05	4.5E-04	6.9E-07	3.8E-03	2.8E-03	2.1E-05	7.8E-05	7.2E-03
Acidification Potential (kg SO_x)	1.1E-07	2.2E-05	2.6E-09	2.9E-05	1.3E-05	1.5E-07	4.9E-07	6.5E-05
Eutrophication (kg NO_x)	5.1E-08	5.2E-05	1.8E-09	5.4E-05	6.7E-06	5.9E-08	2.3E-07	1.1E-04
Land Use (m^2a)	5.9E-06	2.8E-05	1.4E-08	1.8E-05	3.1E-04	8.4E-06	3.6E-06	3.8E-04
Freshwater aquatic ecotoxicity (FAETP 100a)	9.9E-06	1.3E-04	1.3E-07	2.1E-04	1.7E-03	3.6E-06	2.3E-05	2.0E-03
Freshwater sediment ecotoxicity (FSETP 100a)	2.1E-05	2.8E-04	2.6E-07	4.6E-04	3.6E-03	7.5E-06	4.7E-05	4.4E-03
Marine aquatic ecotoxicity (MSETP 100a)	2.9E-05	4.9E-04	4.9E-07	8.9E-04	5.8E-03	1.6E-05	8.7E-05	7.4E-03
Marine sediment ecotoxicity (MSETP 100a)	3.3E-05	5.3E-04	5.0E-07	1.0E-03	6.2E-03	1.6E-05	9.0E-05	7.8E-03
Human Toxicity (HTP 100a)	1.2E-05	4.0E-04	7.2E-07	2.4E-03	4.7E-04	6.5E-06	3.9E-05	3.3E-03
Terrestrial ecotoxicity (TAETP 100a)	6.6E-07	9.3E-07	1.3E-10	3.6E-07	9.5E-07	1.6E-08	2.6E-08	2.9E-06
Ionising radiation (DALYs)	1.9E-14	2.7E-13	6.0E-16	5.4E-12	3.0E-11	3.5E-14	3.3E-13	3.6E-11
Malodours air (m^3 air)	1.2E+00	1.0E+01	1.3E-02	6.1E+00	1.9E+01	7.6E-02	7.2E-01	3.7E+01
Ecosystem quality	7.30E-07	3.20E-05	4.30E-09	3.10E-05	4.90E-05	1.00E-06	8.10E-07	1.15E-04
Human health	6.30E-07	6.90E-05	1.50E-08	1.70E-04	6.60E-05	1.10E-06	2.40E-06	3.09E-04
Resources	5.10E-07	9.10E-06	5.70E-08	1.50E-04	7.40E-05	5.90E-07	9.60E-06	2.44E-04

Table S49: LCIA results of SSP fertilizer across environmental sustainability metrics

Impact category	Sulphuric acid	Electricity	Phosphate rock	Total
Climate change (kg CO2-eq)	0.2819425	0.8207155	0.30681	1.409468
Acidification Potential (kg Sox)	0.0131733	0.003952525	0.0021911	0.019316925
Eutrophication (kg Nox)	0.00250845	0.001991895	0.0015411	0.006041445
Land Use(m3)	0.3736075	0.496614	0.073962	0.9441835
Freshwater aquatic ecotoxicity (FAETP 100a)	0.752465	1.0691335	0.15617	1.9777685
Freshwater sediment ecotoxicity (FSETP 100a)	1.3466775	1.742256	0.28175	3.3706835
Marine aquatic ecotoxicity (MSETP 100a)	1.3710375	1.8350335	0.30484	3.510911
Marine sediment ecotoxicity (MSETP 100a)	0.000175805	0.000282347	0.0030955	0.003553652
Human Toxicity (HTP 100a)	0.34839	0.1404779	0.097928	0.5867959
Terrestrial ecotoxicity (TAETP 100a)	1.12915E-09	9.07647E-09	7.997E-10	1.10053E-08
Ionising radiation (DALYs)	6086.5	5544.08	2717.7	14348.28
Malodours air ((m^3 air)	0.036309	0.09317895	0.040273	0.16976095
Ecosystem quality (points)	0.013264825	0.014589655	0.0034569	0.03131138
Human Health (points)	0.04485775	0.01963775	0.023351	0.0878465
Resources (points)	0.0333515	0.02210935	0.0096706	0.06513145

Table S50: LCIA results of TSP fertilizer across environmental sustainability metrics

Impact category	Electricity	Thermal energy	Phosphoric acid	Phosphate rock	Total
Climate change (kg CO2-eq)	0.33360976	0.10446008	0.91985418	0.092043	1.44996702
Acidification Potential (kg Sox)	0.001606648	0.0007134	0.018288312	0.00065733	0.02126569
Eutrophication (kg Nox)	0.000809678	0.000290803	0.004730792	0.00046233	0.006293603
Land Use(m3)	0.20186688	0.01768644	0.57445122	0.0221886	0.81619314
Freshwater aquatic ecotoxicity (FAETP 100a)	0.43458832	0.03676426	1.1734002	0.046851	1.69160378
Freshwater sediment ecotoxicity (FSETP 100a)	0.70820352	0.07874656	2.2515528	0.084525	3.12302788
Marine aquatic ecotoxicity (MSETP 100a)	0.74591632	0.08028102	2.3804172	0.091452	3.29806654
Marine sediment ecotoxicity (MSETP 100a)	0.00011477	8.05891E-05	0.004593813	0.00092865	0.005717822
Human Toxicity (HTP 100a)	0.057102368	0.0320616	0.54046734	0.0293784	0.659009708
Terrestrial ecotoxicity (TAETP 100a)	3.68946E-09	1.7174E-10	2.66249E-09	2.3991E-10	6.7636E-09
Ionising radiation (DALYs)	2253.5936	373.0446	12913.488	815.31	16355.4362
Malodours air ((m^3 air)	0.037875984	0.04125084	0.52383282	0.0120819	0.615041544
Ecosystem quality (points)	0.005930498	0.004918302	0.019970118	0.00103707	0.031855988
Human Health (points)	0.00798248	0.005446968	0.091374906	0.0070053	0.111809654
Resources (points)	0.008987152	0.002891822	0.055486074	0.00290118	0.070266228

Table S51: LCIA results of KCl fertilizer across environmental sustainability metrics

Impact	Diesel	Electricity	Salt tailing	Thermal energy	Total
Climate change impact	0.003747	0.088545	0.052466	0.031865	0.176624
Acidification impact	2.81E-05	0.000344	0.000337	3.96E-05	0.000749
Eutrophication Impact	5.24E-05	0.000156	0.000404	3.5E-05	0.000647
FAETP impact	0.000203	0.085916	0.007167	0.000972	0.094259
FSETP impact	0.00045	0.182721	0.015414	0.002069	0.200654
MAETP impact	0.000863	0.298115	0.031061	0.00373	0.33377
MSETP impact	0.000978	0.306322	0.033809	0.003892	0.345
Terrestrial ecotoxity	3.53E-07	1.41E-05	1.89E-05	1.49E-06	3.48E-05
HTP impact	0.002315	0.009302	0.020524	0.003411	0.035552
Ionising Radiation impact	4.87E-12	6.16E-12	1.37E-10	2.11E-12	1.50E-10
Maladous air impact	5.876254	589.0669	927.4553	1776.128	3298.527
Land use impact	1.79E-05	0.000244	0.030305	7.31E-05	0.03064
Ecosystem quality impact	3.01E-05	0.000419	0.002623	4.84E-05	0.00312
Human Health impact	0.000161	0.001791	0.00168	0.000243	0.003875
Resources impact	0.00015	0.002027	0.003896	0.001518	0.007591

Table S52: LCIA results of K_2CO_3 fertilizer across environmental sustainability metrics

Impact category	carbon dioxide	electricity	Thermal energy	Nitrogen	Total
Climate change impact	0.242802	0.322666	0.020766	0.007161	0.593395
Acidification impact	0.000785	0.001425	7.14E-05	3.14E-05	0.002313
Eutrophication Impact	0.00042	0.000788	3.02E-05	1.78E-05	0.001255
FAETP impact	0.069484	0.119658	0.002138	0.002476	0.193756
FSETP impact	0.145581	0.256755	0.004556	0.005309	0.412201
MAETP impact	0.252836	0.425443	0.008589	0.008832	0.6957
MSETP impact	0.261179	0.444704	0.00901	0.009221	0.724113
Terrestrial ecotoxity	4.15E-05	5.38E-05	1.81E-06	1.07E-06	9.82E-05
HTP impact	0.329052	0.052008	0.00307	0.001176	0.385306
Ionising Radiation impact	2.60E-10	9.35E-10	1.19E-11	1.47E-11	1.22E-09
Maladous air impact	2421.672	1707.098	221.1414	37.5185	4387.43
Land use impact	0.00926	0.009268	0.000156	0.000146	0.01883
Ecosystem quality impact	0.002005	0.001987	6.45E-05	3.63E-05	0.004093
Human Health impact	0.006823	0.010931	0.000281	0.00025	0.018286
Resources impact	0.005735	0.008649	0.00072	0.000479	0.015583

Table S53: LCIA results of KOH fertilizer across environmental sustainability metrics

Impact category	Electricity	Thermal natural gas	Thermal (other than natural gas)	Potassium chloride	Salt Tailing	Total
Climate change impact	0.825196	0.263787	0.188171	0.236108	0.000263	1.513526
Acidification impact	0.003974	0.000187	0.001285	0.001096	1.69E-06	0.006545
Eutrophication Impact	0.002003	0.000209	0.000524	0.00083	2.03E-06	0.003568
FAETP impact	0.499325	0.004325	0.03186	0.125636	3.6E-05	0.661182
FSETP impact	1.07497	0.009395	0.066226	0.254353	7.74E-05	1.405023
MAETP impact	1.751768	0.036793	0.141852	0.46693	0.000156	2.397498
MSETP impact	1.845052	0.040877	0.144616	0.470864	0.00017	2.501579
Terrestrial eco toxicity	0.000284	8.89E-06	0.000145	8.43E-05	9.48E-08	0.000522
HTP impact	0.141245	0.02912	0.057755	0.26126	0.000103	0.489483
Ionising Radiation impact	9.13E-09	5.55E-11	3.09E-10	2.93E-10	6.89E-13	9.78E-09
Malodours air impact	5574.348	7398.311	671.9913	4215.89	4.65773	17865.2
Land use impact	0.093688	0.000436	0.074308	0.0322	0.000152	0.200784
Ecosystem quality impact	0.014669	0.000225	0.00886	0.005363	1.32E-05	0.02913
Human Health impact	0.019745	0.001643	0.009812	0.009517	8.44E-06	0.040726
Resources impact	0.02223	0.012817	0.005209	0.010313	1.96E-05	0.050588

Appendix E: Supplementary Information for Chapter 9 (Comparative LCA natural silicate and artificial silicate waste)

Table S54: Material and energy input for cement kiln dust from cement production

Input	Quantity	Unit
Clinker	0.9025	Kg
electricity, medium voltage	0.0376	kWh
ethylene glycol	0.00019	Kg
gypsum, mineral	0.0475	Kg
limestone, crushed, for mill	0.05	Kg
steel, low-alloyed	0.00011	Kg

Table S55: Material and energy input for steel production- Steel slag waste

Input	Quantity	Unit
coke	0.00025	MJ
dolomite	0.00275	Kg
electricity, medium voltage	0.021944	kWh
ferrochromium, high-carbon, 68% Cr	0.032853	Kg
ferromanganese, high-coal, 74.5% Mn	0.015278	Kg
ferronickel, 25% Ni	0.045	Kg
iron ore, beneficiated, 65% Fe	0.022	Kg
molybdenite	0.00059649	Kg
natural gas, high pressure	0.00095537	m3
oxygen, liquid	0.07145	Kg
pig iron	0.9	Kg
quicklime, in pieces, loose	0.0425	Kg

Table S56: Material and energy input for coal as from electricity production

Input	Quantity	Unit
hard coal	0.48969	Kg
light fuel oil	0.00019006	Kg
NOx retained, by selective catalytic reduction	0.00073	Kg
SOx retained, in hard coal flue gas desulfurisation	0.00201	Kg
water, decarbonised, at user	2.236	Kg

Appendix F: Awards and scholarly activities during this PhD

RESEARCH GRANTS

1. **Awarded GCRF Agri-Food Africa Innovation (2020):** "Triple Bottom line Sustainability assessment of agri-food circular economy in Sub-Saharan Africa". (**My role:** I am the grant writer for this project and Co-principal investigator).

2. **Post graduate Research Programme (PREP) Award:** Grant awarded by University of Sheffield to undertake internship at local business in Sheffield.

RESEARCH CONSULTANCY AND PUBLIC ENGAGEMENT

1. ***Research Consultant (2020):*** Research consultant at Translational Energy Research Centre (TERC) University of Sheffield, *LCA Scoping study for Grobotic Systems Limited.*

2. ***Research Consultant (2020):*** Research consultant at Translational Energy Research Centre (TERC) University of Sheffield, *Environmental Management Systems ISO 14001 Scoping study for LabLogic Systems Limited.*

3. **Research Consultant on Impact Assessment of Food Surplus—2019** at Food Works Sheffield, UK

4. **Short-term consultant for UK Department of Food and Rural Affairs (DEFRA)—2019,** research consultant at Advanced Resource Efficiency Centre (AREC), University of Sheffield, *Brexit impact on Food supply chain and international trade in the UK.*

5. **Food Waste Awareness in Schools**: workshop organized at St Ann Grove Primary School, Sheffield, 2018

6. **Referee**: Environmental Research Journal

PRESENTATIONS AND CONFERENCE PARTICIPATION

1. "Comparative Lifecycle Assessment between basalt and industrial fertilizers" paper presented at **Leverhulme Centre for Climate Change Mitigation 3rd Annual Conference,** University of Sheffield, 2019

2. Grantham Centre for Sustainable Futures Participant at **UNFCCC COP 24 Session** Katowice, Poland December 2018

3. "Environmental impact of Enhanced weathering in the UK" paper presented at **Leverhulme Centre for Climate Change Mitigation 2nd Annual Conference,** University of Sheffield, 2018

4. “Ecological Exchanges between UK and Africa” paper presented at **Annual Ghanaian Scholars’ Conference**, Coventry University, 2018

5. “Natural ecological resource embodied in international trade with Africa and developed countries” paper presented at the **Annual Conference of The All African Postgraduate Research Group (AAPORG),** University of Sheffield, 2018.

6. “Lifecycle Assessment Methodology”**, seminar organizer and presenter,** University of Sheffield,2017

7. **Best Operational Research paper**: “Enhanced weathering as a carbon dioxide removal strategy” presented at the **Annual Kent Business School Conference,** 2017

8. **“**Sustainability of Enhanced weathering as a carbon sequestration technique” presented at **Annual Sheffield University Management School Conference,** 2017

9. **“Using Supply Chain Environmental Analysis Tool (SCEnAT) software for environmental impact assessment of supply chains”** presented at at TrainERGY conference at University of Naples, 2017