DURBAN UNIVERSITY OF TECHNOLOGY
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A Novel Environmental Framework for Cleaner Cement Production in a Cement Plant.

Submitted in fulfilment of the academic requirements for the degree of **Doctor of Engineering** in the **Department of Industrial Engineering,** Faculty of Engineering, and the Built Environment at the Durban University of Technology.

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MEng *(Cum Laude)*

Supervisor: Prof Oludolapo Akanni Olanrewaju

PREFACE

This doctoral study was carried out under the Department of Industrial Engineering at DUT. The candidate was the principal investigator under the project leadership and supervision of Prof. Oludolapo Akanni Olanrewaju. The investigation was carried out using dataset from literature and ecoinvent database. This thesis has seven chapters compiled and discussed with the author's published and unpublished journal papers.

DECLARATION

I, **Busola Dorcas Akintayo**, the undersigned candidate declares that:

(i) The research reported in this thesis, except where otherwise indicated, is my original work.

(ii) This thesis has not been submitted for any degree or examination at any other university.

(iii) This thesis does not contain other persons' data, pictures, graphs, or other information unless specifically acknowledged as being sourced from other persons.

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Busola Dorcas Akintayo

Sign: Date: 21/05/2025

As the candidate supervisor, I do agree to the submission of this thesis.

Prof. Oludolapo Akanni Olanrewaju.

Sign: Date: 04/08/2025

DEDICATION

This research is dedicated to God, who has been my source of inspiration from the beginning to the end of this work.

ACKNOWLEDGMENT

The journey towards finalizing this dissertation has been filled with both highs and lows, but ultimately, it stands as a testament to faith and triumph. This achievement would not have been possible without the unwavering support I have received from many individuals across diverse aspects of my life. I am deeply grateful for the financial, moral, emotional, professional, spiritual, social, and academic guidance that has helped me reach this point.

First and foremost, I owe a special debt of gratitude to my husband: Dr Damilola Caleb Akintayo whose love and encouragement have been a constant source of strength throughout this entire process. He was the spark that lit the fire without him, this journey wouldn't have even gotten off the ground. I am also deeply thankful to my parents and siblings for their endless care, both practical and emotional, which kept me established and inspired. A special appreciation goes to my kids Oluwasemileniola Charis Akintayo and Oluwadarasimi Joy Akintayo, who were patient with me and endured throughout this doctoral journey.

I would like to express my heartfelt appreciation to my supervisor, whose patience, expertise, and constructive feedback have been valuable in shaping this dissertation. Additionally, I am grateful to the Babatunde family: Dr. Olubayo, Dr. Oluwagbotemi, Samuel, and Nathaniel for their kindness and support, which meant so much during this journey.

My family friends, scattered across Nigeria, South Africa, Spain, and beyond, also deserve my sincere thanks. Their understanding, friendship, and encouragement provided a crucial balance in my life, especially in challenging times. I would also like to acknowledge the staff in the Department of Industrial Engineering at Durban University of Technology for their administrative and academic assistance, as well as the institution itself for providing an environment conducive to growth and learning.

Furthermore, I extend my gratitude to the DUT scholarship scheme; the opportunities they provided were instrumental in furthering my research and development. Also, a special mention goes to the University of Valladolid in Spain, particularly Professor Ángel Manuel Gento Municio, whose support during the Erasmus+ KA171+ exchange mobility program greatly improved my academic experience. The learning opportunities made available to me during my time at the University of Valladolid have been inestimable, and I am truly thankful for the kindness and assistance provided by all involved.

In conclusion, this dissertation is not just a proceed of my efforts alone but a representation of the collective support I have received from many people, each of whom has played a crucial role in my academic and personal growth. To all of them, I am eternally grateful.

ABSTRACT

Meeting the Paris Agreement goal of maintaining the global temperature 'less than 2°C and towards 1.5°C above preindustrial temperatures requires combined CO_2 emissions from all countries and sectors to fall to zero and then become progressively negative by 2050–2055 (1.5°C) to 2070–2075 (2°C). Cement production is a critical component of modern infrastructure but is associated with significant environmental impacts, including high greenhouse gas (GHG) emissions, substantial energy consumption, and excessive resource usage. To address these challenges, this doctoral study proposes a novel environmental framework for cleaner cement production, structured into four integrated components: (i) Environmental Impact Assessment, (ii) Material Substitution Strategies, (iii) Optimized Production Model, and (iv) Validated Cleaner Production System.

The urgency of mitigating these environmental consequences necessitates a comprehensive assessment of cement production, particularly within the South African (SA) context, where research remains limited. This study conducts a Life Cycle Assessment (LCA) of SA cement plants utilizing both midpoint and end-point approaches of the Life Cycle Impact Assessment (LCIA). A cradle-to-gate analysis of 1 kg of cement produced in a typical South Africa plant revealed that 0.993 kg CO_2 eq emissions are released per kilogram of cement, with 98.8% attributed to actual CO_2 emissions, significantly contributing to global warming. Furthermore, emissions of 1.6 kg of 1,4-Dichlorobenzene (1,4-DCB) eq into air and water exacerbate toxicity levels, while 0.139 kg of oil eq is linked to fossil resource scarcity. The end-point analysis highlights the potential endangerment of 55,404 human lives and 133 species annually, with a projected economic impact of R6.2 billion due to resource scarcity.

To mitigate these environmental concerns, material substitution emerges as a viable strategy. This study reviews the effectiveness of various material replacement approaches, including waste and recycled materials, in reducing energy use and GHG emissions in cement production. Findings indicate that partial (1%-60%) and total material substitution can reduce energy consumption by 5.5%-40% and GHG emissions by 1%-94%.

To determine the most environmentally beneficial method of cement manufacturing, an integrated life cycle assessment multi-criteria decision-making technique was employed. The LCA is employed to quantitatively evaluate the environmental effects of ten different methods of cement production across eighteen distinct categories. Meanwhile, the CRITIC weighted TOPSIS and EDAS MCDM approaches are utilized to rank the various alternatives by determining their proximity to the optimal solution. The LCA results showed that CEM III/A slag cement had lower environmental impacts than Portland cement. With a ranking score of 0.9094 and 1.7228 for EDAS and TOPSIS techniques, respectively, both MCDM identified CM10: ground granulated blast furnace slag (GGBFS) as the most recommended.

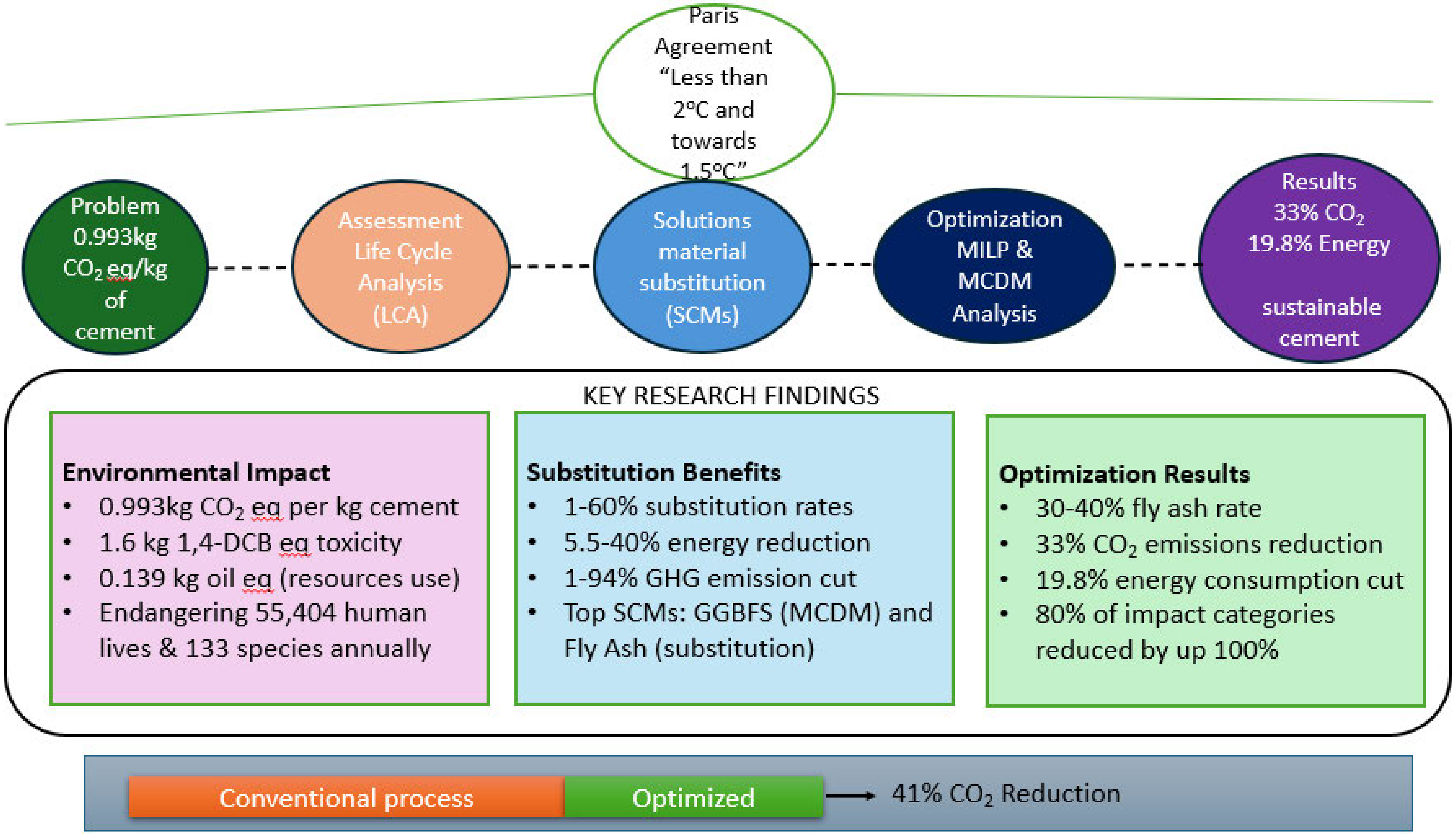
Also, material substitution strategies were assessed through the valorisation of industrial waste as supplementary cementitious materials (SCMs) for sustainable concrete was carried out using two-step framework and screening over 25 waste materials, followed by a multi-criteria decision-making (MCDM) analysis using the EDAS method to rank top-performing SCMs Fly Ash, GGBFS, Silica Fume, Calcined Clay, and Metakaolin with Fly Ash emerging as the most suitable SCM. The evaluation incorporated technical parameters, pozzolanic reactivity, environmental benefits, and regulatory compliance. These findings are validated by life cycle assessment (LCA) results indicating major carbon and energy savings and highlights the importance of waste consistency, regional supply chains, and performance-based material standards in scaling SCM implementation.

To systematically optimize cement production processes, this study employs Mixed-Integer Linear Programming (MILP) to model adaptive fly ash substitution strategies. The MILP model minimizes GHG emissions while maintaining production efficiency, with optimal substitution rates of 30%-40% reducing CO_2 emissions by 33% and energy consumption by 19.8%. Coupled with LCA, this approach ensures a quantitative evaluation of environmental impacts, aligning industry practices with sustainability goals. In the LCA of 1 ton of cement production process with and without replacement shows that estimated amount of 80% of the impact categories reduced by 100% in the system that incorporates the partial replacement when compared to the one that doesn't. Global warming potential and Terrestrial ecotoxicity reduces by 41% and 38% respectively. Significant reduction in CO_2 as a major contributor to GW was observed. However, further analysis on TE suggests that partial replacement of clinker with fly ash (30-40%) can slightly increase the amount of some heavy chemicals (Lead, Mercury, Nickel, Vanadium and Zinc) that is emitted into the environment.

In conclusion, this research provides a holistic evaluation of cement production's environmental footprint and offers practical mitigation strategies. It underscores the urgent need for sustainable practices in cement production, highlighting material substitution as a key strategy to mitigate environmental impacts. By integrating LCA methodologies with optimization technique, the study analyses the potential of material substitution in reducing energy consumption and GHG emissions, thereby promoting a more sustainable cement industry.

In conclusion, this research presents a novel environmental framework for cleaner cement production, integrating LCA, SCM screening with MCDM, MILP-based optimization, and validation through impact reduction. The framework both improves environmental performance and supports industry alignment with global sustainability goals through actionable, evidence-based strategies.

GRAPHICAL ABSTRACT



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LIST OF ABBREVIATIONS/ ACRONYMS

AAC	Activated cements and concretes
AFs	Alternative fuels
AHP	Analytic Hierarchy Process
AoSL	Area of significance to life
APIs	Application programming interface
AR	Alternative resource
AS	Alternative scenario
AS	Appraisal score
ASTM	American Society for Testing and Materials
BAT	Best available technique
BCC	Blended cement concrete
BREF	Best Available Techniques Reference
BS	Biological sludge
CCA	Corncob ash
CFC-11	Trichlorofluoromethane
CCS	Carbon capture and storage
CKD	Cement kiln dust
CM	Cement
CRITIC	Criteria Importance Through Inter Criteria Correlation
DALY	Disability adjusted life years
DCB	Dichlorobenzene
DE	Diatomaceous earth
DEMATEL	Decision-Making Trial and Evaluation Laboratory
EDAS	Evaluation based on Distance from Average Solution

EIPPCB	European Integrated Pollution Prevention and Control Bureau
ELECTRE	Elimination and Choice Expressing Reality
Eq	Equivalent
FA	Fly ash
F-PROMETHEE	Fuzzy Preference Ranking Organization Method for Enrichment Evaluation
GDP	Gross Domestics Product
GCEE	Global Commission on the Economy and Environment
GHG	Greenhouse gas
GPC	Geopolymer concrete
GT	Giga tonnes
GGBFS	Ground granulated blast furnace slag
GWP	Global warming potential
HH	Human health
IFC	International Finance Corporation
IFA	Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung
ILCD	International Reference Life Cycle Data System
IMF	International Monetary Fund
IPCC	Integrated Pollution Prevention and Control
ISO	International Standard Organization
LCA	Life cycle assessment
LCI	Life cycle Inventory
LCIA	Life Cycle Impact Assessment
LCC	Life cycle costing
$LCCO_2$	Life cycle CO_2
LC^3	Limestone Calcined Clay Cement

LOIs	Loss of ignition
LP	Linear Programming
MCDM	Multicriteria Decision making
MILP	Mixed-Integer Linear Programming
MK	Metakaolin
MT	Million/ Mega tonnes
NGO	Non-government organization
NMVOC	Non-methane volatile organic compound
OBM	Oil-Based-Mud
OPC	Ordinary Portland cement
PPC	Pretoria Portland cement
PPM	Part per million
RDF	Refuse derived fuel
RHA	Rice husk ash
SCMs	Supplementary cementing materials
SF	Silica fume
SNCR	Selective non-catalytic reduction
SETAC	Society of environmental toxicology and chemistry
SRF	Solid recycled fuel
SSA	Sub-Saharan Africa
TE	Terrestrial ecosystem
TDF	Tyre derived fuel
Tons	Tonnes
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TS	Traditional scenario

UNFCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
USGS	United State Geological Society
UV	Ultraviolet
VOCs	Volatile organic compounds
VPA	Vitellaria Paradoxa ash
VRM	Vertical Roller Mill
WBCSD	World Business Council for Sustainable Development
WSM	Weighted Sum Model
1,4-DCB	1,4-Dichlorobenzene.

RESEARCH OUTPUTS

This thesis is based on the author's published journal Papers (1-12), book chapters (1), published, unpublished works under consideration for publication. The present author was also presenter at international conferences (I - II) and awards (I - II).

List of journal publications

Out of the published journal articles listed below, Papers (1-5) and conference (I-II) as referred were linked to the objectives of this study as supporting information to compile the Chapters of the thesis.

1. **Busola Dorcas Akintayo,** Damilola Caleb Akintayo, Oludolapo Akanni Olanrewaju, 2023. Material Substitution Strategies for Energy Reduction and Greenhouse Gas Emission in Cement Manufacturing: A Review. *Atmosphere* 2023, *14*(8), 1200; https://doi.org/10.3390/atmos14081200. **(Published)**

2. **Busola Dorcas Akintayo**, Olubayo Moses Babatunde, Oludolapo Akanni Olanrewaju, 2024. Comparative Analysis of Cement Production Methods Using a Life Cycle Assessment and a Multicriteria Decision Making Approach: An Article. *Sustainability* 2024, *16*(2), 484; https://doi.org/10.339 0/su16020484. **(Published)**

3. **Busola Dorcas Akintayo,** Oludolapo Akanni Olanrewaju, Oludolapo Ibrahim Olanrewaju, 2024. Life Cycle Assessment of Ordinary Portland Cement Production in South Africa: Mid Point and End- Point Appr oaches. *Sustainability* 2024, *16*(7), 3001; https://doi.org/10.3390/su16073001. **(Published)**

4. **Busola Dorcas Akintayo,** Damilola Caleb Akintayo, Olubayo Moses Babatunde, Oludolapo Akanni Olanrewaju, 2025. Transforming Industrial Waste into Low-Carbon Cement: A Multi-Criteria Assessment of Supplementary Cementitious Materials for Sustainable Concrete Design. **(Under-review).**

5. **Busola Dorcas Akintayo,** Ogbemhe, John, Olubayo Moses Babatunde, Oludolapo Akanni Olanrewaju, Optimizing Fly Ash Cement Production Using Mixed-Integer Linear Programming and Life Cycle Assessment: A Multi-Plant Strategy for Carbon and Resource Efficiency. Journal of cleaner technologies **(Under-review)**

Other contributions:

6. Ayoninuoluwa Oluwadare, **Busola Dorcas Akintayo**, Olubayo Moses Babatunde, Oludolapo Akanni Olanrewaju, 2024. Assessing the Impact of Healthcare 4.0 Technologies on Healthcare Supply Chain Management: A Multi Criteria Evaluation Framework. *Logistics* 2024, *8*(2), 44; https://doi.org/10.3390/logi stics8020044. **(Published)**

7. Olubayo Babatunde, Michael Emezirinwune, John Adebisi, Khadeejah A Abdulsalam, **Busola Akintayo**, Oludolapo Olanrewaju, 2024. A Fuzzy Multi-Criteria Approach for Selecting Sustainable Power Systems Simulation Software in Undergraduate Education. *Sustainability* 2024, *16*(20), 8994; https://doi.org/10.3390/su16208994. **(Published)**

8. **Busola D Akintayo**, Oluwafemi E Ige, Olubayo M Babatunde, Oludolapo A Olanrewaju**,** 2023. Evaluation and Prioritization of Power-Generating Systems Using a Life Cycle Assessment and a Multicriteria Decision-Making Approach. *Energies* **2023**, *16*(18), 6722; https://doi.org/10.3390/en16186722. **(Published)**

9. Olubayo Moses Babatunde, **Busola Dorcas Akintayo**, Michael Uzoamaka Emezirinwune, Oludolapo Akanni Olanrewaju, 2024. Environmental Impact Assessment of a 1 kW Proton-Exchange Membrane Fuel Cell: A Mid- Point and End- Point Analysis. *Hydrogen* 2024, *5*(2), 352 - 373; https://doi.org/10.3390/hydrogen5020020. **(Published)**

10. Babatunde, O., **Akintayo, B.,** Ighravwe, D., & Olanrewaju, O. (2025). Transdisciplinary approach to accelerate the adoption of hybrid renewable energy systems through sustainable design. *Frontiers in Built Environment*, *11*, 1520883. **(Published)**

11. Olufemi Ogunniran, Olubayo Babatunde, **Busola Dorcas Akintayo**, Kolawole Adisa, Desmond Ighravwe, John Ogbemhe, Oludolapo Akanni Olanrewaju, Risk-Based Optimization of Renewable Energy Investment Portfolios: A Multi-Stage Stochastic Approach to Address Uncertainty *Applied Sciences* 2025, Vol 15, Issue 5, p2346; https://doi.org/10.3390/app15052346. **(Published)**

12. Olubayo Babatunde, Oluwaseye Adedoja, Oluwaseun Oyebode, Uthman Abiola Kareem, Damilola Babatunde, Toyosi Adedoja, **Busola Akintayo**, Michael Emezirinwune, Desmond Eseoghene Ighravwe, Olufemi Ogunniran, Olanrewaju Oludolapo; Techno-Economic Optimization and Assessment of Solar Photovoltaic Battery Hydrogen Energy Systems with Solar Tracking for Powering ICT Facility. *Resources* ***2025****, 14(5), 74; https://doi.org/10.3390/resources14050074.* **(Published).**

13. Kehinde Afolabi, **Busola Akintayo**, Olubayo Babatunde, Uthman Abiola Kareem, John Ogbemhe, Desmond Ighravwe, Olanrewaju Oludolapo; Stochastic Optimization of Quality Assurance Systems in Manufacturing: Integrating Robust and Probabilistic Models for Enhanced Process Performance and Product Reliability. *J. Manuf. Mater. Process.* **2025**, *9*(8), 250; https://doi.org/10.3390/jmmp9080250 **(Published).**

List of book chapters

The book chapter enlisted below contributed to the conceptualization development of this project.

1. Oludolapo Akanni Olanrewaju, Oluwafemi Ezekiel Ige, **Busola Dorcas Akintayo**, Ahad Ali, 2023. Life Cycle Assessment of Natural Gas Power Plant: Calculation of Impact Potentials, intechopen: Climate Smart Greenhouses – Innovations and Impacts, DOI:10.5772/intechopen.113059. 02 November 2023. **(Published).**

List of conference presentations

The author was the main presenter at both the local and international conferences of the papers listed here

I. **BD Akintayo,** OA Olanrewaju, 2025. Utilizing Industrial Waste for Sustainable Concrete: A Critical Analysis of Ground Granulated Blast Furnace Slag in Cement Production. 2024 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). https://ieeexplore.ieee.org/abstract/document/10857161. **(Published)**

II. **BD Akintayo,** OA Olanrewaju, 2025. Industrial Waste for Sustainable Cement Production: A Review on the Use of Fly Ash. 2024 IEEE International Conference on Industrial Engineering and Engineering Manage ment (IEEM) https://ieeexplore.ieee.org/abstract/document/10857252. **(Published)**

List of awards and honours

The author is the recipient of the following awards and accolades

I. DUT bursary

II. Erasmus+ KA171+

III Winner of SANORD Three-minute thesis competition in DUT.

CHAPTER 1

INTRODUCTION

This chapter provides an overview of the thesis structure. It introduces the research context, research problem, research aims, objectives, and key research questions. Additionally, it outlines the hypothesis, justification and benefits of study, background study, methodology, research outputs, and presents the overall framework of the report.

1.1. Introduction

With an average global use of 1 ton of cement each year, the cement sector is one of the most significant worldwide. As the world's population rises, there must be a corresponding increase in cement output. In recent years, the energy consumption of cement alongside its environmental consequences have taken a geometric progression. These environmental issues range from high raw material needs to high energy usage, and greenhouse gas emissions. There has been different recommendation on material replacement that will lead to reduction of the environmental issues. Seeing that an attempt to reduce energy will lead to material replacement and eventually reduction in the greenhouse emission and material used, this study intends to generate a model for a cleaner production of cement by using Mixed-Integer Linear Programming (MILP) model. This will be done by adapting the most economical and viable material replacement recommendation to the model. Thereafter, life cycle assessments will be carried out on the system to know the environmental gains in this new system.

1.2. Context of the Research

Concrete has been around for a long time and is still frequently used as a principal building material around the world. Nearly twelve billion metric tons of concrete are used every year [1-3], making it the lifeblood of the contemporary construction sector. Concrete has been improved over the years by being mixed with various additives to increase its strength, durability, and other desirable qualities [4-7]. To meet the vast global construction needs, Portland cement (PC) is a critical component with massive production and environmental impact [8, 9]. Global cement sector's carbon emissions must be decreased by at least 16% by 2030 to keep the planet within the pre-global warming temperature range of 1.5ºC or 2ºC [10, 11]. Figure 1.1 presents the CO_2 emission per sector. This follows the Paris Agreement of 2015. However, data showed that within the next 30 years, global cement production will increase from the current 4.08 billion tonnes to 5 billion tonnes [12, 13]. This increase is due to the continuous growth of urban land, population, and economic development. According to the Global Commission on the Economy and Environment (GCEE), if developing nations raise their infrastructure to global average levels by 2050, the building industry will release 470 gigatons of CO_2 into the sky.

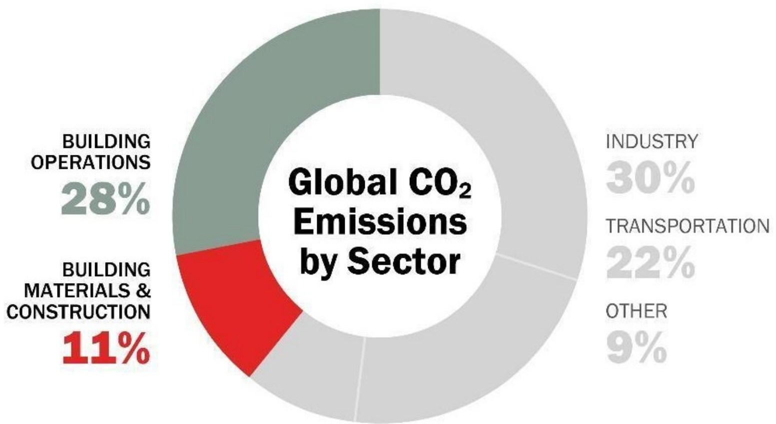


Figure 1.1. Global CO_2 emission per sector [14].

At present, the CO_2 emissions from manufacturing 1 ton of cement amount to about 1 ton. Worldwide, the cement industry is responsible for 7.1% of CO_2 emissions and 2.5% of energy use [15, 16]. Cement contributes to rapid landscape degradation, dust production during transportation, noise generation in quarries, and raw material exhaustion [17, 18], in addition to generating massive amounts of greenhouse gases (such as CO_2, SO_x, and NO_x emissions) and consuming high amounts of energy during the heating process. These are all significant environmental problems that have an essential effect on ecosystems that support human life. It's important to address concerns about these repercussions on the environment, which include high levels of energy usage and carbon dioxide emissions, among others. Figure 1.2 presents the emission of CO_2 between 1960 and 2023.

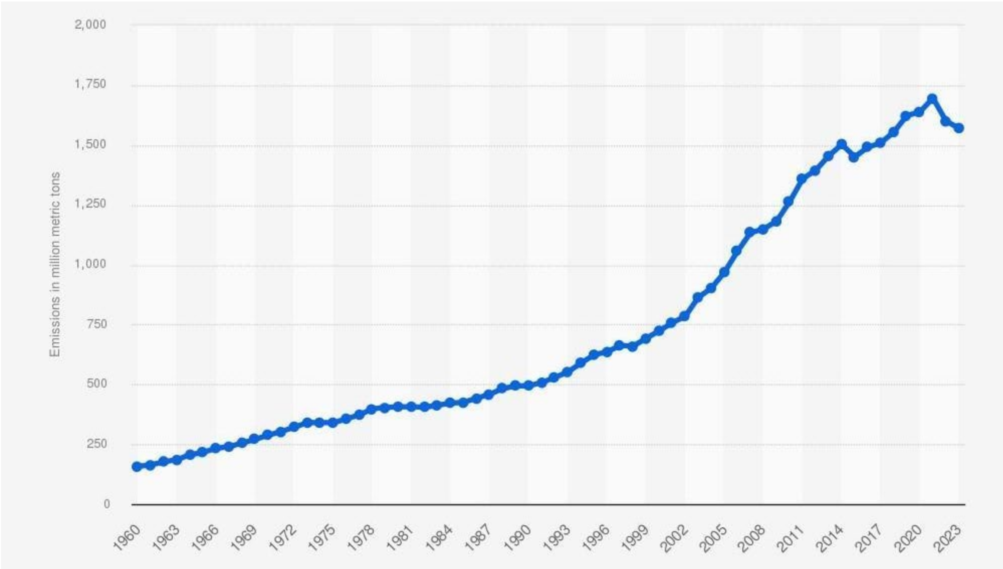


Figure 1.2. Carbon dioxide emissions from the manufacture of cement worldwide from 1960 to 2023 (in million metric tons) [19].

Several groups of scientists are looking at potential replacements for cement that are more environmentally friendly. With so many people using computers in construction, even a small step forward in creating environmentally friendly binders can have a big impact. Cement output may be improved with the use of performance analysis and process parameter monitoring. The innovation in this study is generating a more environmentally friendly model to produce cement using Mixed-Integer Linear Programming (MILP) tool by employing material substitution strategy and a life cycle assessment (LCA) to account for these environmental gains.

1.3 Problem Statement

As earlier delineated, the cement industry is one of the major contributors to global CO_2 emissions, responsible for approximately 7.1% of anthropogenic GHG emissions and 2.5% industrial energy consumption worldwide [20, 21]. With increased urbanization and population growth, global cement demand is expected to rise from

4.08 billion tons to nearly 5 billion tons by 2050 [1, 17]. This rise will escalate environmental implications, including high energy consumption, resource depletion, and significant CO_2 emissions more than at 0.82–1.00 metric tons per ton of cement [22-24].

Regardless of the wide-ranging research on supplementary cementitious materials (SCMs) such as fly ash (FA), ground granulated blast furnace slag (GGBFS), and agricultural waste by-products like shea nutshell ash, a critical gap remains in optimizing their substitution proportions to guarantee sustainability without undermining cement quality [25, 26]. Many existing studies often address standalone aspects such as environmental impact, cost, or mechanical performance without incorporating these dimensions into an integrated and practical decision-making framework [27, 28]. Furthermore, while Life Cycle Assessment (LCA) methods are useful for estimating environmental benefits, they rarely consider real-world operational constraints such as material availability, production scalability, and cost fluctuations [29, 30]. This study addresses these gaps by developing a Mixed-Integer Linear Programming (MILP) model to optimize SCM substitution in cement production. The model integrates LCA, multi-criteria decision-making (MCDM), and economic viability analysis to propose a realistic and scalable approach that reduces emissions and resource use while maintaining the structural integrity and economic feasibility of cement.

1.4. Research Aims, objective and questions.

This research aims to develop an optimized model for supplementary cementitious material (SCM) substitution in cement production using Mixed-Integer Linear Programming (MILP), with a focus on minimizing environmental impacts assessed through Life Cycle Assessment (LCA) and ensuring economic and technical viability, thereby enabling cleaner and more sustainable cement production.

This study aims to answer the following research questions:

- Is the current state of cement production sustainable?
- What are the sustainable drivers to achieving cleaner cement production?
- What environmental impacts are these drivers likely to address to assure cleaner production of cement?

- What is the assurance that these drivers when incorporated into cement production would maintain quality cement production?
- How economically viable are these drivers?
- How can industrial waste be valorised to support sustainable and cleaner production in the cement industry?

The objectives of this study are:

- To analyse the environmental impacts of cement production in supply chain management using Life Cycle Assessment (LCA) and mid-point and endpoint Life Cycle Impact Assessment (LCIA) methodologies.
- To assess the effectiveness of material substitution strategies in reducing energy consumption and greenhouse gas emissions in cement manufacturing through a systematic review of recent advancements.
- To evaluate and compare the environmental impacts of different cement production methods using an integrated Life Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM) approach to identify the most sustainable alternative.
- To investigate the potential of industrial waste as supplementary cementitious materials (SCMs) and assess their applicability in achieving cleaner and more sustainable cement production processes.
- To develop and optimize a Mixed-Integer Linear Programming (MILP) model for adaptive fly ash substitution strategies in cement production, aiming to minimize carbon emissions and energy consumption while ensuring production efficiency, economic viability, compliance with operational constraint and standards, and not compromising the quality of cement; thereafter conduct an impact assessment to know the environmental gains.
-

1.5 Hypothesis

The study is guided by two contrasting hypotheses:

- Null Hypothesis (H_0): The integration of optimized material substitution strategy FA in cement production neither generate statistically substantial reductions in CO_2 emissions or energy consumption compared to conventional Portland cement, nor does it improve mechanical performance.

- Alternative Hypothesis (H_1): The MILP-optimized cement production model, leveraging on SCMs, significantly reduces CO_2 emissions and energy consumption while preserving or enhancing mechanical properties, presenting a sustainable alternative to traditional methods.

These hypotheses will be tested through comparative LCA, mechanical performance analysis, and cost-benefit assessments, ensuring empirical justification of the proposed model.

1.6. Justification and Benefits of the Study.

The urgent need for mitigating climate change and attaining net-zero emissions by 2050 emphasizes the need for sustainable cement production [25]. This research offers three key contributions:

- Environmental Sustainability: The study is in alignment with the Paris Agreement's obligation to reduce cement sector emissions by 16% by 2030 [10]. Through the optimization of the use of SCM, the model could reduce CO_2 emissions by 13–22% per ton of cement [26] and lower energy consumption by 20–67% [27]. For instance, substituting 50% of Portland cement with FA or GGBFS minimizes clinker production which is the most carbon-intensive phase [28].
- Economic and Industrial Viability: SCMs like FA and shea nutshell ash are often low-cost and also waste-derived, reducing material expenditures by 33–80% [29, 30]. The MILP model accounts for supply chain instability, ensuring possibility of industries in developing regions where demands for infrastructure are rising [31, 32].
- Policy and Academic Advancements: The combination of MILP with LCA provides a novel methodological framework for sustainable material science, environmental science, bridging

engineering, and economics [33, 34]. Policymakers can take advantage of the findings to incentivize green cement implementation, while industries benefit a tool for compliance with carbon taxation and circular economy mandates [35, 36].

1.7. Background study

Demand for Portland cement (PC) in the construction industry has risen because of increased population growth and urbanization. This in turn has increased energy use and environmental damage in built natural-environment [37-39]. PC is widely used as a binder in the construction industry to make concrete [40, 41]. However, as PC manufacturing has advanced, so have the environmental consequences like global warming, climate change among many others. The limestone heating for clinker formation in PC manufacture is a major source of energy generation, accounting for around 7% of global anthropogenic carbon dioxide (CO_2) emissions [21, 42, 43] and 14% of global energy consumption from the industrial sector [20]. Figure 1.5 represents a pictorial representation of global annual CO_2 emission and figure 1.4 is the graphical representation of selected country.

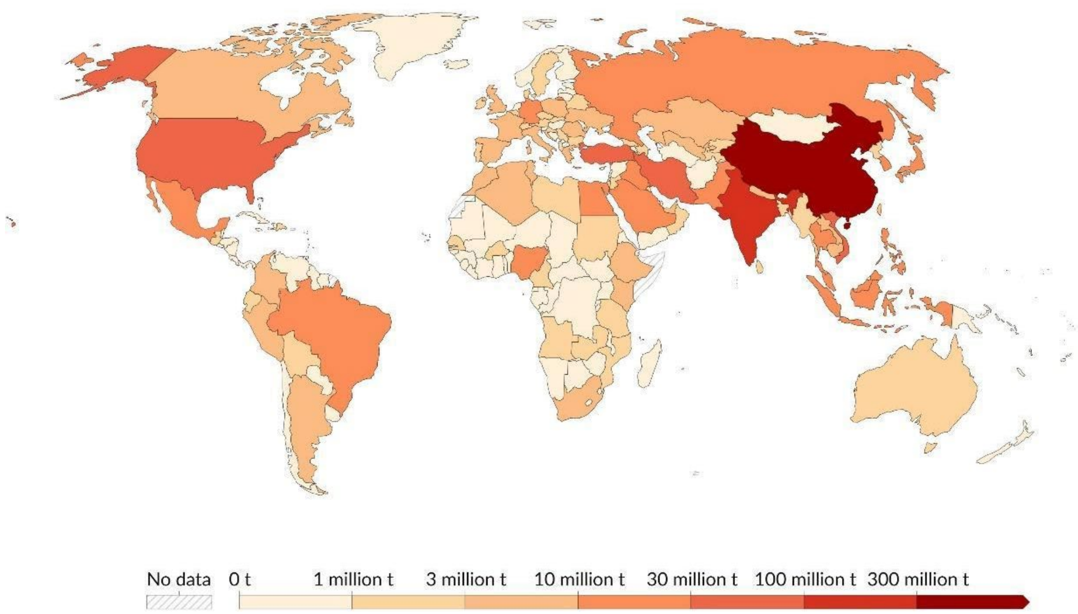


Figure 1.3. Global annual emission from cement production [29].

In addition, it has been reported by Huntzinger and Eatmon [22], Li et al. [23], Maji and Adamu [44], and Peng et al. [45] that each ton of PC produced results in CO_2 emissions of between 0.82 and 1.00 metric tons. An important fact to keep in mind is that buildings use up about 40% of global energy output [46, 47]. Over time, both the quantity of energy needed and the ecological toll of producing that energy rise [48-50].

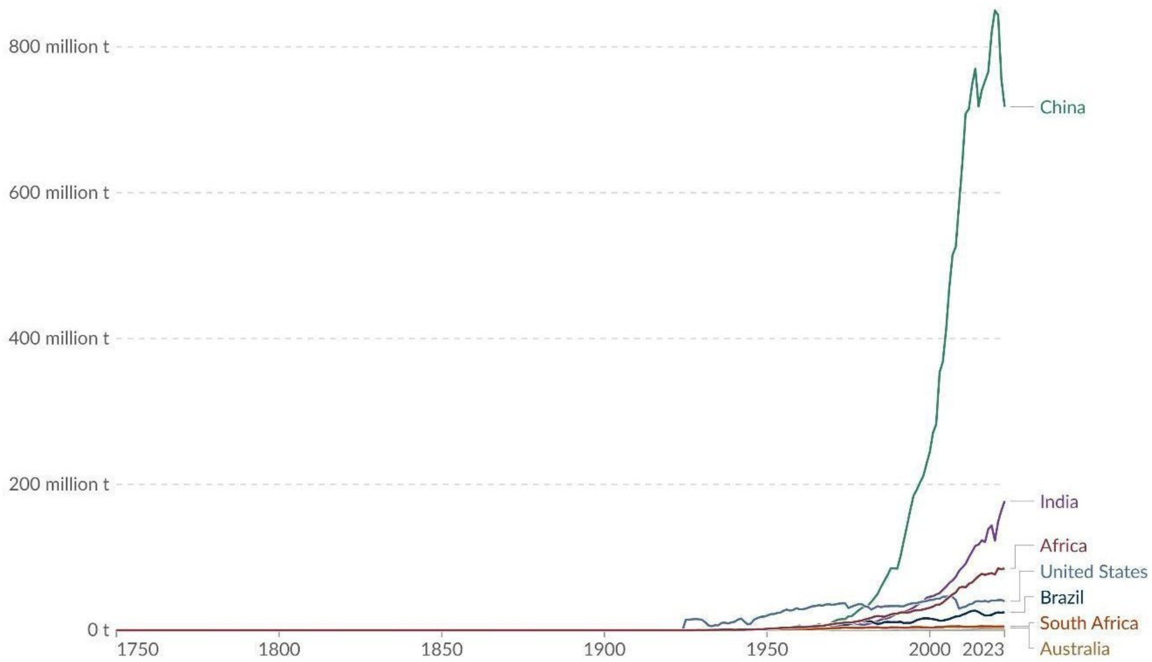


Figure 1.4. Annual CO_2 emission from cement production [29].

About 80% of greenhouse gas (GHG) emissions and energy consumption are released during a building's operating stage, as determined by Fernando et al. [50][38]. Importantly, rising GHG levels are the root cause of climate change. The increased production and use of PC and concrete led to approximately 54 $GtCO_2$-eq of emissions in 2017.

As a result, PC substitutes are viewed as the most practical choices for sustainable concrete production in the construction industry to reduce greenhouse gas emissions [24, 37, 38], which are associated with the building's operating energy and embodied energy materials. Utilizing agro-industrial by-products is one of such option. Supplementary cementitious materials (SCMs), which include agro-industrial waste materials, are more environmentally friendly than PC because they produce lower greenhouse gas emissions [35]. It has been suggested that using blended cement concrete (BCC) can lessen the need for Portland cement concrete (PCC) and the emissions that come from using PCC. In blended cement, SCMs such as fly ash (FA), rice husk ash (RHA), corncob ash (CCA), silica fume (SF), and ground granulated blast furnace slag (GGBFS) are used to replace some of the Portland cement. SCMs have been shown to reduce energy consumption and environmental impacts in the construction industry [49, 51-53], all of which aid in energy and environmental preservation and sustainable development. To enhance concrete qualities and environmental consequences, SCMs are increasingly being used in place of PC [53, 54]. It's interesting to note that by substituting 25-50 wt% SCMs for a PC, energy consumption may be reduced by 20-67% and material costs can be cut by 33-80% [27]. As an additional bonus, when SCMs are used in place of PC, emissions of carbon dioxide decrease between 13 and 22 percent, as indicated by Flower and Sanjayan [26]. Carbon dioxide emission reductions, as reported by Ali et al. [43], are sensitive to blend quantities of SCMs, raw material sources, and manufacturing procedures. With regards to durability, composite concrete modified SCMs such as GGBFS, CCA, fly ash, RHA, SF, and metakaolin (MK) have proven to be superior to PCC in terms of acidic and sulfate resistances [51, 55-58].

In 2017, shea nuts were produced at a global level of about 0.55 million metric tonnes [59][50]. Vaporization of the shea nutshell yields shea nutshell ash (Vitellaria Paradoxa ash [VPA]), while shea nuts are used to make shea butter [60]. Savannas in southern and eastern Africa are rich in shea trees [61]. According to estimates, the shea industry harvests around 16.2 million shea nuts annually, with Africa and West Africa accounting for 1,760,000 and 680,000 metric tonnes, respectively [62]. Shea nuts have monetary and nutritional value, but there is a growing worry that their careless disposal after shelling poses a threat to the environment. Methane (CH_4) emissions are a serious problem caused by this careless waste disposal. Since its GWP per molecule is 21 times that of carbon dioxide (CO_2) [62], recycling it in a way that is both environmentally friendly and effective is a formidable intellectual problem. According to both Hatskevich et al. [63] and Rousseau et al. [32], construction is a sector with a realistic opportunity to value-add shea nutshells for construction purposes.

Till date shea nutshell has no market value; it ends up in landfills where it pollutes the earth's ecosystems. Recent research has focused on finding ways to lessen the operational embodied energy (EE) and embodied carbon dioxide emissions (EC) of building materials. Using a cradle-to-grave framework, embodied energy quantifies the total amount of energy used in all processes involving the material [64].
Cradle-to-gate, as defined by Hammond and Jones [64], encompasses the entire life cycle of a product, from its initial creation through its ultimate disposal in the industry gate. In addition, EC totals the carbon emissions from fuels without considering the feedstock's embodied energy. Cement production contributed about 4.1 Gt to the nearly 33 Gt of worldwide energy-related CO_2 emissions in 2019 [25].

Moreover, the building industry is responsible for over 40% of CO_2 emissions (both direct and indirect) and uses about 33.33% of the world's total energy [64]. In addition, estimates for 2021 indicate an approximately 4.8% [60] rise in worldwide energy-related CO_2 emissions [65]. However, with rising demand comes increased difficulty in simultaneously cutting back on world energy-related CO_2 emissions and meeting cement needs. Through 2030, annual cement production is predicted to rise at a steady rate, without diminishing demand. By leveraging agro-industrial symbiosis opportunities, such as the use of alternative binding materials and waste or by-products to make another value product [66], 0.8% annual drop and getting back on track with the 2030 sustainable development target may be achieved. These would aid in decreasing energy embodiments and carbon dioxide emissions [33, 36]. As a result, both GTs can be drastically cut by switching to SCMs from PCs. For their study, Abubakar et al. [30] assessed the CCA-modified concrete's EE and EC. According to the data, both EE and EC dropped as the CCA concentration in the mixtures rose. Gonz'alez and Navarro [31] estimated that low impact building materials might cut CO_2 emissions by 30%. Figure 1.5. shows the percentage usage of SCM in the cement industry over the years.

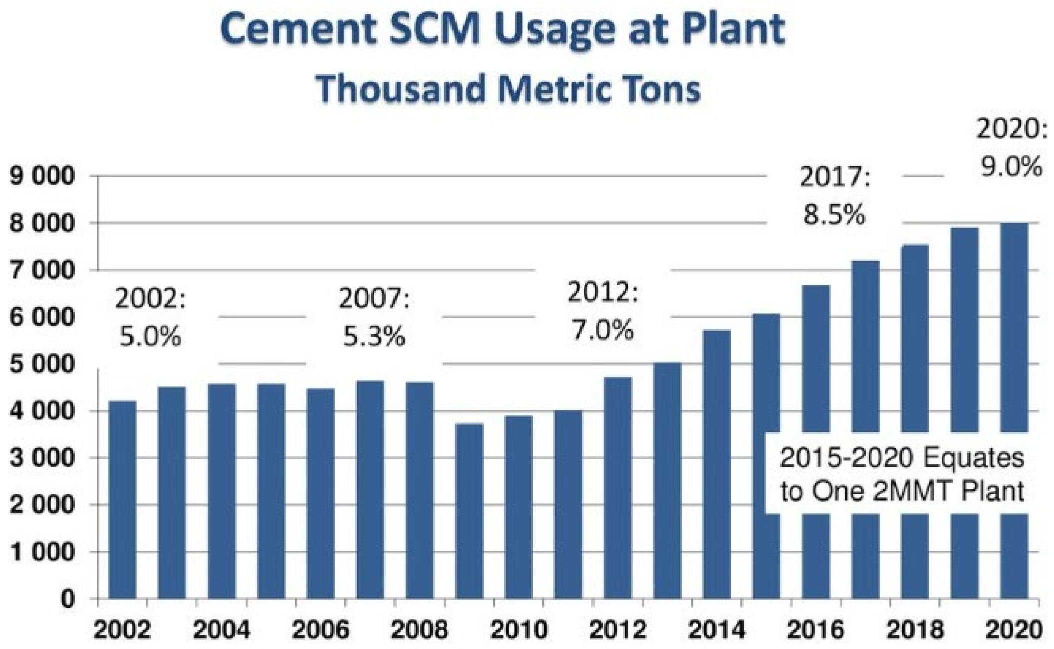


Figure 1.5. Cement SCM percentage usage over the years [67].

The environmental impact of binders and concrete can be drastically reduced by using materials with low embodied carbon and low energy, as indicated by Coffetti et al. [34]. Considering the growing importance of environmental and economic considerations in international research and policy, an evaluation of blended cement concrete (BCC) is crucial from a sustainability perspective. With so much SCMs that has been recommended to both reduce emission and energy consumption when incorporated, there is need therefore to create models indicating the quantity of required SCMs necessary to produce quality cement, demand minimal cost, yet sustainable in nature.

1.8. Research Methodology

To create a model depicting cleaner production in the cement industry, this study employed a quantitative strategy. To safeguard human health and natural habitats at the lowest possible cost, sustainable environmental engineers study, develop, and construct environmental engineering infrastructure systems that work in harmony with nature. This study incorporated optimization algorithm technique to provide a better model for potentially optimal/cleaner cement production. This was achieved by using variable of reducing energy consumption, which in turn led to the replacement of materials; this will consequently connote a decrease in greenhouse gases (GHG) and the pressure on resource usage. The environmental implications of the new system were thereafter measured using LCA. All the materials, from fuel to raw materials required for cement production, was analysed to determine the most cost-effective and high-quality alternatives. As a result, both energy use and emissions of GHG will decrease. After implementing methods and recommendations to reduce energy consumption, an LCA was performed on the updated system or manufacturing process to evaluate the system's environmental benefits relative to those described in the literature.

Optimization is a way of finding the very best solution that exists for a particular mathematical problem. Typically, optimization models make use of objective function which can either be minimized or maximized to be able to solve the mathematical problem [68]. The objective function is guided by prenoted constraints on the variables of the problem within a feasible set. Generally, mathematical optimization problem can be presented as:

$$\text{Minimize } a(x), \text{ subject to } d(x) \leq c, \tag{1.1}$$

Where x the entity variable to be optimized, a on the other hand is the objective function to be minimized in this case. It could also be a scenario of maximization, d is the constraint function which could be equality or inequality, c is the limit or boundary for constraint function. Linear programming (LP) is one in which the objective function and constraint function must have a linear relationship. The objective function is often written as:

$$\text{Minimize } k^U x, \tag{1.2}$$

$$\text{Subject to } Px \leq i \qquad \text{Where } x \geq 0$$

X is the entity that constrains the optimization variable, where x is the vector containing the optimization variables, P is a coefficient matrix, and k and i are vectors [69].

Mixed-Integer Linear Programming (MILP) as the name implies gives room for several integers. It is one of the variants of LP in which most or the variables are restricted to the integers. Considering that there are several variables in this study, a mixed would be Mixed-Integer Linear Programming (MILP) tool to be used for model formation in this study. Different solvers can be used in MILP, including baron, cplex, conopt, gurobi, knitro, path, snopt, and xa, may be easily modified to work with [68]. Additionally, uncertainty data can be into models using ideas like stochastic programming and robust optimization. Afterwards, these systems can function as either independent programs or integral parts of a larger optimization scheme [70]. In this study, material replacement strategies were employed that would minimize energy consumption, reduce the greenhouse gas emission and pressure on resource usage. However, this will be on the condition that the quality cement produced remains uncompromised and there is no increase in the price of cement (constraints). Life Cycle assessment (LCA) can be used to evaluate the environmental and economic impacts of a product or production/ manufacturing process; giving scientists more data with which to evaluate the material and develop methods to make it more sustainably manufactured. According to ISO [71], a life cycle assessment is an established and analytical method used to analyse the environmental impacts of a product over the course of its entire existence; more reason why it will be used to evaluate the environmental gains of the new system having incorporated the model.

1.9. Thesis Structure and Layout

This thesis consists of 9 chapters, as shown in Figure 1.6, with a clear framework linking the study objectives to the papers in each chapter. Each chapter begins with a brief remark (abstract) that gives the reader an overview of the content and its relevance to the thesis. The chapters are structured as follows:

Chapter 1: *Introduction:* This introductory chapter provides a comprehensive overview, background information, the problem statement, and the conceptualisation of the research. It justifies the urgent need to mitigate the environmental impact the results from the continuous production of cement using efficient and economically viable supplementary cementitious materials

Chapter 2: *Life Cycle Assessment of Ordinary Portland Cement Production in South Africa: Mid Point and End- Point Approaches . (Paper 3):* This chapter presents a life cycle assessment of a typical south African cement plant. It presents the environmental impact of cement production on humans (South African), ecosystem and fossil fuels. It further enlightens on the need for mitigation. This Chapter is linked to objective 1.

Chapter 3: *Material Substitution Strategies for Energy Reduction and Greenhouse Gas Emission in Cement Manufacturing: A Review. (Paper 1):* This chapter carried out a state of- art review on the available material replacement strategies for greenhouse gas emission and energy reduction. This chapter is linked to objective 2.

Chapter 4: *Comparative Analysis of Cement Production Methods Using a Life Cycle Assessment and a Multicriteria Decision Making Approach (Paper 2):* This chapter addresses objective 3 where a comparative life cycle analysis of ten cement production process is presented to know the plant with lowest environmental impacts having seen the recommended material replacement strategies in the previous chapter. This study employs the integration of Life Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM).

Chapter 5: *Transforming Industrial Waste into Low-Carbon Cement: A Multi-Criteria Assessment of Supplementary Cementitious Materials for Sustainable Concrete Design. (CF paper I&II, Paper 4):* Aligned with objective 4, this chapter provides insights into the diverse agro-industrial by-products and industrial which includes ground granulated blast furnace slag (GGBFS), fly ash, silica fume, red mud, biomass ash, metakaolin, amongst many others for their suitability as SCMs Using a robust multi-criteria framework.

Chapter 6: *Minimizing Carbon Footprint in Cement Production: A Robust MILP Model for Adaptive Fly Ash Substitution Strategies. (paper 4):* Objective 5 develops a mixed-integer linear programming model to adapt substitution strategy and carried out LCA to see the environmental gains

Chapter 7: *Conclusion:* This concluding chapter summarises the study's overall findings and implications and provides recommendations for further research based on the research outcomes.

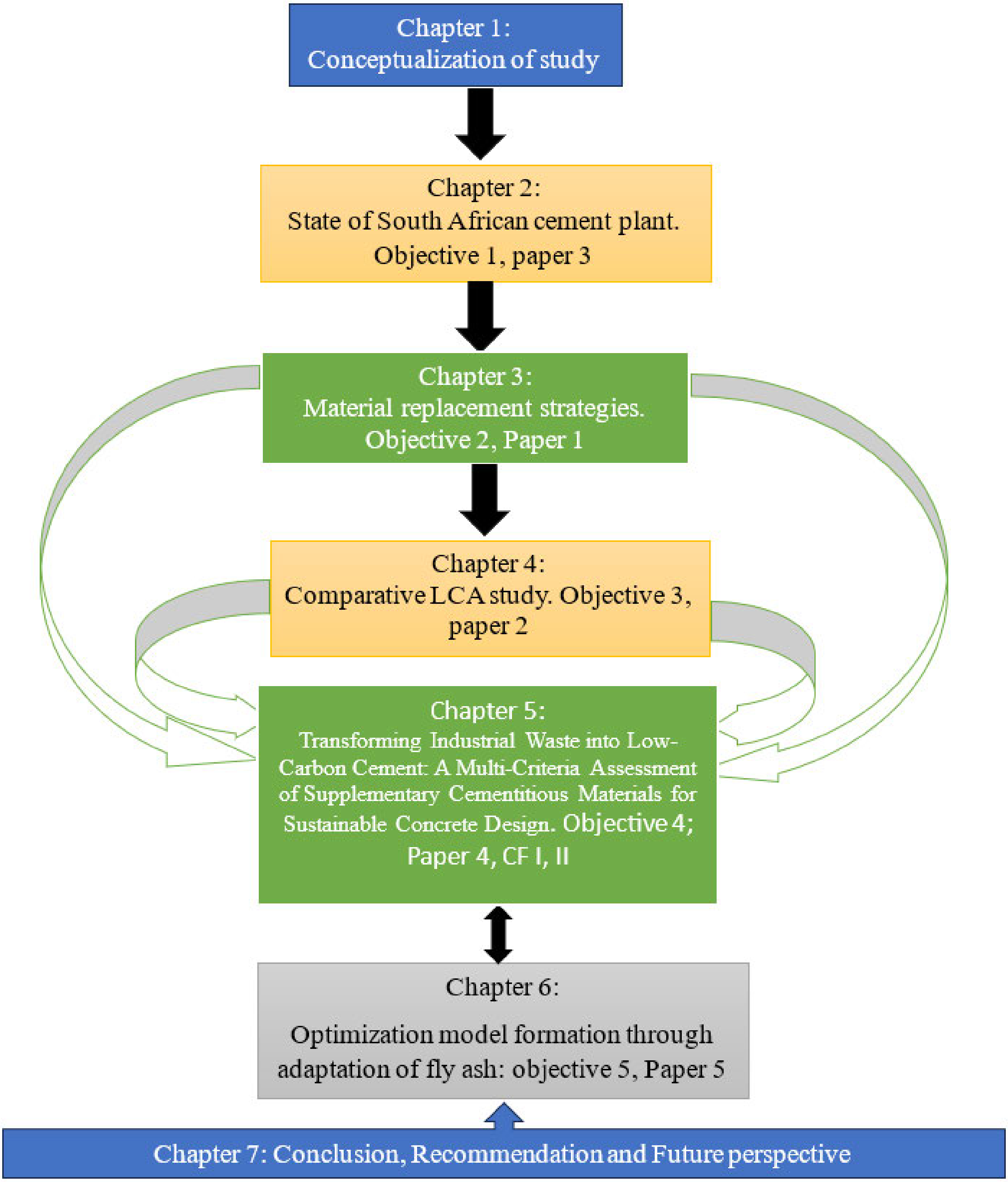


Figure 1.6. Pictorial representation of thesis layout, linking objectives and papers to chapters.

1.10 Contribution of the thesis to knowledge

This doctoral research presents a novel and holistic framework for fostering cleaner production in the cement industry, with a specific focus on South Africa. It enhances academic and practical understanding in several major areas:

1.10.1. Comprehensive Life Cycle Assessment (LCA) of South African cement plants

- This thesis provides one of the most detailed cradle-to-gate environmental assessments of Ordinary Portland Cement (OPC) production in South Africa using both midpoint and endpoint LCIA approaches.
- It quantifies emissions, resource depletion, human health and ecological dangers filling a key data gap in the South African cement industry research.
- The analysis presents localized insight into the environmental hot spots in cement production, which can inform sustainability policies and regulatory standards across Sub-Saharan Africa.

1.10.2. Integrated material substitution strategy evaluation

- The research integrates broad empirical data and literature to evaluate the effectiveness of the total and partial substitution of cement materials using supplementary cementitious materials (SCMs) and industrial waste.
- It shows that material substitutions (1%–60%) can reduce GHG emissions by up to 94% and energy use by up to 40%, emphasizing their benefits and applicability for sustainable cement production.

1.10.3. Application of Multi-Criteria Decision-Making (MCDM) techniques

- By combining LCA with advanced MCDM methods (TOPSIS and EDAS), the study presents a novel methodology to rank cement production alternatives.
- The blend of LCA and CRITIC weighting in evaluating environmental performance of ten cement production methods is a substantial methodological innovation, identifying GGBFS-based cement as most sustainable.

1.10.4. Valorisation framework for industrial waste as SCMs

- A two-step framework was developed to screen, score, and rank over 27 potential SCMs based on technical, environmental, economic, and regulatory criteria.
- Fly ash, GGBFS, silica fume, calcined clay, and metakaolin were identified as the most promising. This work promotes the waste valorisation circular economy agenda in construction materials.

1.10.5. Optimization through Mixed-Integer Linear Programming (MILP)

- A robust MILP model was formulated to optimize fly ash substitution, ensuring minimal environmental impact while preserving production efficiency and cement quality.
- The model established that 30%–40% fly ash replacement can cut CO_2 emissions by 33% and energy use by 19.8%. This provides a practical tool for operational decision-making in cement industry.

1.10.6. Empirical Validation and Real-World Application

- The findings were validated using case studies and data, bridging the gap between theory and practice.
- The integration of policy implications, sensitivity evaluation, and uncertainty analysis improves the relevance and robustness of the work to stakeholders including researchers, manufacturers, and policymakers.

1.10.7. Methodological and theoretical innovation

- The research pioneers the incorporation of LCA, MCDM, and MILP in one unified study for cleaner cement production.
- It offers a cross-disciplinarily linking operations research, industrial sustainability, and environmental engineering presenting a template for similar applications in other sectors.

1.10.8. Significant academic outputs and recognition

- The thesis resulted in multiple peer-reviewed journal publications, book chapters, and conference presentations, demonstrating its scholarly impact.
- It has also been supported by prestigious scholarships and exchange programs (e.g., DUT bursary, Erasmus+KA171+), confirming its academic merit and global relevance.

In Summary, this thesis makes original contributions to knowledge by:

- Filling key data gaps in South African cement sustainability studies.
- Validating and proposing novel tools for environmental optimization.
- Incorporating interdisciplinary methods for real-world impact.
- Supporting global decarbonization targets under the Paris Agreement.

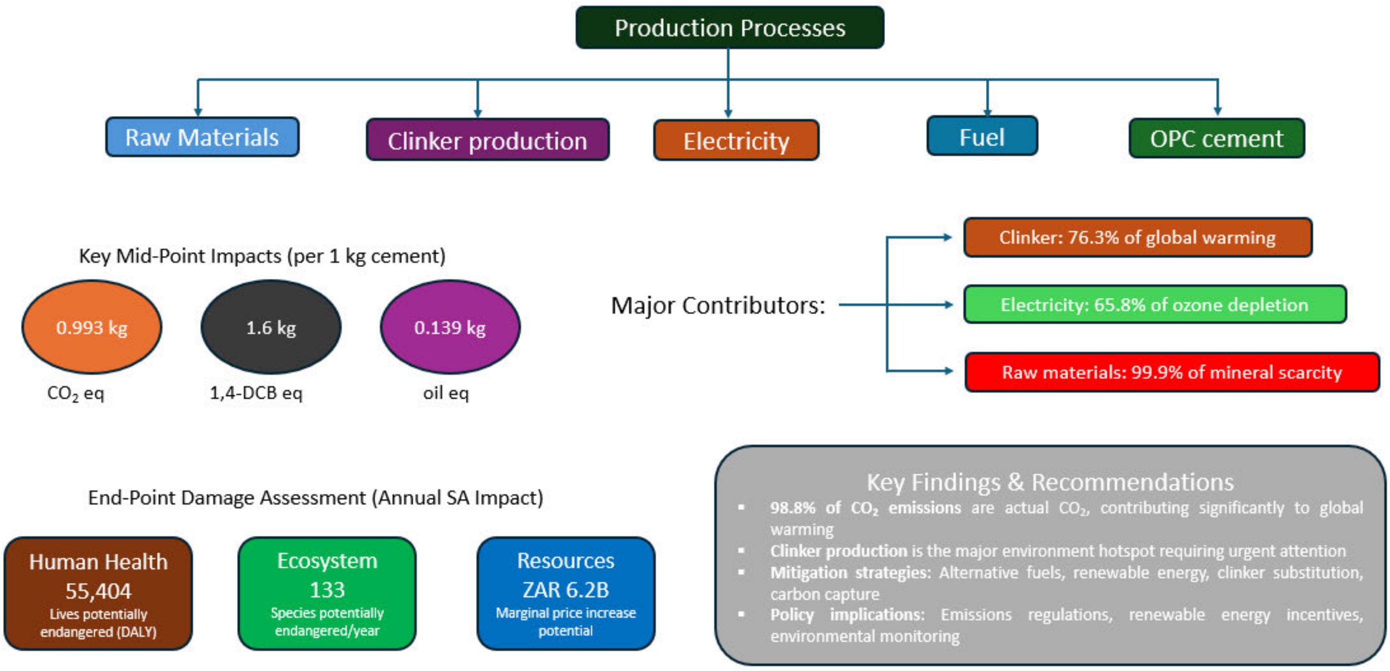
It sets a benchmark for future studies on sustainable industrial production and environmental decision support systems in emerging economies.

CHAPTER 2

LIFE CYCLE ASSESSMENT OF ORDINARY PORTLAND CEMENT PRODUCTION IN SOUTH AFRICA: MID-POINT AND END-POINT APPROACHES

In this chapter, an analysis of the production model of South African (SA) cement plants was carried out to quantify its impacts and decipher how they consequently affect lives, resources, and the ecosystem. This chapter begins by giving a brief overview of the cement industry and particularly the South African cement industry. Several environmental impacts are associated with cement production, ranging from high greenhouse gas (GHG) levels to high energy consumption (fossil fuel and electricity) to high resource usage. Due to the growing demand for cement in the industry and limited studies in South Africa, it is essential to evaluate the environmental impact to understand the state of cement production in a typical South African cement plant. The content in this chapter being a published article was co-authored with Oludolapo A. Olanrewaju and Oludolapo Ibrahim Olanrewaju in atmosphere [72].

GRAPHICAL ABSTRACT



2.1 Introduction

The global landscape is currently undergoing a substantial change in population growth, leading to the increasing migration of individuals to urban areas, and thus, resulting in the growing need for infrastructure and housing, which therefore establishes the construction industry to play a crucial role in influencing the trajectory of global development [73]. In 2019, the global production of cement reached a staggering 4.2 billion tons [74], with projections indicating a possible moderate growth rate of 1.3-1.4% over the next decade, resulting in an estimated production volume of 4.83 billion metric tonnes by the year 2030. Cement, being an essential construction material, plays a pivotal role in meeting the increasing demands of the construction sector, by offering the necessary structural integrity to support the growing populations and urban development. Despite the importance of the cement industry for the sustainability of environmental development, its manufacture has had various environmental consequences such as high energy consumption, excessive use of raw materials and noteworthy global warming. This results in the alteration of climatic conditions, due to the significant GHG emissions in the atmosphere that affect lives including human beings and other species. The cement industry has been reported to be responsible for approximately 12-15 % of the overall energy consumption in the global industrial sector [75], with the cost of energy being about 20-40% of the entire production cost [76]. In 2018, cement was reported to account for around 8% of global carbon dioxide (CO_2) emissions, 5% of which can be attributed to emissions generated during the production process, excluding those resulting from energy generation [77]. Given the environmental concerns raised about the cement industry, researchers have engaged in various life cycle assessment (LCA) studies for cement production.

The use of LCA for the assessment of the environmental impacts of the process of manufacturing cement has been explored by different scientists in various parts of the world. According to the results of an LCA study, which employed the use of a plant to produce two types of OPC in Brazil [78], transportation, clinker and fossil fuel production were responsible for more than 70% of CO_2 equivalent and 90% of CFC-11 equivalent. In 2014, the LCA conducted by [79] for cement and clinker produced from 11 plants in Italy showed that over

85% of the total CO_2 was from clinker production, while over 79% was from the entire production process. Their result further showed that cement production accounted for 793 kg/Milligram of global warming potential. They also suggested that over 95% of the energy source of a cement plant in Italy was from a non-renewable primary energy source. In another study, [80] observed that the cement production process was the major emitter of about 4.92 GT of CO_2 emissions, contributing about 94.7% of the entire emissions caused by the South African (SA) concrete industry for an average of 45.4 MT of concrete produced yearly in SA between 2005 and 2008. Just recently in 2019, the world ranking showed South Africa to be among the top eight countries and the first in the continent of Africa, in relation to the emission of GHGs, and this could be attributed to the dependence on the use of coal [81]. In South Africa, industries like cement are known to play a crucial role in the achievement of the developmental goals set by the government, for the reduction of the emission of GHGs. Notwithstanding, the cement industry remains one of the highest GHG emitters in the country, accounting for approximately 1% of the total emitted GHGs [82]. Thus, the environmental impact of the cement manufacturing process in South Africa, cannot be overemphasized, and this heralds the need for LCA studies which can help reduce these emissions.

Generally, South African cement plants make use of the dry process and therefore produce only the "Ordinary Portland Cement (OPC) and blended cement Products" [83]. In different parts of the world, LCA studies on OPC, have focused on the use of alternative fuels [20, 78]; environmental performance of different concrete mixes [84]; the use of waste materials in cement production [85]; and the assessment of the environmental impacts of the production process of cement in different geographical context [86]. However, in South Africa, only a few literatures are available on the use of LCA for OPC [82, 83], which gives room for more studies to be carried out. Thus, this study seeks to fill this gap by exploring the environmental impacts of OPC production in SA using a problem and damage-oriented approach, with the view of providing policymakers with possible pathways to help reduce the impact of cement production on the environment in South Africa.

Additionally, no studies have combined this assessment with an uncertainty analysis and projected annual impacts on human health, ecosystems, and resources based on South Africa's population and cement demand.

This research fills these gaps by providing a comprehensive LCA integrating midpoint categories, endpoint damages, uncertainty analysis, and projected nationwide impacts. The study also discusses difficulties in conducting LCA in Africa such as lack of localized life cycle inventory databases. By utilizing the best available secondary data coupled with sensitivity analysis, this research provides valuable insights into environmental hotspots that can inform emissions regulations and sustainability initiatives for the South African cement industry. The findings present potential pathways for enhancing efficiency and adopting cleaner production technologies to mitigate future impacts.

2.1.1. Cement in the Sub-Saharan Africa (SSA) Region

One of the most energy-intensive industries is the cement industry, as the cost of energy is about 20-40% of the entire production cost. This energy is often more frequently utilized as fuel for the calcination process and as electricity for pulverizing the resources and even the cement itself. The energy consumed is about 4-5GJ/ton which amounts to 8-10EJ annually [76]. In 2004, about 75 cement plants were in operation, as seen in Table 2.1. Many of these plants were in Zimbabwe, Tanzania, SA, Senegal, Nigeria, Kenya, and Ethiopia. Africa's market growth was about 9.4% in 2006, which gave producers space to increase their market share and expand their plant capacities. Also, the cement industry accounted for about 5-8% of the global anthropogenic CO_2 gas annually; while half of this CO_2 was from clinker production, the other half was from fossil fuels. It was, therefore, a major emitter of greenhouse gas and this made CO_2 mitigation important for this industry. According to a US Geological Survey (USGS) [87], data available from 2006 showed that cement plant capacity in SSA (excluding SA) was 41.6 Mtpa and had 45 MTs capacity in 2004 from about 75 plants in the continent, including SA as shown in Table 2.2.

Table 2.1. Sub-Saharan Africa's Leading Cement Producers by 2013 Capacity [88].

Company	Production capacity **(MTs)**	Countries of operation in SSA
Dangote cement	20.7	Nigeria, Benin, Cameroon, Senegal, Cote d'Ivoire, Sierra Leon, Liberia,

		Ghana, Congo- Brazzaville, Etiopia, Kenya, Tanzania, Zambia, South África
Lafarge	19.5	Nigeria, Benín, Cameroon, Kenya, Tanzania, Zambia, South Africa, Uganda, Malawi, Mozambique, Botswana, Zimbabwe
PPC	18.0	South Africa, Zimbabwe, Botswana
Heigelberg	6.7	Sierra León, Liberia, Ghana, Tanzania, Benín, Gabon, Togo
AfriSam	5.8	South Africa, Lesotho, Botswana, Tanzania, Swaziland
ARM cement	5.5	Tanzania, South Africa, Kenya, Rwanda
Sococim	4.2	Senegal
Holcim	3.0	Nigeria, Cote d'Ivoire, Morocco, Tanzania, South Africa, Guinea
Derba Midroc Cement	2.5	Ethiopia
WACEM	2.0	Ghana, Togo

Table 2.2. Breakdown of Cement Plants and Installed Capacity in SSA [87].

Region	No. of Plants	Production Capacity (tons)	Actual Production (tons)	Capacity Utilization
West Africa	29	19,241,000	8,779,130	46%
Central Africa	11	3,613,000	1,720,000	48%
East Africa	29	8,954,000	6,768,110	76%
Southern Africa	6	13,145,000	12,348,000	94%
Total	75	44,953,000	29,615,240	66%

West and East Africa had 29 cement plants each, showing that most of the cement workstations were situated in these regions. The Central African region and Southern African (majorly South Africa) region had 11 and

6 plants, respectively. Many of the plants were in the following countries: SA, Kenya, Nigeria, Zimbabwe, Ethiopia, Ghana, Senegal, and Tanzania. The cement industry had its thrust in Nigeria with about nine plant stations and a capacity of 9.75Mtpa, which was about 51% of the production capacity of West Africa. In East Africa, however, Kenya was taking the lead with about 2.75Mt capacity, and Cameroon in the central African region was ahead with 1.2Mt production capacity in the year 2004. In 2004, the total amount of cement produced in Africa, excluding SA, was 17.3Mt, and West Africa accounted for about 51% of this production, followed by 39% in East Africa, then Central Africa with 10%. The 51%, which was about 2.1MTs, from West Africa was majorly from Nigeria, Ghana, and Senegal. Excluding SA, the capacity utilization in the rest of SSA cement was low (54%) as of 2004 when compared with that of India and SA, which was around 80-94%. Different regions varied in their consumption; while East Africa had a capacity utilization of about 76%, West Africa had 46%, and Central Africa had 48%.

Nigeria's utilization capacity was as low as 22%. In East and Central Africa, the specific energy consumption of the plants varied from 105 to 140 kWh/ton and 800 to 1,000 kcal/kg of clinker for specific thermal energy and was distributed majorly in West Africa and East Africa and accounted for about 46% and 42% respectively. In these regions, the major countries with the potential to cause high CO_2 emissions were Tanzania, Nigeria, Ethiopia, Kenya, and Senegal. As one of the most expensive inputs in the cement production process, energy could reduce the entire production cost of cement if it was used more efficiently. Particular attention should be paid to countries with high production capacity in different regions to improve the plants' energy consumption efficiency and effectiveness. Such countries are Togo, Nigeria, and Senegal in West Africa, and Tanzania, Kenya, and Ethiopia in East Africa [89]. Increased cement consumption in Africa has been primarily a function of four factors: rising populations, rising infrastructure expenses, economic growth, and increasing urbanization. The International Monetary Fund (IMF) forecasted the economic growth in SSA to be over 5% annually in the next six years from 2014 [90]. Generally, urbanization, acceleration of economic performance for sustainability, and demographic growth have been some of the factors that have driven Africa's industrial, residential and commercial sectors as well as tourism and structural projects such as dams (for power), roads, railways, among others. In certain countries, the infrastructure sector has equally been driven by post-conflict reconstruction.

The cement industry in Africa is majorly operated by five top international companies, which are Lafarge (France), CEMEX (Mexico), Holcim (Switzerland), Italcementi (Italy), and Heidelberg Cement (Germany). However, the CEMEX and Italcementi plants are mostly situated in North Africa. The production capacity of the CEMEX plant in Egypt is 4.9 MTs per year, whereas Italcementi has five plants with 12 MTs per year production capacity in Egypt and three plants and one grinding unit in Morocco with about 3.2 MTs capacity. Of the top five companies, only Heidelberg, Holcim and Lafarge have companies across several countries in the SSA regions, with Lafarge being the largest of them, all in the Eastern and Southern parts of Africa, while Heidelberg has its operations concentrated in West and Central Africa. However, these companies have had their ups and downs. In 2007 and early 2008, Heidelberg sold all its operating plants in Nigeria and Niger and had plans to sell its plants in other SSA regions. As part of the restructuring of the cement industry in SSA, part of the Dangote group business in Nigeria, Dangote Cement, entered the cement market with only two cement plants and two terminals with a total production capacity of 11 MTs annually (7mt from plants and 4mt from terminals). However, the order of things changed since Dangote cement of Nigeria entered the cement market in the 2000s. Dangote became the single largest producer with growth into 14 other countries on the continent and a production capacity of 20.7 MTs, as seen in Table 2.2. The post-merger Holcim-Lafarge became the largest producer on the continent, with a capacity of 22.5+ MT per annum [91]. These are two potential major rivals with a history of collusive conduct in African countries' cement sector, but other globally recommended organizations could weaken the competition. Holcim also implemented important restructuring by divesting significant operations in Southern and East Africa to a new company known as AfriSam.

2.2. Overview of existing studies

Table 2.3 presents a summary of related studies on the environmental impacts of cement. Several studies have applied life cycle assessment (LCA) to quantify the environmental impacts of cement production worldwide.

Meshram and Kumar (2022) [92] performed a cradle-to-gate LCA to compare the manufacturing of geopolymer cement and regular Portland cement in India. Geopolymer cement was discovered to decrease impacts such as global warming potential and toxicity indicators by 49-77% because of avoiding clinker generation. Nevertheless, their study did not investigate the damage categories at the endpoint or conduct any sensitivity analysis. In a study by Morsali [93], LCA was employed to examine the effects of cement production on human health, ecosystems, and resources in Western Europe. The analysis revealed that cement production and coal mining were the primary contributors to environmental harm, while cement and crude oil extraction were the main drivers of resource depletion. One drawback was the exclusion of sensitivity analysis. Nigri et al. [94] used LCA to examine the environmental implications of cement manufacture in Brazil. The authors employ an LCA methodology based on ISO 14040 principles to quantify the consequences throughout the product life cycle, from raw material extraction to end-of-life disposal. The analysis reveals that the production process has various effects, including greenhouse gas emissions from fuel burning, air pollution from particulate emissions, and solid waste formation. In another study, Li et al. [95] analysed cement production in China and Japan. They concluded that China had larger emissions, except for CO_2, due to less advanced technology. Also, like the preceding literature, sensitivity analysis was not performed.

Stafford, Raupp-Pereira et al. [78] used LCA to investigate the Brazilian cement sector for its environmental impacts. Transportation has the most significant impact, followed by fossil fuel use and clinker production. Only midpoint impact categories were examined. The study discovered that transportation and fossil fuel use were substantial contributors to environmental damage. The authors argue that substituting fossil fuels with alternative fuels could reduce consequences, but transportation distances must be considered. Using LCA, Stafford, Dias et al. [86] provided a detailed assessment of a cement plant's impacts on the environment. By utilizing primary data, their study achieved greater precision and accuracy in the obtained conclusions. It demonstrates the advantages of utilizing alternate fuels to mitigate effects. Nevertheless, the range of damage categories was limited in comparison to ReCiPe and other more recent methodologies. Furthermore, Bushi and Meil [96] estimated the advantages of mixed Portland-limestone cement over ordinary Portland cement in Canada. Reducing clinker content with limestone addition reduced affects by 7-12%. Tun et al. (2020) [97] used a life cycle assessment to quantitatively compare the global warming potential of several cement production methods. It identifies potential for reducing cement's carbon footprint, such as employing mixed cement and carbon sequestration in cement kiln dust. However, the current high demand for cement may limit the adoption of mixed cement in the USA.

The studies have provided useful insights on which this present study will be based. However, in contrast to previous work, this study adopts a holistic approach to life cycle impact evaluation by incorporating both midpoint and endpoint indicators using the ReCiPe methodology. This comprehensively assessed several damage categories, encompassing human health, ecosystems, and resources. In addition, sensitivity analysis is conducted to evaluate the reliability of outcomes considering uncertainty in modelling assumptions. Previous research lacked concurrent investigations into midpoint, endpoint models, and sensitivity analysis. Prior research on the cement sector in South Africa has primarily focused on midpoint analysis, with limited scope. This study provides novel insights into this geographical context by measuring the individual impacts and damages experienced.

Table 2.3. Summary of previous life cycle assessment studies on cement production

Reference	Aim	Country	Themes			Findings
			LCIA Approach	Sensitivity analysis	Damage to human health	
(Meshram & Kumar, 2022)	To conduct a life cycle assessment (LCA) of two types of geopolymer cement and compare it to traditional Portland cement in an Indian context.	India	Cradle-to-gate life cycle assessment following ISO 14040 principles	Not considered	Not considered	Geopolymer cement based on fly ash and blast furnace slag reduces global warming potential by 70%, abiotic depletion potential fossil by 49%, abiotic depletion potential element by 34%, and terrestrial ecotoxicity potential by 77% compared to ordinary Portland cement.
(Morsali, 2016)	To analyze the life cycle impacts of Portland	Western Europe	Life cycle assessment using SimaPro	Not considered	Not considered	The cement production process and coal tailings landfilling caused the most damage to

	cement production on human health, ecosystem quality, and resource depletion using LCA methodology.		software and Eco-Indicator 99 methodolog y			human health. Crude oil and coal mining were the biggest contributors to resource depletion. Cement production, uranium mining, and transportation caused the most damage to ecosystem quality. The key emissions contributing to impacts were CO_2, NOx, SOx, CH4, and metals like Ni, Zn, Cr, As, and Cd.
(Nigri et al., 2010)	Apply life cycle assessment (LCA) to evaluate environmental impacts of Portland	Brazil	Life cycle assessment based on ISO 14040 principles	Not considered	Not considered	Cement production causes environmental impacts including greenhouse gas emissions, air pollution, and waste generation

	cement manufacturing					
(Li et al., 2015)	Evaluate the environmental impacts of cement production in China and identify potential improvements	China	Life cycle assessment, comparative analysis	Not considered	Not considered	The study finds China has higher emissions except for CO_2 compared to Japan due to less advanced technologies.
(Stafford, Raupp-Pereira, et al., 2016)	To analyze the environmental impacts of cement production at a Brazilian cement plant through life cycle	Brazil	Life cycle assessment guided by ISO 14040 and ISO 14044	Not considered	Not considered	Transportation had the largest contribution to most environmental impact categories. After transportation, fossil fuel production and the cement kiln (clinkering process) were the major contributors.

	assessment (LCA).					
(Stafford, Dias, et al., 2016)	Assess environmental impacts of using wastes as fuel in cement manufacturing in a plant in Southern Europe.	Portugal	Life cycle assessment based on primary data from the cement plant and secondary data from the Ecoinvent database.	Not considered	Not considered	Atmospheric emissions from the kiln were the main contributor to most impact categories except abiotic depletion. Using alternative fuels like refuse derived fuel and scrap tires reduced impacts compared to studies using only fossil fuels.
(Bushi & Meil, 2014)	To quantify the environmental impacts of Portland limestone cement (PLC) compared to	Canada	Cradle-to-gate life cycle assessment of cement and concrete	Not considered	Not considered	PLC has 9-12% lower environmental impacts than OPC across all indicators studied. PLC concrete mixes have 7-9% lower impacts than OPC concrete mixes. Reducing clinker

	ordinary Portland cement (OPC) using life cycle assessment.		mixes following ISO standards.			content in cement through PLC provides reductions in energy use and emissions.
(Tun et al., 2020)	To evaluate the environmental impacts of cement production in Myanmar using life cycle assessment (LCA) and identify key contributors to impacts.	Myanmar	Life cycle assessment following ISO standards, using site-specific data from 8 cement plants in Myanmar.	Not considered	Not considered	Major impacts, including climate change, photochemical oxidant formation, particulate matter formation, terrestrial acidification, and fossil resource scarcity, were observed. The main contributors to these impacts were CO_2, NO_x, SO_2, and $PM_{2.5}$ emissions resulting from clinker production and fossil fuel use. Among the various damage categories, human

						health emerged as the most affected
(Huntzinger & Eatmon, 2009)	Assess environmental impacts of four cement manufacturing processes: traditional Portland cement, blended cement with natural pozzolans, cement production with CO_2 sequestration in cement kiln dust (CKD),	United States	Life cycle assessment using SimaPro software to model environmental impacts of different cement production processes. Functional unit of analysis was production of 1 ton of cement.	Not considered	Not considered	Blended cements with natural pozzolans had the lowest global warming potential. Carbon sequestration in CKD reduced global warming potential by about 5% compared to traditional Portland cement.

	and cement production with CKD recycling.					
Present study	To conduct a life cycle assessment of the environmental impacts of cement production in a typical South African plant	South Africa	Life cycle assessment using midpoint and endpoint approaches on 1 kg of cement produced.	Considered	Considered	To be presented in the discussion section

In contrast to other cement manufacturing LCA studies, the primary innovative elements of this research are incorporating a comprehensive damage assessment and sensitivity analysis to address the shortcomings identified in the existing literature. Additionally, the study projects the annual potential number of human lives and endangered species in South Africa, considering the country's cement demand and population. Furthermore, the monetary value of resource depletion is computed. The findings will give the South African cement industry a comprehensive insight into important environmental sustainability indicators and how they can be enhanced.

2.3. Methods

LCA gives a holistic view of the entire production process. Effective application of LCA is a function of the intended goal to be achieved in a study. Thus, there is flexibility in the implementation of LCA from one study to another based on the defined goal [71, 98]. The four stages of LCA, as recommended by ISO, include 1) Goal and scope definition, 2) Life cycle Inventory Analysis (LCI), 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation [71, 99].

The present study employs the ReCiPe technique [100] to assess the impact of the life cycle, incorporating both midpoint and endpoint indicators. The integration of these methods offers a comprehensive outlook on the possible environmental consequences of cement manufacturing in South Africa. The midpoint technique categorizes inventory flows into impact categories such as climate change and toxicity, based on distinct environmental mechanisms [101]. One significant benefit of using the midpoint method is its ability to offer transparency by providing contributions to different impact categories without any subjective weighting between the categories. Nevertheless, a drawback is the absence of integration, as the impact categories remain distinct. On the other hand, the endpoint approach quantifies the harm caused to human health, ecosystems, and resources, allowing for a comprehensive assessment of the total possible consequences. Endpoint modelling, however, is dependent on assumptions to establish a connection between inventory flows and damage categories. This phenomenon may underestimate the contributions made by specific compounds and increase uncertainties [100, 102].

Relying exclusively on midpoint or endpoint approaches entails inherent compromises [103]. The midpoint approach quantifies the contributions to environmental impacts, but it does not account for the overall integrated damages. The endpoint analysis offers a comprehensive view of the total damage, but it does not clearly highlight the specific contributions of pollutants. A combined midpoint and endpoint method allow for harnessing the benefits of both strategies [101, 103]. The midpoint assessment identifies the individual environmental mechanisms that are affected by certain contributions, whereas the endpoint analysis indicates the potential overall harm caused. Collectively, they offer a more comprehensive perspective on emissions and the resulting harm than each approach individually.

The ReCiPe methodology was selected due to its capability to ensure uniform calculation from midpoint to endpoint inside a single framework [100]. This study offers a full assessment of potential impacts resulting from cement production by including both LCIA methodologies. The aim is to give valuable information for the development of effective mitigation solutions. The Life Cycle Assessment (LCA) adheres to the ISO requirements for the aim, inventory, and interpretation stages as outlined in ISO 2006 [104].

2.3.1. Goal and Scope Definition

It is very important to clearly define the goal when carrying out a life cycle assessment of a process or product. The scope definition of an LCA study describes the jurisdiction of the assessment. Thus, the following must be clearly explained in the scope definition: the system to be studied and its function, the functional unit, the system boundaries, the types of impact and impact assessment method, data quality requirements, and the assumptions and limitations [105, 106]. In this study, the functional unit is the kg of cement, so the results would be in kg as well. This study aimed to carry out a life cycle assessment of 1 kg of cement produced in a typical South African cement industry. This study only covered the 'cradle-to-gate' assessment of the cement's production process; the data used for this analysis was from the extraction of raw material through to cement production. This study did not consider the packaging, use, disposal/end-of-life, or waste treatment data. The software used for the LCA in this study is SimaPro 9.1.1. Figure 2.1 gives a summarized material flow diagram to produce 1kg of Portland cement. The intended audience of this study includes researchers, policymakers in South Africa, and the cement industry community in South Africa. The intended application of this study is to improve the environmental impacts of the cement industry in South Africa.

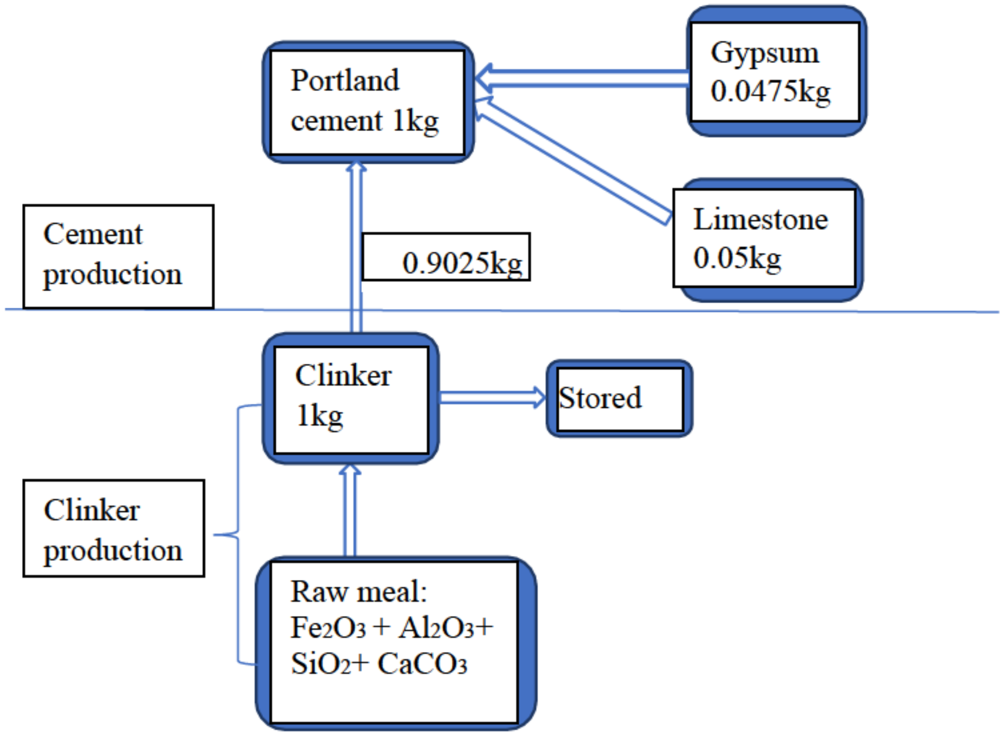


Figure 2.1. Material Flow Diagram to produce 1kg of Portland Cement (adapted from the Ecoinvent database).

2.3.2. Life Cycle Inventory

LCI analysis involves the compilation of input and output inventory data that are consistent with the product under assessment and have several environmental coverages [107]. For the cement industry, a cradle-to-gate inventory involves all the processes, raw materials, and essential requirements needed to make cement ready for use. Secondary data from the ecoinvent database was used for this study due to lack of localized data. The Ecoinvent 3.6 database documentation of clinker production and Portland cement production in South Africa (ZA) can be seen in Appendix: chapter 2 (Table 1 and Table 2).

2.3.3. Life Cycle Impact Assessment

LCIA is a multiple-issue tool used to evaluate potential environmental impacts in line with environmental resources (inputs and outputs) identified in the life cycle inventory. This assessment addresses several environmental issues, such as energy, climate change, water pollution, and thus, giving room for a comprehensive evaluation of the impact of the system [99, 108]. This attempts to establish the connection between a product and its potential environmental impact [109]. ReCiPe was used as the LCIA method in this study because it provides both mid-point and end-point results. To the best of our knowledge, only a few studies that used both midpoint and end-point analysis of OPC in a typical South African plant have been conducted. Thus, there was a need to carry out more studies in this area.

2.3.4. Interpretation

Interpretation, which is the last of the stages, is an efficient method used to evaluate, compute and categorize the results from the information provided by the LCI and the LCIA, and establish their effective relationship [110].

2.4. Results and Discussions

The study aimed to prioritize specific impacts (impacts with high value) and discuss remedies to reduce these impacts for the purpose of making meaningful recommendations on the most appropriate mitigation measures. It focused on identifying environmental impacts and hotspots emanating from the South African cement industry. This analysis embraced the cradle-to-gate approach of LCA without providing packaging and dispatching information. The mass-based functional unit used in this study is the kilogram; thus, 1 kg of Portland cement produced in a South African cement plant was used.

2.4.1. Mid-point Analysis (Process-Oriented Approach)

In the mid-point approach, flows were categorized into the environmental impact to which they contribute. This approach presented about 18 impact categories which covered several impacts. This approach helped to simplify numerous flows by streamlining them into a few prevalent environmental impacts. Figure 2.2 represents the contribution of five production processes to the impact categories, including 1) Clinker production, 2) Raw material consumption, 3) Electricity usage, 4) Fuel consumption, and 5) Transportation, where clinker production includes calcination and burning of fuel.

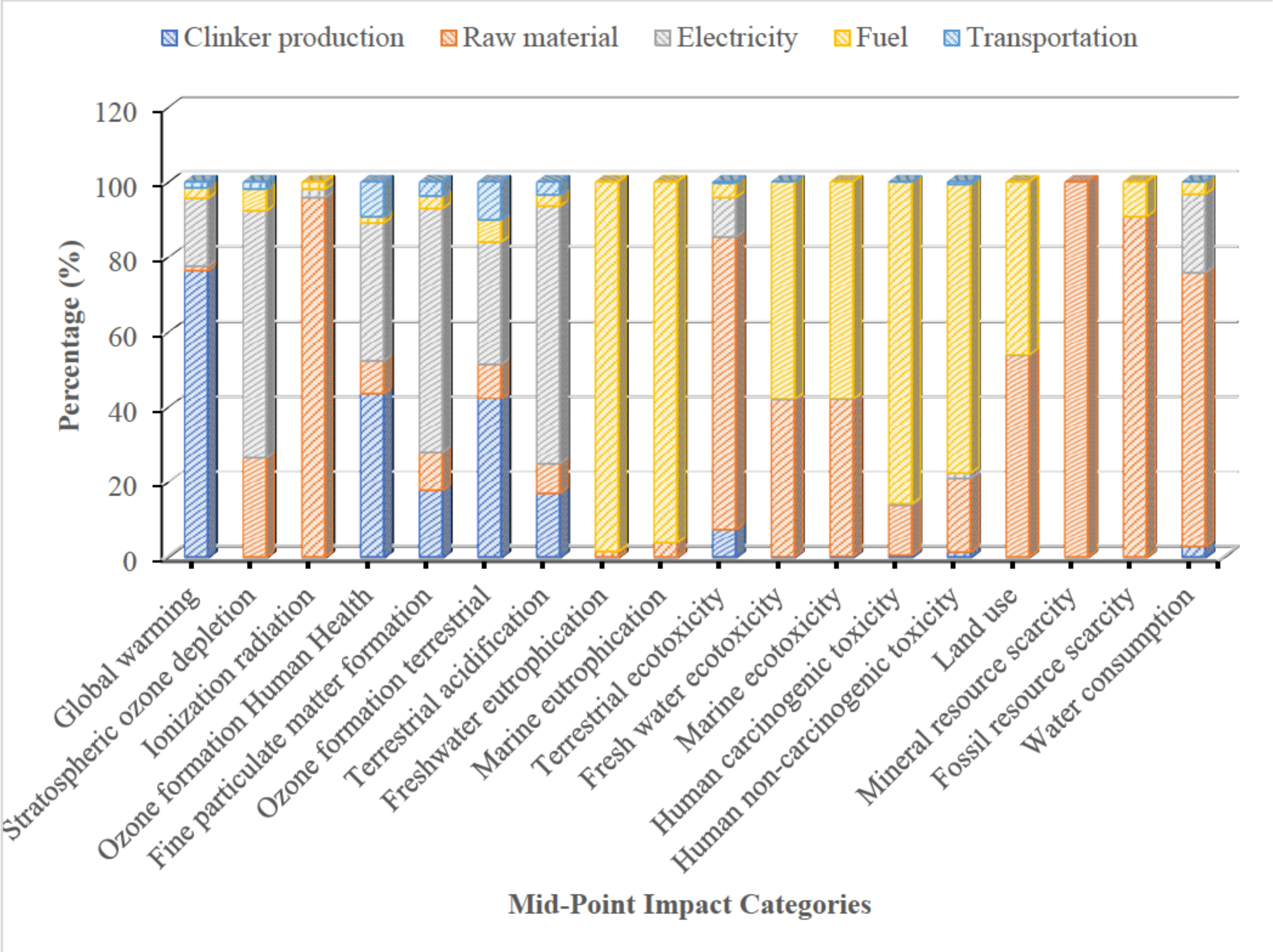


Figure 2.2. Contribution of Five Production Processes to Impact Categories (Mid-Point).

2.4.1.1. Clinker Production

The impact of cement manufacturing processes on climatic change has been the recent focus, with emphasis on the contribution of these emissions to global warming [96]. As presented in Figure 2.2, the clinker production stage has significantly contributed to global warming. It contributes 76.3% to the global warming impact category. In ozone formation (human health) and ozone formation (terrestrial), clinker production contributes 42.6% to each impact category. This comes with no surprise, because the clinker production process is usually the most extensive stage and thus, is associated with the largest amount of emission of gases into the atmosphere. Interestingly, these results were similar to those obtained by other groups of researchers in different parts of the globe including Europe [86, 111], Peru [112], as well as Brazil [113]. Fine particulate matter formation, terrestrial acidification, and terrestrial ecotoxicity contribute 17.7% 16.9%, and 7.3% respectively. The contribution of clinker production to freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and water consumption is 0.005%, 0.116%, 0.43%, 1.23%, and 2.6%, respectively: the contribution is minimal. Clinker production did not contribute to stratospheric ozone depletion, ionization radiation, marine eutrophication, land use, mineral scarcity, and fuel resource scarcity impact categories.

2.4.1.2. Raw Material Consumption

As seen in Figure 2.2, Raw material consumption contributed to all the impact categories. The largest contribution is seen in Mineral scarcity (99.99%), Ionization radiation (95.9%), Freshwater scarcity (90.7%), Terrestrial ecotoxicity (77.9%), and Water consumption (73.1%). Other relatively large contributions are made by Land use (53.9%), Freshwater ecotoxicity (41.9%), and Marine ecotoxicity (41.9%). Raw material consumption has made a minimal contribution to Stratospheric ozone depletion (26.4%), Human non-carcinogenic toxicity (19.8%), Fine particulate matter formation (10.3%), Ozone formation terrestrial ecosystem (9.2%), Ozone formation Human health (8.7%), Terrestrial acidification (7.9%). These results were better than the results obtained in another study [114]. According to the study, raw material consumption contributed 84%; 34%; 32% and 13% to terrestrial ecotoxicity; human non-carcinogenic toxicity; ozone layer depletion; and terrestrial acidification, respectively [29]. Also, our results showed Marine eutrophication (3.67%), Freshwater eutrophication (1.4%), and Global warming (1.2%). The highest raw material consumption effect is found in mineral scarcity (99.99%).

2.4.1.3. Electricity Usage

Electricity usage has also been identified as a major contributor to the depletion of the ozone layers due to the fact that the electricity used is usually generated from fossil fuels, and this results in the emission of gases that deplete the ozone layers [82]. As seen in Figure 2.2, Electricity usage contributed 68.6% to Terrestrial acidification, 65.8% to Stratospheric ozone depletion, and 64.8% to Fine particulate matter formation. These results showed consistency with those obtained by a group of researchers in another study which obtained values within the range of 65 – 71% [82]. However, these results were significantly different from those obtained from a study in Turkey [114], which reported terrestrial acidification due to electricity usage to be 6.5%. Electricity usage had a minimal contribution to ozone formation human health (36.7%), ozone formation terrestrial (32.4%), Water consumption (21.04%), global warming (18.3%), and terrestrial ecotoxicity (10.7%). The contribution of electricity usage to Ionization radiation was 2.2%, followed by human non-carcinogenic toxicity (1.38%), human carcinogenic toxicity (0.38%), Freshwater ecotoxicity (0.32%), and marine ecotoxicity (0.26%). The impact categories are minimal. Electricity usage did not contribute to Freshwater eutrophication, Marine eutrophication, Mineral scarcity, or Freshwater scarcity.

2.4.1.4. Fuel Consumption

Fuel consumption made a significant contribution to Freshwater eutrophication, as seen in Figure 2.2. Other contributions were seen in human carcinogenic toxicity: 85.7%, human non-carcinogenic toxicity: 76.9%, freshwater scarcity: 57.765%, marine ecotoxicity: 57.7% and Land use: 46.1%. minimal contributions were made to freshwater ecotoxicity: 9.3%, ozone formation terrestrial: 6%, stratospheric ozone depletion: 5.9%, terrestrial ecotoxicity: 3.7%, marine eutrophication: 3.67%, fine particulate matter formation: 3.5%, terrestrial acidification: 3.2%, water consumption: 3.2%, global warming, 2.7%, ionization radiation: 1.9%, and ozone formation human health, 1.6%.

2.4.1.5. Transportation

As seen in Figure 2.2, the transportation usage contribution to the impact category was minimal. The contributions made were 3.4% to terrestrial acidification, 1.9% to stratospheric ozone depletion, 3.7% to fine particulate matter formation, 9.3% to ozone formation Human health, 9.3% to ozone formation terrestrial, 0.02% to water consumption, 1.6% to global warming, 0.4% to terrestrial ecotoxicity, 0.69% to human non-carcinogenic toxicity, 0.05% to human carcinogenic toxicity and 0.005% to freshwater ecotoxicity.

The characterization results of the environmental impacts of 1 kg of cement produced using a midpoint are shown in Table 2.4. Impacts with the same units were further grouped into global warming and fossil resource scarcity were further analysed because of their high impact value. Also, ozone formation (terrestrial and ecosystem) and toxicity (all forms of toxicity in the impact category) were further analysed because of their relatively high value.

Table 2.4. Characterization Results of the Environmental Impacts of 1 kg Cement (Mid-point).

S/N	Impact category	Unit	Cement Portland [115]
1	Global warming	kg CO_2 eq	0.993
2	Stratospheric ozone depletion	kg CFC11 eq	1.94E-07
3	Ionization radiation	kBq Co-60 eq	0.00997
4	Ozone formation, Human health	kg NOx eq	0.0021
5	Fine particulate matter formation	kg PM2.5 eq	0.000793
6	Ozone formation, Terrestrial ecosystem	kg NOx eq	0.00212
7	Terrestrial acidification	kg SO_2 eq	0.00244
8	Freshwater eutrophication	kg P eq	0.000316
9	Marine eutrophication	kg N eq	1.93E-05
10	Terrestrial ecotoxicity	kg 1,4-DCB eq	1.04
11	Freshwater ecotoxicity	kg 1,4-DCB eq	0.0158
12	Marine ecotoxicity	kg 1,4-DCB eq	0.0214
13	Human carcinogenic toxicity	kg 1,4-DCB eq	0.0244
14	Human non-carcinogenic toxicity	kg 1,4-DCB eq	0.497

15	Land use	m2a crop eq	0.00783
16	Mineral resource scarcity	kg Cu eq	0.00216
17	Fossil resource scarcity	kg oil eq	0.139
18	Water consumption	m3	0.00136

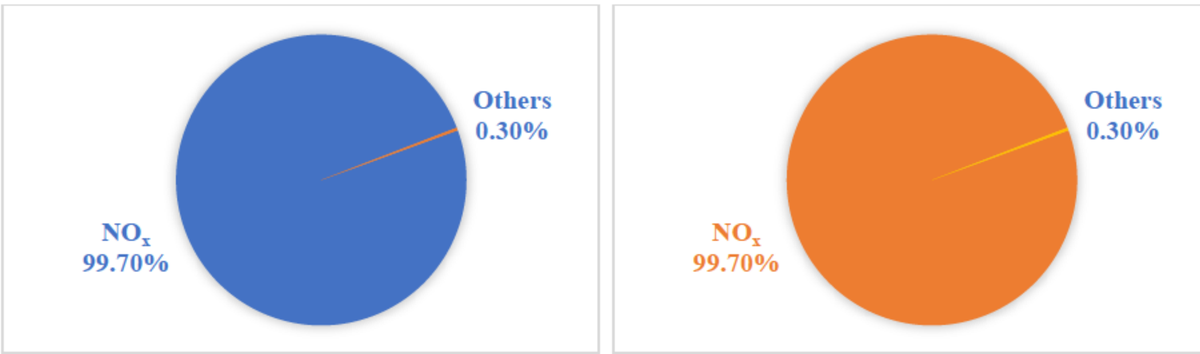
2. 4.1.6. Ozone Formation

This includes Ozone formation, Human health (HH) and Ozone formation, and Terrestrial ecosystem (TE). The formation of ozone formation ultraviolet (UV) radiation occurs naturally, which interacts with oxygen. Ozone layer formation is a protective mechanism to prevent the ash effect of UV radiation on the earth. The anthropogenic ozone formation starts with the emission of nitrogen oxides (NO_x) and/or the non-methane volatile organic compound (NMVOC) into the atmosphere, and with chemical reactions, the ozone layer is formed. The high concentration of ozone formation in the atmosphere affects both humans and other species (the ecosystem). Its effect is seen in health complications and even the death of species [116]. As seen in Table 2.4, the environmental impact is seen in two phases with respect to human health and the terrestrial ecosystem. It is observed that for every 1kg of cement produced, 0.00421kg of NO_x eq is emitted into the atmosphere, and its effect is seen as ozone formation.

NO_x is one of the major air pollutants. Its chemical reaction with oxygen in the atmosphere can produce nitrogen dioxide, and an increased concentration in the human system has a comprehensive list of possible complications [117, 118]. Further analysis was done on Ozone formation, Human health and Ozone formation, and Terrestrial ecosystem to find what percentage of NO_x was causing this impact category and to which sub-compartment it was emitted. The result of the analysis is presented in Figure 2.3. This impact category is the result of the emission of 99.7% of NO_x into the atmosphere. As presented earlier in Figure 2.1, in both cases, it was realized that about 42.6% of the emission of NO_x was from the clinker production stage, and about 37% of the emission was from the electricity consumption stage.

2.4.1.7. Toxicity

Toxicity impacts in LCA encompass several categories, including Marine ecotoxicity, Freshwater ecotoxicity, Terrestrial ecotoxicity, Human carcinogenic toxicity, and Human non-carcinogenic toxicity. These categories represent hazardous stressors that can harm ecosystems and human health through physical, chemical, or biological means. In the context of cement production, toxicity-related impacts arise primarily from the release of heavy metals (e.g., chromium, lead, cadmium, and mercury) during raw material extraction, clinker production, and fuel combustion processes. Additionally, the use of alternative fuels and raw materials



(a) HH impact category (b) TE impact category

Figure 2.3. Substances Contributing to the Ozone Formation Impact Category.

(AFRs), including industrial by-products and waste-derived materials, can introduce new toxic substances if not properly managed. These pollutants may leach into soil and water or be emitted into the air, contributing to ecotoxicity and human toxicity concerns across various environmental compartments.

In humans, toxicants can be carcinogenic or non-carcinogenic in nature yet still very harmful. As seen in Table 2.4, for every 1kg of cement produced, about 1.6kg of 1,4- Dichlorobenzene (1,4-DCB) eq is produced, and its effect is seen in the toxicity of humans, water bodies, and the ecosystem. 1,4-DCB is an inorganic compound with high malodour and consists of molecules of benzene and chlorine. Terrestrial ecotoxicity and Human non-carcinogenic toxicity were further analysed, as they have significant value compared to the others, to ascertain the actual substance released into the environment, their percentage, and sub-compartments of emission.

Figure 2.4 represents the results of the analysis of Terrestrial ecotoxicity. In Table 2.4, it is observed that 1.04 of 1,4-DCB eq was produced, resulting in 63% copper, 12.3% antimony, and 7.1% mercury being emitted into the atmosphere, as shown in Figure 2.4. Human non-carcinogenic toxicity is mainly emitted into the water but also into the air. In Table 2.4, it is observed that 0.49 kg of 1,4-DCB eq was produced for every 1kg of cement produced; this was a result of 60% of zinc, 31% of arsenic, and 1.7% of lead being emitted into the water body and a very minimal amount of this substance being emitted into the air as seen in Figure 2.5. In high concentrations, zinc presents a severe level of toxicity. As much as it is needed by organisms for metabolism, it is only needed in trace amounts, and a high concentration is deadly to organisms.

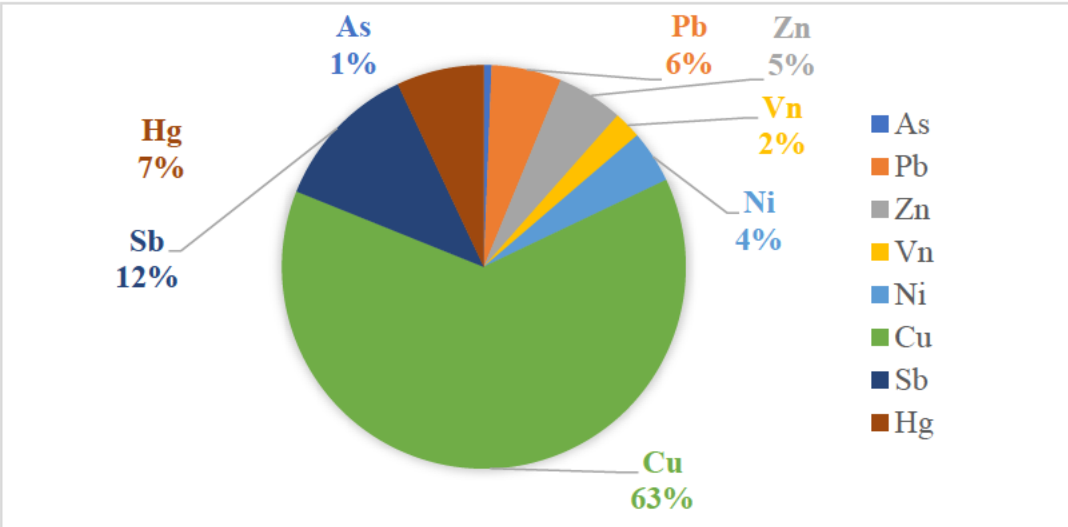
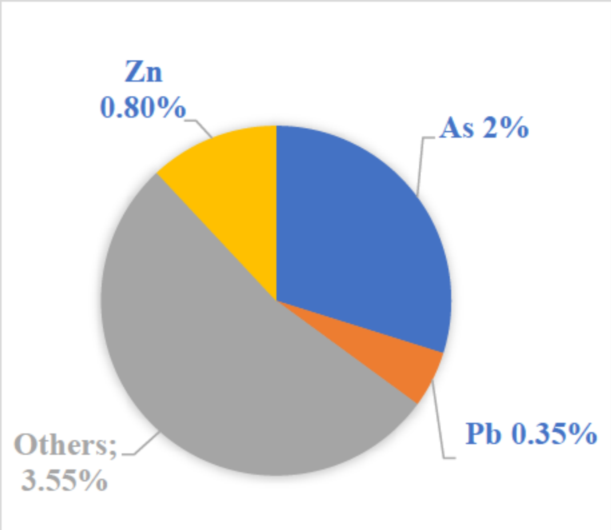
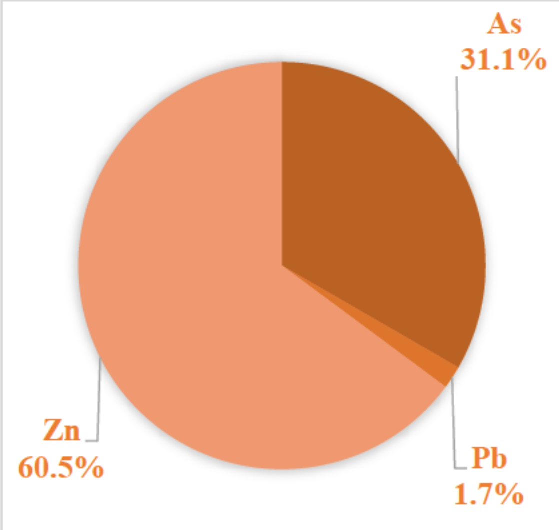


Figure 2.4. Substances contributing to Toxicity - Terrestrial Ecotoxicity Impact Category



(a) Emissions into Air



(b) Emissions into Water

Figure 2.5. Substances contributing to Toxicity - Human Non-Carcinogenic Toxicity Impact Category.

2.4.1.8. Global Warming

The concept of global warming and its relationship with changes in climatic conditions is fast becoming a highly relevant topic that has created awareness globally. In nature, some gases are present in the atmosphere to serve as an umbrella-like covering for protection from the effects of solar energy experienced on earth. This greenhouse effect causes the energy from the sun to be trapped by these gases and prevents them from escaping from the earth, thereby keeping the planet a warm and habitable place for both humans and the ecosystem.

As seen in Table 2.4, 0.993kg of CO_2-eq was produced for every 1 kg of cement produced, and its effect has been seen in global warming. Of this value, 78.3% was contributed at the clinker production stage, while 18.3 % was from electricity and the rest of the percentages were from raw material consumption, fuel consumption, and transportation. Further analysis of global warming was carried out, and the results are presented in Figure 2.6. The results showed that CO_2, CO, and CH_4 were emitted in the following percentages: 98.8%, 0.5%, and 0.6%, respectively, and 98.8% (0.981kg of CO_2) of 0.993kg of CO_2 eq was from the emission of CO_2

gas. This implies that for every 1 kg of cement produced, 0.981kg of CO_2 was emitted, and the effect of this emission can be seen in global warming.

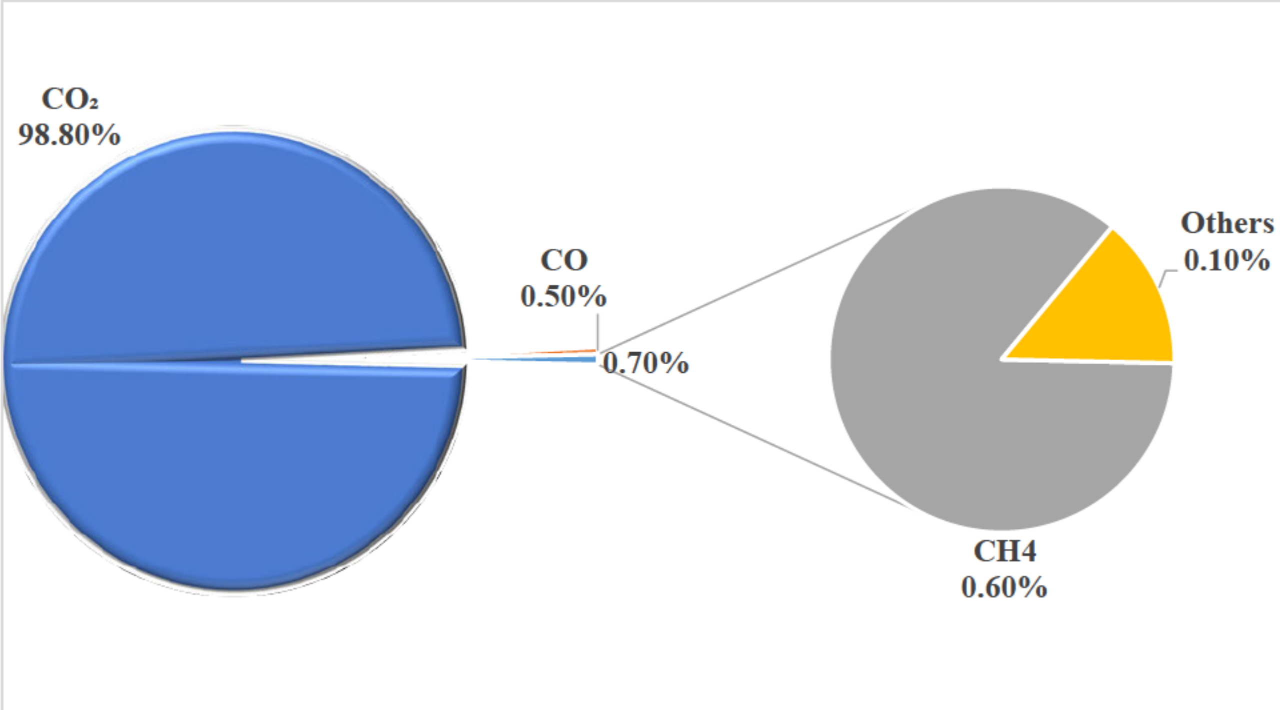


Figure 2.6. Substances Contributing to Global Warming.

2.4.1.9. Fossil Resource Scarcity

Fossil resources (fuel), typically crude oil, petroleum, and natural gas are not infinite in nature. They will run out after protracted use globally. About 80% of global energy comes from fossil resources, and over 40% of this energy source comes from oil. Fossil fuels are used by about 90% of the transport sector. These resources are carbon-based substances that react with organic substances in the presence of sunlight. This process is known as the geological process.

As seen in Table 2.4, for every 1 kg of cement produced, 0.139kg of oil eq is produced and its effect is seen in fossil resources scarcity. A further analysis was carried out on this impact category and the result of this analysis is shown in Figure 2.7 where 89.7% of 0.139kg scarcity is from burning coal. Other percentage sources are crude oil: 8.3%, gas: 1.89%, and peat: 0.02%.

Typically, coal is one of the major sources of energy in South Africa. Over 77% of primary energy in South Africa comes from coal. Coal is mostly made up of carbon but contains other elements such as sulphur, nitrogen, oxygen, and hydrogen. Coal emits nitrogen oxides, nitrous oxides (N_2O), and sulphur dioxide (SO_2) when burnt. SO_2 causes respiratory diseases in humans and contributes largely to acid rain. N_2O is about 300 times more potent than CO_2 in its ability to cause global warming and can reduce the ozone layer. The burning of coal has a wide range of impacts on humans and the environment, ranging from various health issues to the greenhouse effect, climate change, acid rain, and air pollution. A need to have a sustainable source of energy is therefore imperative.

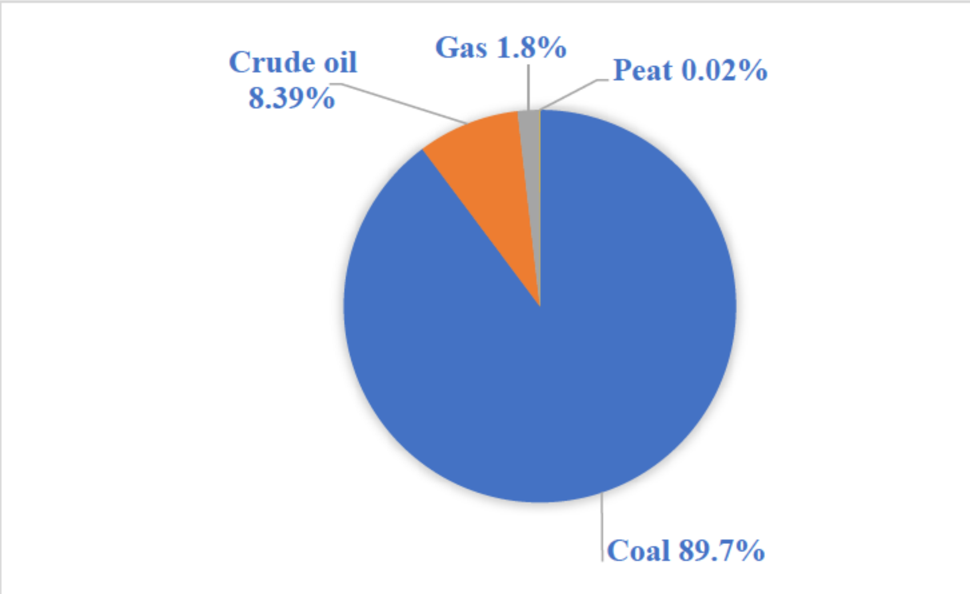


Figure 2.7. Substances Contributing to Fossil Resource Scarcity.

2.4.2. End-point Analysis (Damage-Oriented Approach)

The end-point approach, on the other hand, categorizes flows into 22 impact categories. These impacts are thereafter classified into their damage categories. Impacts are simplified into the damage to three areas of significance to life (AoSL): human health, the ecosystem, and resources. Figure 2.8 represents the contribution of the five production processes to the damage categories, including 1) Clinker production, 2) Raw material consumption, 3) Electricity usage, 4) Fuel consumption, and 5) Transportation, where clinker production includes calcination and burning of fuel.

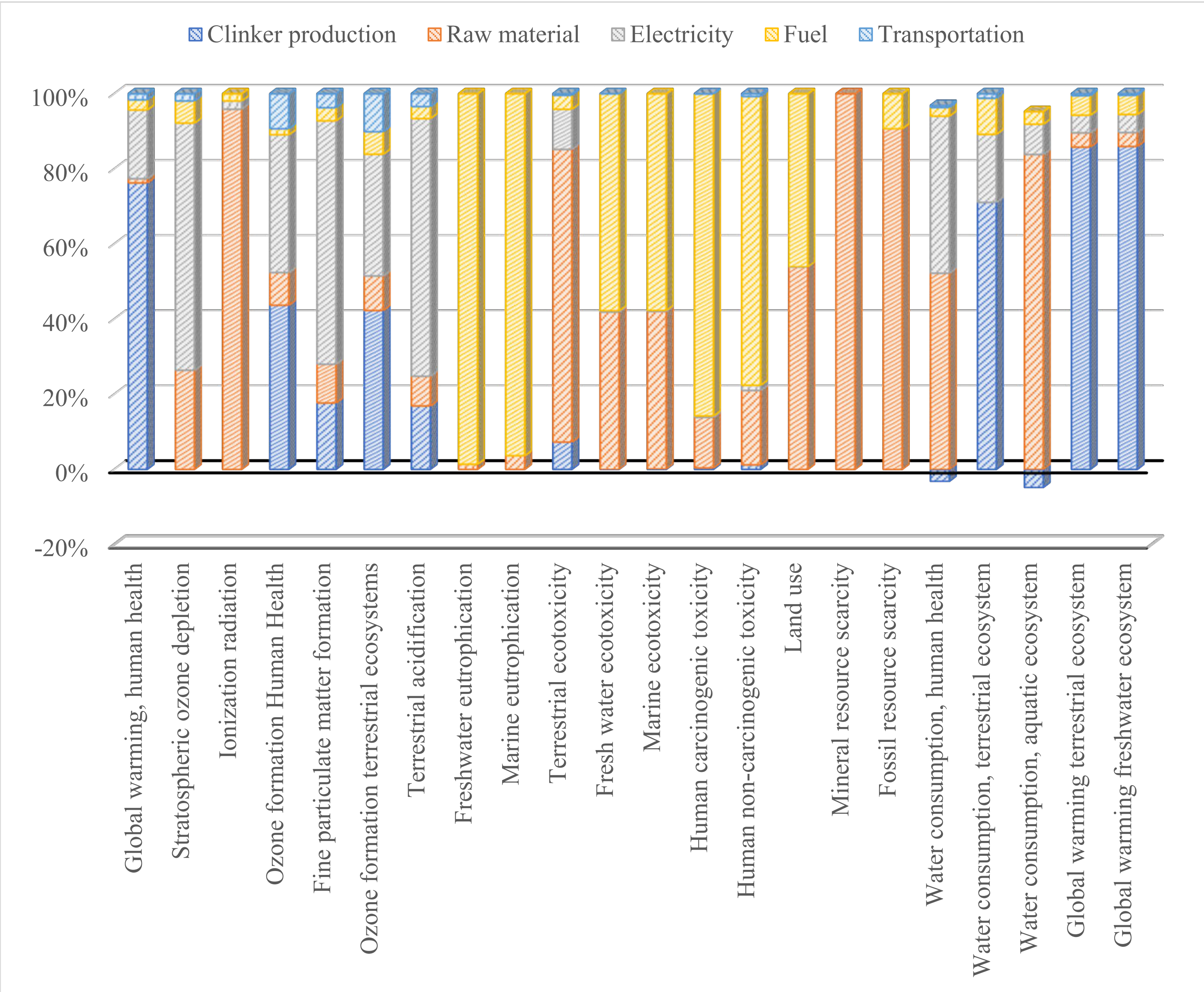


Figure 2.8. Contribution of Five Production Processes to Impact Categories (Endpoint).

The characterization result of the environmental impacts of 1kg of cement using the end-point approach is presented in Table 2.5. The analysis of the impact categories based on the five production processes is presented in Figure 2.8. The result follows the same trend as that of the midpoint approach but with four other impacts: Global warming Freshwater ecosystems, Water consumption Terrestrial ecosystems, Water consumption Aquatic ecosystems, and Freshwater eutrophication. The various impacts presented in Table 2.5 are classified into their damage categories based on the area of significance to life, as seen in Table 2.6.

Table 2.5. Characterization Results of the Environmental Impacts of 1kg Cement (Endpoint).

S/N	Impact category	Unit	Cement Portland [115]
1	Global warming, Human health	DALY	9.21E-07
2	Stratospheric ozone depletion	DALY	1.03E-10
3	Ionizing radiation	DALY	8.46E-11
4	Water consumption, Human health	DALY	1.50E-09
5	Ozone formation Human health	DALY	1.91E-09
6	Fine particulate formation	DALY	4.98E-07
7	Human carcinogenic toxicity	DALY	8.10E-08
8	Human non-carcinogenic toxicity	DALY	1.13E-07
9	Global warming, Terrestrial ecosystems	Species/yr	2.78E-09
10	Global warming, Freshwater ecosystems	Species/yr	7.60E-14
11	Ozone formation Terrestrial ecosystems	Species/yr	2.73E-10
12	Terrestrial acidification	Species/yr	5.18E-10
13	Freshwater eutrophication	Species/yr	2.12E-10
14	Marine eutrophication	Species/yr	3.29E-14
15	Terrestrial ecotoxicity	Species/yr	1.19E-11
16	Freshwater ecotoxicity	Species/yr	1.09E-11
17	Marine ecotoxicity	Species/yr	2.25E-12
18	Land use	Species/yr	6.95E-11
19	Water consumption, Terrestrial ecosystems	Species/yr	2.01E-10
20	Water consumption, Aquatic ecosystems	Species/yr	2.14E-15
21	Mineral resource scarcity	USD2013	5.00E-04
22	Fossil resource scarcity	USD2013	1.64E-02

Table 2.6. Classification of Impacts into Damage Categories.

S/N	Damage Category	Unit	Value
1	Human health	DALY	1.62E-06
2	Ecosystems	Species/yr	3.90E-09
3	Resources	USD2013	0.0169

2.4.2.1. Clinker Production

As presented in Figure 2.9, the clinker production stage contributed 49.4% to Human health and 60% to the Ecosystem but did not contribute to Resources.

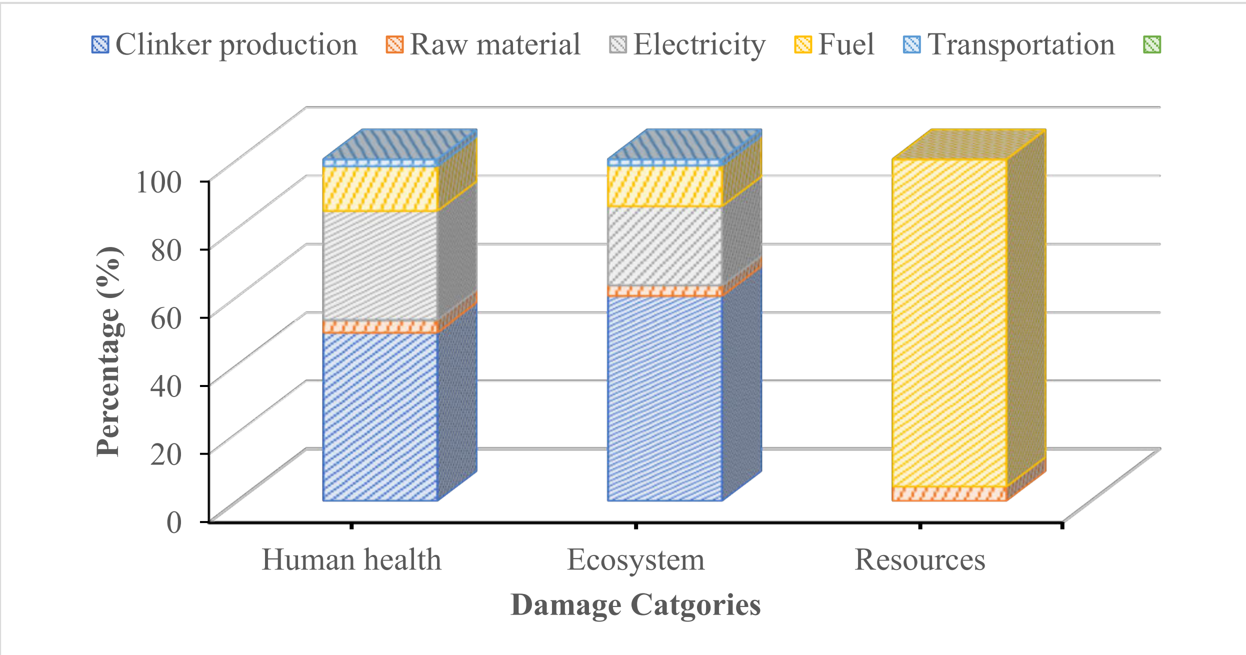


Figure 2.9. Contribution of Five Production Processes to Damage Categories**.**

2.4.2.2. Raw Material Consumption

Figure 2.9 shows that Raw material consumption contributed to all the impact categories: 3.6% to Human health, 3.1% to the Ecosystem, and 4.2% to Resources. Overall, the contribution of raw material consumption to the damage categories was minimal.

2.4.2.3. Electricity Usage

As seen in Figure 2.9, Electricity usage did not contribute to damage to Resources but contributed 31.9% to Human health and 23.2% to the Ecosystem.

2.4.2.4. Fuel Consumption

Fuel consumption contributed to the three damage categories but made a significant contribution to damage to the ecosystem. As seen in Figure 2.9, 13.1% of its contribution to damage was to Human health, 11.9% to the Ecosystem, and 95% to Resources.

2.4.2.5. Transportation

As seen in Figure 2.9, transportation usage contributed minimally to the damage categories. The contributions were 2% to Human health 1.8% to the Ecosystem and no contribution to Resources. The damage category was further analysed, and the result of the analysis is explained below.

2.4.2.6. Human Health

As seen in Table 2.6, the damage to human health was 1.62E-6 DALY. DALY was defined by the World Health Organization as the annual summation of potential life lost due to a pandemic or disease, or another phenomenon. This means that for every 1kg of cement produced, 1.62E-6 lives are endangered. This might seem almost negligible until the population of South Africa is considered, and the annual amount of cement required per individual. In concrete production, cement, sand, and water are present in the ratio of 1:1.5:3. A medium-grade concrete (M20-M30) would contain a maximum quantity of cement of approximately 19% when cement wastage is also considered [119-121]. Currently, concrete is the most produced and consumed material and is second only to water consumption, with about three tons used by every individual annually [122]. Therefore 0.57 tons of cement is needed by every South African annually. The latest recorded population of South Africa is about 60 million. This means 34.2 MTs of cement are needed in South Africa in a year. This translates to about 55404 DALY;

about 55,404 lives are potentially endangered due to damage due to the annual cement production requirement in South Africa.

This has a very significant impact on South African lives. Figure 2.10 below represents further analysis carried out on the human health damage category of substances that cause these damages and the mediums in which they were expressed where A represents air and W represents water. The results showed that 1% of ammonia was emitted into the atmosphere, 10% of NO_x was emitted into the atmosphere, less than 2.5 micrometres of particulate matter were emitted into the air, 2% of arsenic was emitted into the water body, 56% of CO_2 was emitted into the air and 8% of other substances were emitted into both the air and water. The consequence of all these emissions, as explained earlier in the midpoint analysis, is damage to human health.

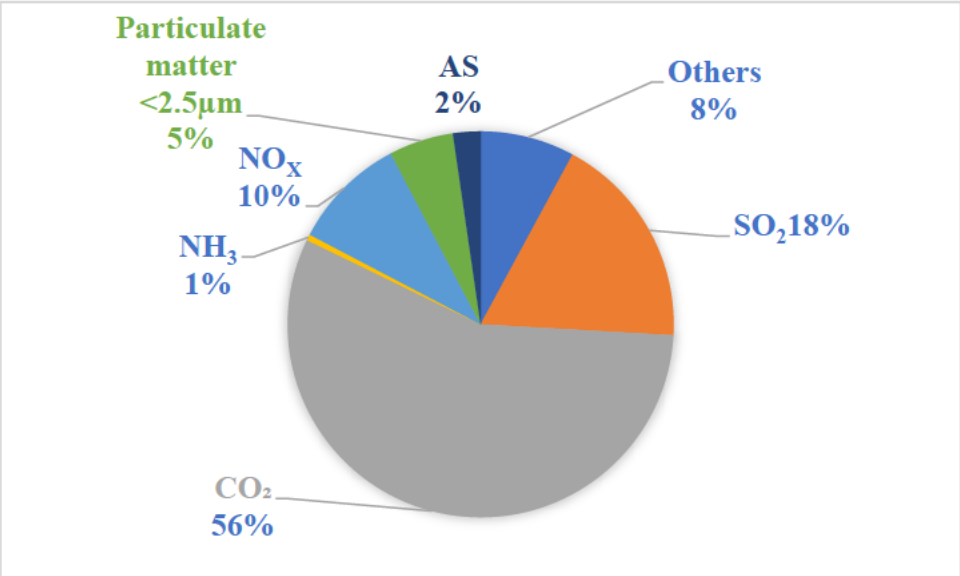


Figure 2.10. Substances Contributing to the Human Health Damage Category.

2.4.2.7. Ecosystem

As seen in Table 2.3, the damage to the ecosystem is 3.9E-9 Species/year. This damage was measured based on the number of species endangered per year. This means that for every 1kg of cement produced, 3.9E-9 species have the potential to die every year. In SA, where about 34.2 MTs of cement is needed every year, about 133 species will potentially be endangered.

Figure 2.11 represents further analysis carried out on the ecosystem damage category on substances that cause this damage and mediums in which they are expressed where A represents air, and W represents water. The results showed that 9% of SO_x was emitted into the atmosphere, 10% of NO_x was emitted into the atmosphere, 5% of phosphorus was emitted into the water body, 71% of CO_2 was emitted into the air, and 5% of other substances were emitted into both the air and water. The consequence of all these emissions, as earlier explained in the midpoint analysis, is damage to the ecosystem.

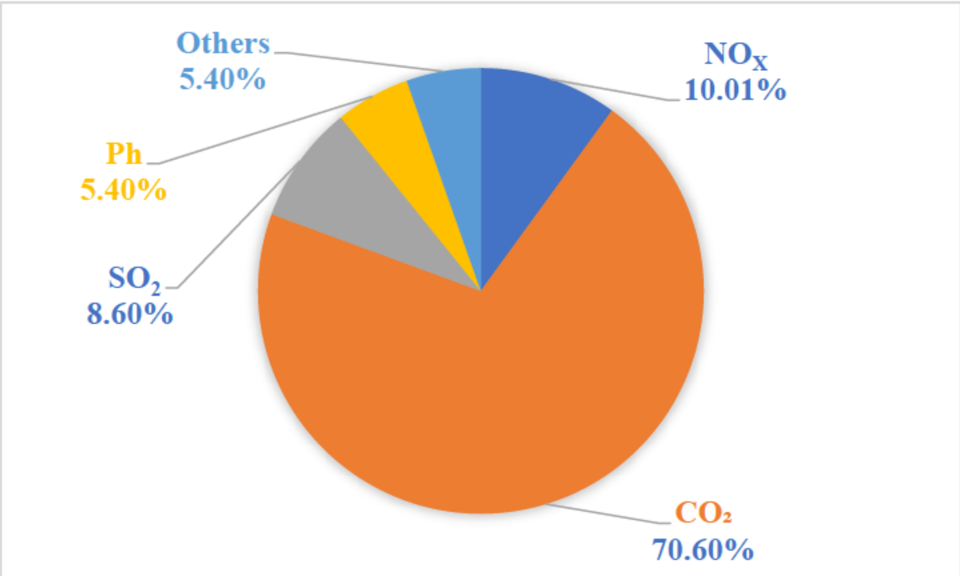


Figure 2.11. Substances Contributing to the Ecosystem Damage Category.

2.4.2.8. Resources

As seen in Table 2.3, the damage to resources was 0.0169 USD in 2013. This represents the potential marginal increase in the cost of resources because of the scarcity of such resources. As of 2013, 1 USD was equal to 10.5 Rand. This means that for every 1kg of cement produced, there was a potential scarcity of resources, resulting in a potential increase in the marginal cost of 0.18 Rand. In South Africa, where about 34.2 MTs of cement is required every year, there would be a potential scarcity of resources causing inflation of the price of these resources by R6.2 billion.

This signifies the potential increase in the cost of resources based on the annual production of cement in South Africa and consequently the annual requirement of resources. This is because these resources are finite in nature and can be exhausted, therefore creating a need for a sustainable source of resources. Figure 2.12 represents further analysis carried out on the resources damage category. The result showed that 60% of the resources in question were for coal, 32% were for crude oil, 6% were for natural gas and 2% were for aluminium.

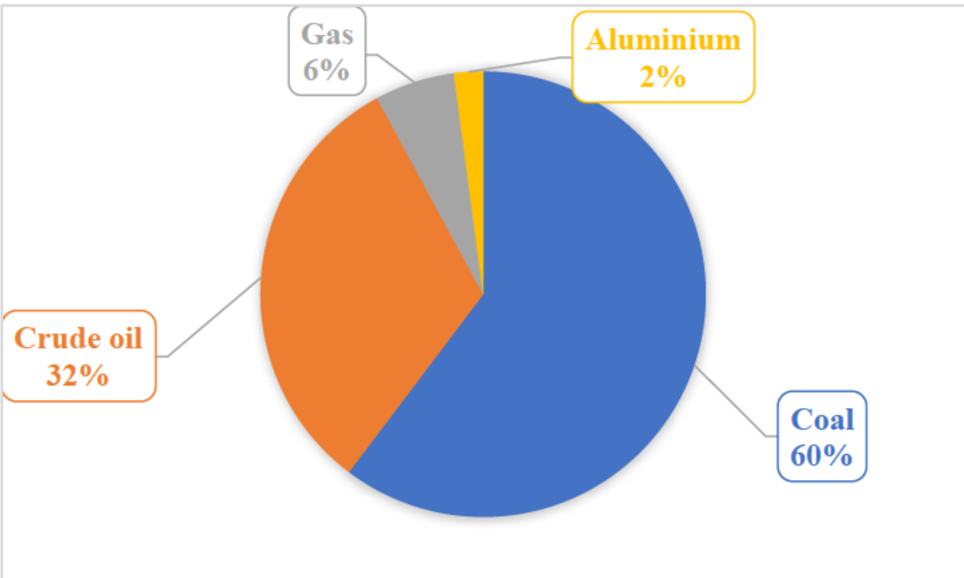


Figure 2.12. Substances Contributing to the Resource Damage Category.

2.4.3. Uncertainty Analysis Result

The uncertainty analysis was carried out with 1000 iterations and a 95% confidence interval. The midpoint, endpoint, and damage assessment uncertainties are shown in Appendix: Chapter 2; Table 3,4, and 5 respectively. In the uncertainty result of the midpoint assessment, Water consumption, ecosystems, Human carcinogenic toxicity, ionizing radiation, Freshwater ecotoxicity, Freshwater eutrophication, Human non-carcinogenic toxicity, and Marine ecotoxicity have a high degree of uncertainty. The same trend is seen in the uncertainty result of the end-point assessment: Water consumption for Terrestrial ecosystems, Water consumption for Human Health, Water consumption for Aquatic ecosystems, Human carcinogenic toxicity, and ionizing radiation have a high degree of uncertainty while Freshwater ecotoxicity, Freshwater eutrophication, Human non-carcinogenic toxicity, Marine ecotoxicity have a relatively high degree of uncertainty. All other impact categories in the approaches were relatively low. Also, in the damage assessment uncertainty result, the uncertainty was averagely low.

2.4.4 Discussion of Results

The cement industry in South Africa accounted for 1% of the country's greenhouse gas emissions. According to the reports issued by the Department of Environmental Affairs (2014), between 2000 and 2010, the annual greenhouse gas emission from cement production increased by 27%, from 3.3MT CO_2e to 4.2MT CO_2e. By this time, Portland cement (which does not allow clinker replacement) was becoming the most prevalent product). Also, the annual emission mitigation potential of the cement industry would be 1.26 MT CO_2-eq, 3.65 MT CO_2-eq, and 15 MT CO_2-eq by 2020, 2030, and 2050 respectively.

In both the midpoint and end-point approaches, the analysis was carried out based on the contribution of five production processes to the impact categories and the end-point damage categories. These production processes were: 1) Clinker production, 2) Raw material consumption, 3) Electricity usage, 4) Fuel consumption and 5) Transportation. The results showed that the clinker production stage contributed 76.3% to global warming. Raw material consumption contributed 99.9% to mineral scarcity, 95.9% to ionization radiation, 90.7% to fossil resource scarcity and 77.9% to terrestrial ecotoxicity. Fuel consumption contributed 98.6% to freshwater eutrophication, 96.3% to marine eutrophication, 85.7% to human carcinogenic toxicity and 76.9% to human non-carcinogenic toxicity. In addition, electricity usage contributed 65.8% and 64.8% to stratospheric ozone depletion and fine particulate matter formation respectively.

The midpoint analysis explanation is based on specific substances emitted and the consequence of their emission into air and water or their extraction from the ground. The end-point analysis on the other hand described why attention should be paid to these impacts by showing how these impacts affect our environment directly. The analysis also showed the damage done to human lives, the environment, and the economy in terms of the value of our resources. From the characterization results of the midpoint analysis, for every 1 kg of cement produced, terrestrial ecotoxicity, global warming, human non-carcinogenic toxicity, and fossil resource scarcity with impact values of 1.09kg 1,4-DCB, 0.993kg CO_2-eq, 0.497kg 1,4-DCB, 0.139kg oil eq respectively were found to have the highest impact values. All the environmental impacts from these analyses were grouped based on their units; the grouped impacts and the individual impacts with high value were further analysed. These impacts are for Ozone formation, toxicity, global warming, and fossil resource scarcity. Ozone formation includes ozone formation, human health, ozone formation, and terrestrial ecosystem; toxicity includes marine ecotoxicity, freshwater toxicity, terrestrial ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity. These impacts were further analysed to find the specific substances causing the impacts and the medium through which these substances were emitted.

From the analysis of ozone formation, it was realized that a high concentration of ozone formation in the atmosphere affects both humans and the ecosystem. It was observed that for every 1 kg of cement produced, 0.00421kg of NO_x eq is emitted into the atmosphere, and its effect is seen as ozone formation. Though 0.00421kg seems minimal, concrete is fast becoming the most produced substance on earth as about 1 ton is produced for every human being annually. There is a continuous emission and accumulation of nitrogen oxides in the atmosphere; thus, it is necessary to reduce it to the barest minimum. This was later confirmed in the end-point analysis on damage made to the ecosystem; one of which was emission of NO_x.

Toxicity can be defined as hazardous stressors which impact both humans and the ecosystem and can lead to a pandemic among humans and even aquatic animals. The analysis showed that for every 1 kg of cement produced, 1.6kg of toxicity in the form of 1,4-Dichlorobenzene (1,4-DCB) eq was produced. The Terrestrial ecotoxicity Human non-carcinogenic toxicity impact category was further analysed. In the case of Terrestrial ecotoxicity, 63% of 1.04 kg of 1,4-DCB eq was due to the emission of copper into the air; 12.3% and 7.1% were because of the emission of antimony and mercury, respectively into the air. With Human non-carcinogenic toxicity, 60%, 31% and 1.7% of 0.497kg of 1,4-DCB eq was the emission result of zinc, arsenic and lead respectively into the water body. A high concentration of zinc is deadly for organisms and can cause brain impairment in humans.

One of the major effects of global warming is climate change caused by the greenhouse effect. The result of the analysis showed that for every 1 kg of cement produced, 0.993kg of CO_2-eq was emitted; 78.3% was contributed by clinker production, and the effect was global warming. Further analysis presented that of this 0.993kg of CO_2-eq, 98.8% (0.981kg) was from CO_2. Meyer's report stated that almost 1 ton of CO_2 is emitted for every one ton of cement produced

[123]. This implies that for every 1kg of cement produced, 0.981kg of CO_2 is emitted, and this emission's effect is seen in global warming. In the end-point analysis, CO_2 contributed 56% and 71% of damage to human health and the ecosystem, respectively. In both the midpoint and end-point analysis, CO_2 had the highest emission value.

Jacobson, Kler et al. 2019 [124] established that exposure to atmospheric CO_2 in a poorly ventilated environment has the potential to cause harm to the human body even in low concentrations. The range of effects on human health is limitless. Evidence shows that high concentrations of less than 5000 ppm of CO_2 pose a high health risk. Other indications are that CO_2 concentration with poor ventilation poses the same risk, and the current concentration in an indoor environment has already exceeded this concentration. Statistics have shown that a typical urban environment with 2100 ppm of CO_2 emissions and increased concentration will pose a greater threat. This is the case globally, and nothing like it has been seen in the previous 200 decades: the alarming incidence of rising temperatures is also now more than it has been in the previous 200 decades [125, 126].

For every 1 kg of cement produced, 0.139kg of oil eq is used, and its effect is seen in the scarcity of fossil resources. In the midpoint analysis, 89.7% of the cause of fossil resource impact was a result of the extraction of coal, while in the end-point analysis, it was realized that coal extraction contributed 60% to the damage to resources. This is because over 77% of energy sources in South Africa come from coal. Combustion of coal emits SO_2 and N_2O. SO_2 contributes largely to acid rain and respiratory disease; N_2O, on the other hand, is a greenhouse gas, and its potential to contribute to global warming is 300 times higher than CO_2, although it has a shorter lifespan. It is estimated that South Africa's coal reserves have been reduced to about 53 billion tons. With the current rate of production, coal will likely only be available for the next 20 decades. Moreover, in the end-point analysis of resources, it was discovered that 60% of the damage caused was because coal was extracted from fossil resources.

In the end-point analysis, 1 kg of cement was analysed based on damage to the area of significance to life, damage to human health, the ecosystem, and resources. They are expressed in DALY, species/year, and USD2013, respectively. The analysis showed that 0.0169 USD2013, 3.9E-9 Species/year, and 1.62E-6 DALY are damages to resources, the ecosystem and human health, respectively. The latest recorded population of South Africa was about 60 million and seeing that about three tons of concrete are needed by every individual annually, which contains only about 19% of cement [119], this study was able to estimate the damage caused to human health, the ecosystem and resources based on the cement production requirements in South Africa. From the analysis, about 55,404 DALY: 55,404 is the potential number of lives that could be endangered based on annual cement production in SA. With respect to the ecosystem, the estimation showed that about 133 species are potentially endangered, while for resources, the effect of the potential scarcity of resources would cause a total marginal price increase of R6.2 billion based on the annual cement production requirements in SA.

The various impacts and damage indicators shown in this study represent a need for effective reduction and mitigation. It is important to note that SA relies on clinker and cement importation. Therefore, the empirical values obtained from this analysis might not necessarily translate into real values. Nonetheless, most of the above results are in line with previous studies [78, 79, 95, 111, 114, 127, 128]. The variations experienced in some of the results result from plant/quarry location, proximity to resources (raw materials and fossil fuels), and electricity sources. There are differences in the transportation systems, type of fuel used, and electricity generation mix, among others; thus, a difference in values can be justified.

2.4.5 Comparison with previous studies

According to this study, 0.993 kg CO_2 eq are emitted for every kg of cement produced. Other studies have found higher levels, including 0.83-1.35 kg CO_2 eq/kg cement in China [95], 1.05 kg CO_2 eq/kg in Italy [79], and 0.8-1.2 kg CO_2 eq/kg in Western Europe [93]. The reduced global warming potential reported in this study could be attributed to differences in energy supplies, production technology, and emission regulations between South Africa and the other countries studied. In addition, this study found that raw material use is a significant factor (accounting for more than 90%) in the depletion of mineral resources. In a similar vein, Morsali (2016) [93] identified the utilization of raw materials, particularly the extraction of limestone and clay, as a significant factor in the depletion of resources caused by cement manufacture. The ecotoxicity impacts observed in this study were lower, measuring 1.04 kg 1,4-DCB eq for terrestrial ecotoxicity. Morsali (2016) [93] found a range of 3.2-5.1 kg 1,4-DCB eq. The level of toxicity is significantly impacted by the type of fuel used, the effectiveness of pollution control measures, and the specific technologies employed, all of which might vary. Based on the studies examined in the literature section, it was determined that clinker manufacturing is the most impactful process stage in terms of its contribution to global warming emissions, accounting for 41-76% of the total. This corresponds to the 76.3% contribution observed in this present study. The dominance of clinker demonstrates why lowering the clinker proportion is an approach for impact minimization.

2.5. Conclusions

This study presented an LCA of the environmental impacts caused by a typical SA cement plant used as the case study. The process-oriented (midpoint) and damage-approach (endpoint) of LCIA were adopted in this study to present a comprehensive understanding of these environmental impacts. It was revealed that cement production contributes significantly to environmental emissions in SA, particularly the clinker production phase of cement production. As a result, recommendations were made to help reduce the environmental impacts of cement production in SA.

2.5.1. Contribution and Practical Implications

This study is one of the most recent studies on the environmental impact of cement production. It combines both midpoint and end-point analyses of OPC production in SA. The findings of this study are useful to the government and key stakeholders of the SA cement industry with the view to formulate policies and as well know the areas to concentrate efforts on in reducing the environmental impacts of cement production. For instance, the findings from this study could be applied to develop a practical pathway to reduce the environmental impact of OPC production in South Africa. This can involve an intervention to improve cement production's material composition and technologies (especially for clinker production) based on best practices in other developed countries.

The South African cement industry has the potential to embrace advanced kiln technology to enhance energy efficiency and minimize fuel use during clinker manufacture. Installation of pollution control equipment such as filters and scrubbers are necessary to limit air emissions from the facility. Another viable solution is to transition to lower-carbon alternative fuels, such as biomass and waste fuels, whenever possible. The industry should enhance process efficiency by implementing computerized controls and automation, as well as by employing waste heat recovery technologies to minimize energy requirements; slag and fly ash are examples of additional cementitious materials that can be used to generate lower clinker cement, which will lessen the clinker content. The goal with these alternative materials should be to maximize the amount of clinker substitution. Reducing carbon emissions can be achieved even further by implementing renewable energy sources which include geothermal, wind, and solar energy. Enhancements in the efficiency of quarrying, raw material transportation, and sourcing would be beneficial as well.

South Africa has the option to enforce emissions regulations for cement plants, which would set limits on the release of CO_2, NO_x, SO_x, particulate matter, and other forms of pollution. Implementing incentives to promote the utilization of renewable energy and establishing mandatory requirements for the procurement of a minimum amount of renewable electricity will effectively promote sustainability. It is necessary to implement regulations that encourage the use of alternate cementitious materials to decrease the amount of clinker fractions. Implementing taxes on fossil fuel consumption and the exploitation of raw materials would provide a more accurate assessment of their environmental impacts. It is also suggested that environmental monitoring and reporting requirements be strengthened.

In addition to developing targets for reducing energy consumption, emissions, and carbon footprint, cement producers can undertake environmental impact assessments for new projects. Sustainability could be institutionalized using ISO 14001 or a comparable environmental management system. Analysis of the life cycle can identify development efforts on "hotspots" [129-131] [62,63,64]

2.5.2 Research gaps and needs.

This study considered the recommendations needed to improve environmental impacts and the damage caused by every 1kg of cement produced. Several approaches have been suggested in the current literature, including using carbon capture technologies [129-131], using supplementary materials, and using renewable energy, among others. However, there is a need for SA and other sub-Saharan countries to conduct elaborate research on how these solutions can be implemented with respect to the economic and environmental benefits. Further research could include strategies to reduce or eliminate the effects of emissions on the population and assess the vulnerability issue to fully understand the potential consequences of continuous and intermittent exposure to indoor air with both high and low CO_2 concentrations. Further research could also focus on discovering the best fit of mitigation strategies recommended in this study.

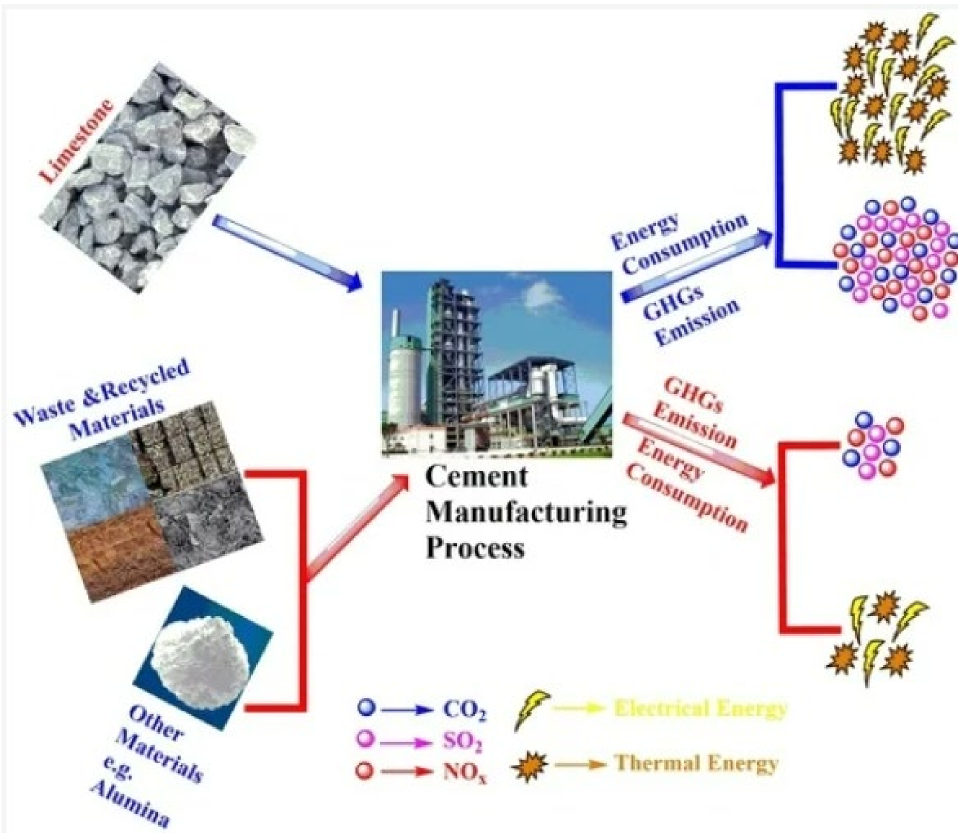
Best fit implies high emission-reduction potential, effective applicability and low cost, and allows the use of existing equipment. In addition, research on sources of sustainable resources could be undertaken.

CHAPTER 3

MATERIAL SUBSTITUTION STRATEGIES FOR ENERGY REDUCTION AND GREENHOUSE GAS EMISSION IN CEMENT MANUFACTURING

This chapter presents a state-of-the art review on various cement production processes and outlined the various material replacement choices available to us which includes use of waste or recycled materials and other materials. We examine the different strategies that have employed material substitution to reduce energy use and GHG emissions during the past decade. It is important to investigate several methods of handling this issue, and material replacement that has been proposed as the best option among many others. This review was published in atmosphere and co-authored by Damilola Caleb Akintayo, Oludolapo Akanni Olanrewaju [132].

GRAPHICAL ABSTRACT



3.1. Introduction

Cement remains an indispensable basic commodity and a resource of great significance that continues to be a fundamental requirement in our everyday life and therefore affects the national and international economic development [133, 134]. Cement industries are well recognized for the vital roles they play in the economic growth of developing nations. This is evident in the value they provide to the home country's production as well as the countless new jobs they generate [135, 136]. As a fundamental material used in the construction and building of structures, it is extensively applied in several fields such as the civil engineering construction, industrial engineering construction, nuclear engineering construction [134, 137, 138]. The constantly increasing demand of cement for various construction projects, steers a corresponding increase in the volume of cement production, and with a lack of hindrance on the side of the demand, the production of cement is expected to experience a constant growth. This growth in cement production has soared rapidly within the past ten years, having recorded an increase in production to a massive 3.4 B ton (Billion Tonnes) [135, 139], and this could not have been achieved without the expense of energy of various forms [140].

Generally, there has been a lofty consumption of energy by various industries in the industrial sector, and this has varied from 30 – 70% of the total amount of energy expended in a list of selected countries as opined by various reports [140-142]. The process of manufacturing cement is known to be an energy intensive process; it involves the consumption of coal (fossil fuel), electrical energy as well as other resources of energy, and this justifies the reason why the cement manufacturing industry alone accounts for 11 – 15% of the total energy expended in the industry [134, 135, 143, 144]. Averagely, the production of a ton of cement utilizes thermal energy of 3.4Gj in the dry process, which in-turn requires electrical energy of about 110kWh [135, 145, 146]. Moreover, the process of producing a ton of cement leads to the release of carbon iv oxide (CO_2) in excess of 0.73 – 0.99 tons, and this is primarily dependent on the ratio of clinker-to-cement along with various factors [135, 147-149]. This CO_2 does not only get released through the combustion of fuel, but rather its release is inherently part of the manufacturing process [150]. Conversely, as opposed to most of the manufacturing companies, the release of GHG such as CO_2 is mostly due to energy consumption; in a cement manufacturing industry, a combination of energy consumption and the manufacturing process of cement results in the emission of CO_2 [150, 151].

The various emissions in the cement industries which are energy-induced could be as a result of direct or indirect energy consumption. The emissions that are related to fuel consumption are as a result of various combustion of these fuels such as fossil fuels (generation of thermal energy), and are referred to as the direct emission, while the indirect emissions are usually spawn from the consumption of electricity (electrical energy) [150, 152, 153]. Emissions from energy generated because of thermal processes involved in raw materials conversion to achieve the clinker, could further add 60 – 90% in amount of CO_2 to the emissions of the manufacturing process, and this is largely dependent on the type of technology applied [154]. Recently, owing to the lofty consumption of energy accompanying the manufacture of cement in the industry, most of the achievements of the cement industries have been tailored to various ways of attaining a high level of energy efficiency improvement without altering the quality of the product and a negative impact on their production capacity [134]. As a result of this, there has been a widespread introduction of commercially retrofitting projects, which are aimed at decreasing the rate of energy consumption and the emission of CO_2.

The major approaches put forward to help check the intensive consumption of energy and emission of CO_2 in the cement manufacturing industry are: (i) The noteworthy emergence of diverse technologies in the cement producing industries for the conservation of energy owing to the non-renewable fossil fuels used as well as a shift to dry process from the conventional wet process of manufacturing cement which has improved the efficiency of energy from 26 –

58% [155, 156]. In the world today, a widespread of these technologies have been applied in various parts of the world; they include the system of transportation of raw materials and the cement produced, roller mills with high efficiencies, highly efficient classifiers, roller presses with high pressure, multiple-stage pre-heating processes with a pre-calciner, a reciprocating extensive cooler, electric motors with great efficiency, adaptable speed drives and a better enhanced refractory [135, 157, 158]. (ii) The utilization of alternate fuels and biomass: this has now become a standard in so many countries, and some have used alternative fuels for replacement of over 50% of the entire quantity of fuels used in the thermal process [153]. The use of petroleum-coke and coal are the universal conventional sources of fuels for the cement plants [135] however, as earlier pointed out that these valuable resources are barely renewable, there have been several alternatives that have been introduced to reduce their use. Some of these include (a) the use of gaseous fuels such as the waste gases from the refineries and gases from landfills as alternatives, (b) the use of liquid fuels such as hydraulic oils, (c) the use of granulated solid or pulverized fuels like the granulated plastics and the sawdust, (d) the use of roughly-crushed fuels such as the crushed tires as alternatives, and (e) the use of lumpy fuels like the plastic bales as an alternative source of fuel [135]. (iii) The replacement of clinker with the use of other products: the raw materials composition and the finished product are known to also contribute to the consumption of energy. The clinker is produced after a host of processes have been carried out such as the raw materials crushing processes, a pre-blend and the grinding of these raw materials which are then calcined to give a semi-finished product, referred to as the clinker. The process of calcination has been reported to use an approximate value of 24% and 38% of electrical and thermal energy respectively, in the cement industry [140, 145]. Reduction of the ratio of clinker-to-cement through the replacement of clinker with a more or less inert limestone filter, pozzolanic materials such as the fly ash; silica fume; eggshells, the use of latently hydraulic substitutes like the granulated slag from the blast furnace, could significantly decrease the required amount of energy [135, 144, 153, 159-161]. (iv) Reduction in the emission of CO_2 by capturing and storing this CO_2 gases: Even though, the vast majority of measures for the efficient use and conservation of energy unconditionally aid in CO_2 reduction, there have been some specific measures that have been specifically implemented to lessen the emission of GHGs [162]. Most of the measures including the Carbon Capture Storage (CCS) do not usually have extensive financial implications with exception to those cement industries which are in countries that impose a significant tax on emission of these gases [163].

Despite all these effort by the cement industries, there is still a large amount of energy being consumed in the manufacturing processes of cement, as well as loft amount of GHGs are being emitted which is far from the vision 2031 plan of one of the notable commissions of the world (the European Commission) to achieve a low-carbon economy [164]. To this effect, there have been some tireless efforts by scientists to come up with various formulas that can help to ameliorate this present situation. Hence in this review, a list of material substitution approaches has been pulled together and discussed, applied in the manufacturing processes of cement within the past ten years, as a means of reducing the intensive energy consumption and GHGs emission in the cement industry. Several researchers have carried out many studies related to this topic, in terms of reviewing the possible solutions to energy conservation: with some of these reviews assessing the improvement of energy efficiency on a long-term [150], comparing the consumption of energy and CO_2 emissions from both recycled cement and clinker production [153], overviewing some of the measures of saving energy [146]. Also, some other reviews on energy reduction and CO_2 emission reduction have focused on substituting some percentage of the finished product (cement) for the preparation of mortars [165, 166], concretes [167-169], and building constructions [170]. However, none of these reviews have discussed the various material substitution approaches employed in reducing the intensive energy consumption and GHGs emission in the manufacturing processes of cement. In this study, a summarized description of the manufacturing process of cement, thus giving insight to the need for material substitution was presented. This study went further to critically review relevant literature that have successfully employed material replacement strategies to reduce the intensive energy consumption and GHGs emission from cement production. Lastly, this study presents a future perspective on how the use of material substitution in the manufacturing process of cement could aid in energy reduction and GHGs emission.

3.2. Description of Manufacturing Processes of Cement

According to Madlool *et al*., the production of cement involves nine distinct stages that are energy-intensive (Figure 3.1), necessitating an improvement to maximise energy efficiency [140, 171]. The very first stage being the extraction and crushing of limestone, a major element quarried by an open mine process, which is usually carried out by drilling with heavy-duty machines or equipment like the dump trucks, bulldozers, and explosives (blasting) before they are transported with the use of a mechanical conveyor. Limestone, which contains 75 – 90% of calcium trioxocarbonate iv ($CaCO_3$) in the raw form with the remaining percentage made up of $MgCO_3$ and other impurities (iron, silica, and alumina), is first fed into a primary crusher, then moved to the secondary crusher which reduces the $CaCO_3$ inlet sizes to 25mm before it is finally reduced through the last crusher (tertiary) [140, 171]. The principal firmness of the cement is usually provided by the lime (CaO) as well as the silica, while the iron helps in the reduction of the temperature of reaction and gives the cement the usual grey colour [140].

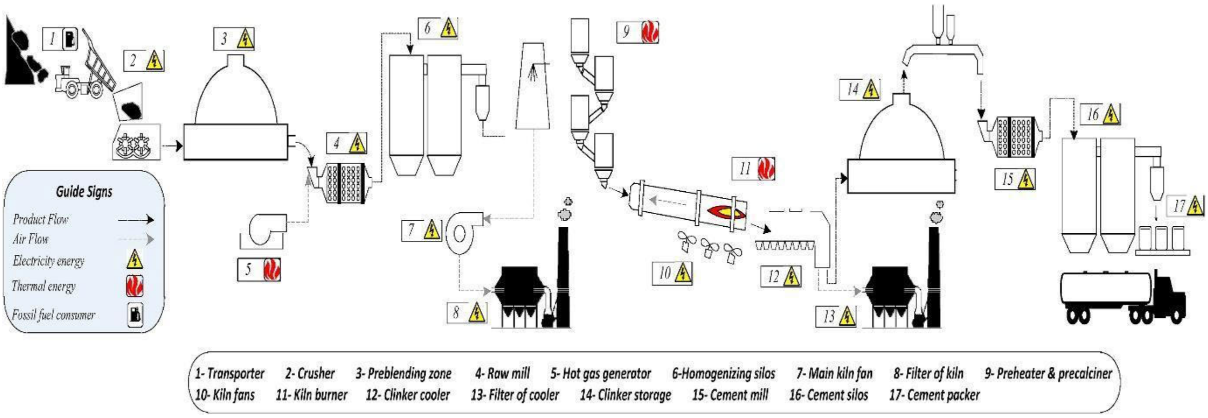


Figure 3. 1. Diagrammatic illustration of energy consumption in the manufacturing process of a cement in the cement industry [135].

To get the required raw feed compositions, other elements such as bauxite, quartzite, iron, and silica must be added prior to the processing stage for the raw mix of $CaCO_3$ and the additives to be grinded to obtain smaller fragmented particles. These additives aid in the prevention of any compositional abnormalities that may arise naturally, thus allowing them to be stored in silos or hoppers and transferred with weigh-feeders via conveyor belts [140, 172, 173]. In this stage, a “Vertical Roller Mill” (VRM) or a “Ball Mill” is employed for the process of raw mix grinding while some of the excessive heat from the kiln are used for drying the raw mixture in this processing stage. There are many factors which governs the choice between the ball mill and the VRM and these include the quantity of moisture present in the raw materials, the material abrasiveness, the level of energy consumption, reliability and viability economically [140, 174, 175].

A major energy consuming aspect of cement production is the clinkering step [176, 177], done inside the kiln (a vital piece of the plant used in manufacturing cement) and the preheating tower, which comes with a combustion chamber referred to as a pre-calciner. At this stage, CO_2 is produced by a series of chemical reactions that causes the raw mix to melt, fuse together, and create a clinker. The red-hot clinker is, thereafter, exuded from the kiln, moved through various coolers in order to recover part of the thermal energy and reduce the handling temperature of the clinker [178]. The clinker when being exuded, possesses an approximate temperature of 1500°C, thus the cooler is used to blow an ambient air above the red-hot clinker, which helps in the reduction of the temperature of the clinker to 170°C approximately [179].

Kiln feed compositional variations adversely affects the effectiveness of kiln [180], however, this natural variation of chemical in the different raw materials can be effectively reduced by increasing the relative blending proportion and homogenizing these raw materials using a consecutive blending silo to reduce the amount of used clinker, which will consequently lead to a reduction in the identified energy consumption of the finishing product. Another important part is the mill, a cylindrically shaped metallic chamber containing balls made of metals, which is grinded with the clinker as well as the mix of additives to form the cement [140]. The grinding of clinker alongside various other additives present in the cement mill is the final step of the process before cement is ready for use or stored in the cement silo before they are transported to their various sites of use.

3.3 Various Material Substitution Approaches Applied for the Reduction of Energy in Cement Manufacturing Process.

Cement production accounts for 11–15% of all industrial energy consumption, and it is crucial to develop strategies to reduce the energy required for this process and the resulting CO_2 emissions, which are the primary cause of global warming. Several researchers have come up with various ways of solving this problem with the use of material replacements such as recycled and non-recycled materials of both biogenic and non-biogenic origin [181-188]. This section of the thesis examined articles that have employed material substitution in cement manufacture from peer reviewed literature databases such as google scholar, Scopus and science direct. Although several studies centred on material replacements have been reported with relation to the production of mortars, concretes and the likes, with various amounts of energy and CO_2 emission reductions reported, but due to these studies not reporting about the reduction of the consumption of energy and emission of CO_2 (GHGs) in the manufacturing process of the cement used for these concretes and mortars, these studies were considered to be out of the scope of this review, and were thus, not included in the discussions below. Therefore, the focus was only on studies which have discussed the various ways of reducing the amount of energy used and CO_2 emitted during the manufacturing process of the cement within the past decade. A total of 40 articles were identified and included in the next section.

3.3.1 Use of Waste or Recycled Materials

There have been several reports on the use of different waste materials as well as the recycling of materials such as oil-based-mud [189], waste glass powder [190], and kaolinitic waste [50] for the manufacture of cement, and various percentages of energy reduction as well as CO_2 emission reduction has been recorded. A research group led by Abdul-Wahab et al., [189] explored the use of an oil-well drilling waste in the form of an Oil-Based-Mud (OBM) as a substitution material for limestone in one of the stages (Kiln) of the manufacturing process of cement. The substitution, which was made in various percentages including 1%, 2%, 3%, 4%, and 5% of OBM in place of limestone reportedly reduced the amount of CO_2 emitted in the manufacturing process by about 1% to 6% depending on the percentage OBM substitution made. Although the authors failed to report the impact on the reduction of energy in the manufacturing process, they believed that this hydrocarbon waste (OBM) could enhance the efficiency of thermal energy used in the plant for the manufacturing process, which will in-turn reduce the consumption of energy in the cement plant. However, this is yet to be proved and therefore calls for more studies to be carried out to evaluate the effect of energy reduction using this OBM.

Recently in another study, Junior et al., (2023), prepared a "Limestone Calcined Clay Cement" (LC^3) with kaolinitic residue as the replacement material, and used "Ordinary Portland Cement" (OPC) and "Portland Composite Cement" (PCC) as their reference materials [191]. The composition of the prepared LC^3 was made up of the clinker of OPC, gypsum, limestone and metakaolin; having a clinker replacement of 45 percent and 60 percent with kaolin to limestone compositional ratio of "2:1, 1.5:1 and 1:1" respectively, for each replacement percentage. From their study it was observed that, the 45% replacement of clinker (LC^3 – 50) had an energy reduction ranging from 28% to 33%, while the 60% replacement of clinker (LC^3 – 35) had an energy reduction ranging from 37% to 44% relative to the reference OPC; while an energy reduction between 10% and 25% were observed across the 45% and 60% clinker replacement (LC^3 – 50 and LC^3 – 35) relative to the reference PCC; depending on the ratio of the kaolin to limestone used (Figure 3.2A). Also, the study reported a significant reduction in the amount of CO_2 emitted during the process of production of the cement (Figure 3.2B). The 45% replacement of clinker (LC^3 – 50) had a CO_2 emission reduction ranging from 35% to 37%, while the 60% replacement of clinker (LC^3 – 35) had a CO_2 emission ranging from 47% to 50% relative to the reference OPC; the 45% replacement of clinker (LC^3 – 50) were observed to have a reduction in the amount of CO_2 emitted with a percentage ranging from 20% to 22%, while the 60% replacement of clinker (LC^3 – 35) were observed to show a CO_2 emission reduction ranging from 35% to 38% relative to the PCC reference, and these were dependent on the ratio of the metakaolin to limestone used [191]. The authors concluded that their proposed formula would be a possible solution to the reduction of energy consumption and CO_2 emission in the manufacturing process of cement in the industry, and this can be arguably correct, given the significant percentage reductions obtained. However, it is important to state that the materials used were acquired from a particular location and this means that the same material from a different location may not yield the same results, owing to their differences in constituents based on the soil type present in the area. Hence, further studies are encouraged with the same formula, with collection of materials from different locations for confirmation of results.

Another group of researchers led by Hossain et al., [190] employing a "Life Cycle Assessment" (LCA), undertook a study to explore comprehensively, the amount of energy consumed and CO_2 (GHGs) emitted from the manufacturing process of OPC in comparison to other types of cement whose manufacturing process were strategically modified. These modifications were in two forms, which include the form of raw materials substitution such as the use of fly-ash (FA) and waste glass powder materials and secondly the use of biofuel generated from wood waste alongside coal (co-fuel). The results from the LCA raw material modification strategy showed that, the 20% FA modified Portland cement (PFC) reportedly consumed about 16% lesser energy (Figure 3.2C) as well as emitting 18% lesser CO_2 (Figure 3.2D), while the other type of cement with 20% modification using waste glass powder (Eco-GC-2) showed similar lesser percentage of energy consumption (about 16%) (Figure 3.2C) and CO_2 emission (17%) (Figure 3.2D), for the manufacturing process compared to the reference OPC [190].

The application of this first strategy can be seen to have an impact on the amount of energy consumed and CO_2 emitted in the manufacturing process of cement. Although the impact may be regarded as being not so significant, it is a light in the positive direction for the reduction of both energy consumption and CO_2 emission in the cement industry. Interestingly, the research group noted that, approximately 64% of the total amount of energy consumed and 32% of CO_2 emitted in the manufacturing process of the OPC were associated with the combustion of coal inside the cement processing plant. This led to the implementation of the second strategy, which was the substitution of 10% to 50% of coal in the plant with a biofuel generated from wood waste. Upon applying the bio-fuel substitution, the consumption of non-renewable energy by the manufacturing process of OPC was significantly reduced by almost 30% (about 5.81% to 28.98%) (Figure 3.2F), while the percentage of CO_2 emitted were reduced with about 2.76% to 13.57%, depending on the percentage replacement of coal with the biofuel (Figure 3.2E).

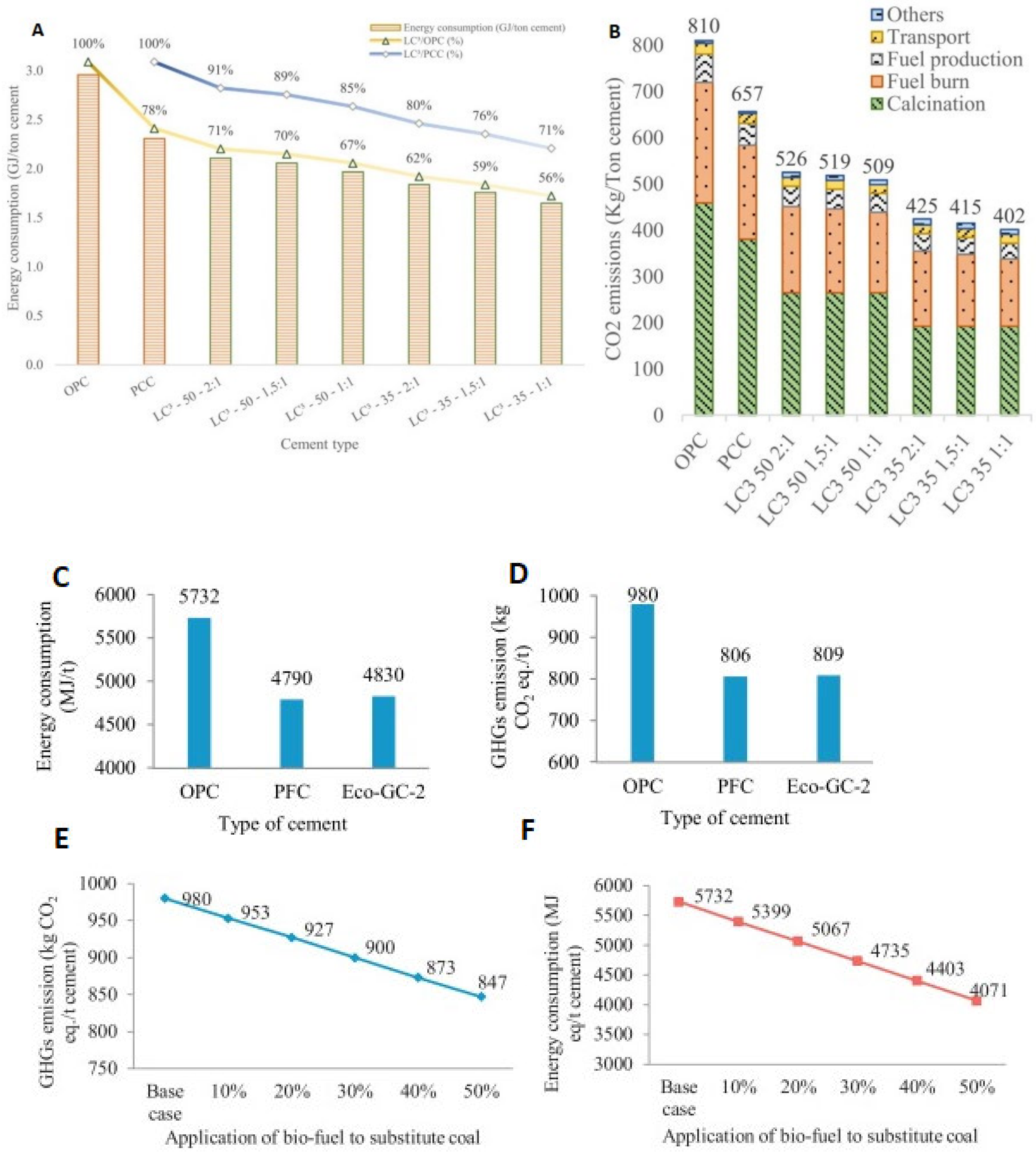


Figure 3.2. (A) Consumption of energy during the process of calcination and the energy consumption reduction for LC^3 relative to the references (B) Emissions of CO_2 for various

cements evaluated [50]; (C) Consumption of energy during the manufacturing process of OPC, PFC and Eco-GC-2 (D) Emission of CO_2 during the manufacturing process of OPC, PFC and Eco-GC-2 (E) Emission of CO_2 during the manufacturing process of OPC upon modification of coal with bio-fuel (F) Consumption of energy during the manufacturing process of OPC upon modification of coal with bio-fuel [49].

Apart from oil-based-mud, waste glass powder, and kaolinitic waste, various scientists have been able to come up with some other alternative sources of waste materials, which can be applied as a supplementary material, to help reduce the amount of energy consumption and GHGs emission in the manufacturing process of cement in the cement industry. In 2020, El-Salamony [192] led a research group in study to explore how a cement plant kiln's efficiency can be enhanced with the use of a modified alternative source of fuel. This group of scientists established the fact that the mixture of rice husk with solid waste derived from refuse (Alternative Fuels [AFs]) such as could be used as an alternative source of fuel in the kiln plant. From their study it was reported that, the successful replacement of 17% of coal with the use 0% to 5% of the mixture of these materials, resulted in a corresponding reduction of about 13% of the consumption of electrical power in the manufacturing process of cement [192]. Also, it was reported that the emission of GHGs such as sulfuric oxides and nitric oxides decreased owing to this substitution.

Another study led by Fyffe et al., [193] explored the use of waste materials obtained from "municipal solid waste" landfills in the form of a "solid recycled fuel" (SRF) as a substitution material for the manufacturing process of cement. According to the researchers, the energy consumption rate was reduced by 5.5% by the SRF compared to the reference cement (OPC). Also, conducting a near-term and future one-year scenario proposition, it was found out that SRF would have an energy consumption reduction of 6.2% and 6.3% respectively, relative to the reference cement (Figure 3.3A). Taking the research further, the research group decided to quantify the percentage of GHGs such as NO_x, SO_2, CO_2 emitted during the manufacturing process of both the reference and SRF cement. From their study, they found out that SRF had reduction in the percentage of GHGs emitted in both the early, near-term and future one-year scenario proposition (Figure 3.3B and 3.3C), compared to the reference cement with exception to NO_x which had a higher emission percentage compared to the reference cement (Figure 3.3D).

Haven obtained the above results, Fyffe et al., [193] then concluded that the use of SRF as a possible replacement of fossil fuel in the kiln of the cement plant during the manufacturing process of a cement in the cement industry is of great benefit for energy efficiency as well as the environment at large. However, based on the fact that the emission values for NO_x obtained was higher than that of the reference, which may be as a result of the compositional content of the SRF (40:60 – percentage ratio of fibrous mixture of materials to plastic materials), there is need for more research using this SRF with varying proportion of the composition, to be able to validate what percentage of what kind of waste would bring about the best possible results.

The synergistic action of the use of both pozzolan and calcium hydroxide as supplementary materials for the manufacturing process of cement has also been explored by Vizcaíno-Andrés et. al., [194]. The study which reported the replacement of up to 50% clinker with pozzolan and calcium hydroxide, employing the percentage amount of 15%, 20% and 25%, was said to have resulted in 15% reduction of electrical energy consumption as well as 31% CO_2 emission reduction relative to OPC.

Also, there have been some groups of researchers who have attempted the use of waste cement, by recycling the cement to produce a new cement and comparing the rate of energy consumption as well as CO_2 emission to the normal traditional cement OPC. Just recently, the use of waste hardened cement by thermo-activating the cement into recycled cement (RC), was explored as a supplementary material in the manufacturing process of cement, with the aim of reducing the consumption of energy and CO_2 emission in the cement industry [155]. According to [155] the production of RC from the cement pastes which was secured in from waste concrete can be seen as one of the solutions to the problem of high energy consumptions and CO_2 emission in cement manufacturing process. This is because in their study, the manufacturing process of RC yielded percentage energy consumption reduction of 30 – 40% and CO_2 emission reduction of 80% relative to the cement produced using clinker. In another study, He, Z., et al., [195]made a comparison between the manufacturing process of OPC and recycled cement (RC–450°C and RC–800°C). From the study, it was observed that the emission of CO_2 from the raw materials per ton was for RC–450°C: 4.3% and for RC–800°C: 24.4% of the CO_2 emission value of OPC.

In addition, the research group went ahead to quantify and compare the CO_2 emission from the entire manufacturing process, and it was observed that the CO_2 emission produced by RC–450°C was around 0.05 in tons while RC–800°C was around 0.19 in tons, which was relatively low as compared to OPC which was 0.78 in tons. These results translate to a reduction percentage of approximately 94% and 76% for RC–450°C and RC–800°C respectively, relative to the value of OPC (Figure 3.3E). Unfortunately, the research group was not interested in the amount of energy involved in the manufacturing process as they did not report the amount of energy expended in the manufacturing process of the cement. However, it can be agreed that, just like the previous study by Sousa et al., [155] who also explored the use of RC as a substitution material, obtaining about 80% CO_2 emission reduction, and between 30% to 40% energy consumption reduction; if the researchers had quantified the energy consumption involved in the manufacturing process, there is a high possibility that they would have obtained close to 50% of reduction of energy consumption for RC–450°C and RC–800°C relative to

OPC, but this can only be an assumption because it was not quantified. This gives room for more research work to be done, to prove this assumption.

Generally, from the studies above, there has been great success recorded in the process of recycling waste materials as a supplementary material in the manufacturing process of cement. A good percent of energy consumption as high as 40% can be reduced while on the other hand, GHGs emission of up to 94% can be reduced with the use of these waste materials from various industries and the environment (Table 3.1). Waste products are often not well-disposed in some countries, especially the developing countries of the world, owing to their large amounts as well as the cost implications involved in disposing of these waste materials, depending on the type of waste [189]. A good example is the oil waste which is known to pose a hazard to the environment and thus, demand some peculiarly specific treatment. These waste materials such as the OBM, the kaolinitic waste, glass waste powder amongst others, have been shown to contain appreciable quantities of some of the major oxides that identifies with the manufacturing processes of cement and are thus, reused in place of the original traditional materials [196-200]. The ability to reuse these waste materials, will go a long way in preserving the traditional materials and natural resources, while at the same time promoting a better efficiency of the consumption of energy and the quest of having a carbon free environment, owing to the reduction in the emission of CO_2 from the manufacturing process of cement.

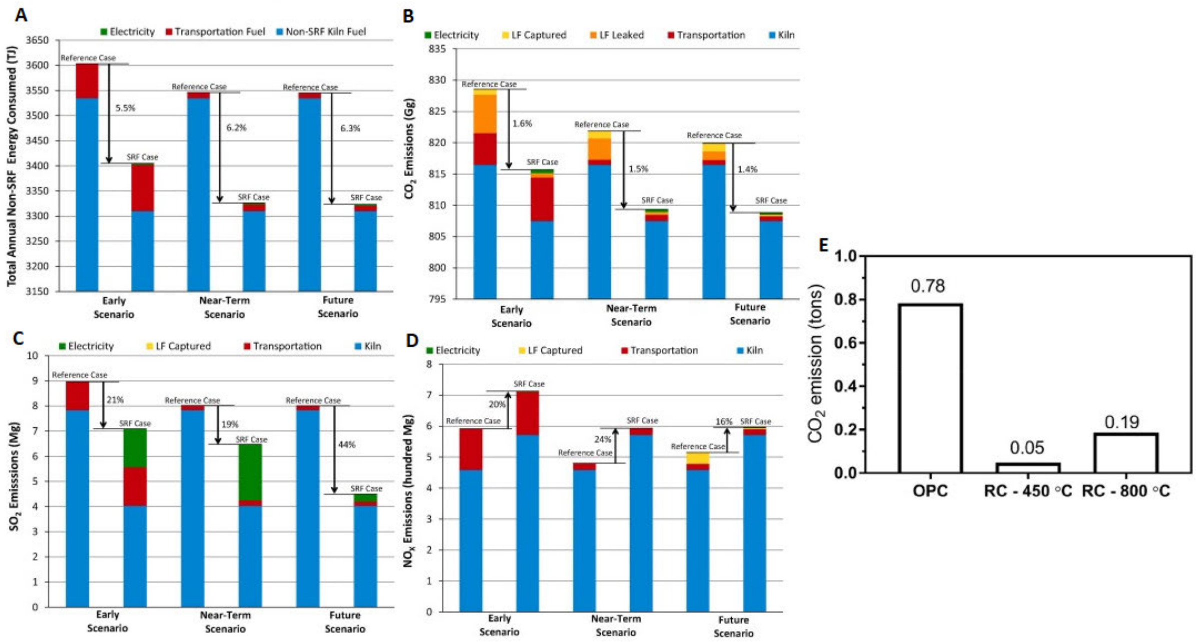


Figure 3. 3. (A) Energy consumption reduction (B) CO_2 emission reduction (C) SO_2 emission reduction (D) NO_x emission increment [193] and (E) CO_2 emission reduction .

Table 3. 1. Use of Waste or Recycled Materials.

Type of Replacement Materials Used	The Percentage Replacement	Percentage of Energy Reduction	Percentage of GHGs (NO_x, SO_2, CO_2) Reduction or Increment	References
Oil-Based Mud; Metakaolin; and Fly Ash + Glass waste + Biofuel				
Oil-Based-Mud	OBM: 1% – 5%	Not Stated	OBM: 1% to 6%	[189]
Metakaolin (Kaolinitic residue)	OPC: 45% & 60% PCC: 45% & 60%	OPC 45%: 28% to 33%. OPC 60%: 37% to 44% PCC 45% & 60%: 10% to 25%	OPC 45%: 35% to 37% OPC 60%: 47% to 50% PCC 45%: 20% to 22% PCC 60%: 35% to 38%	[191]
Fly-ash, Glass waste powder, and Wood waste (Bio-fuel)	PFC: 20% Eco-GC-2: 20% Bio-fuel: 10% – 50%	PFC: 16% Eco-GC-2: 16% OPC: 5.81% to 28.98%	PFC: 18% Eco-GC-2: 17% OPC: 2.76% to 13.57%	[190]
Rice Husk + Solid Waste; Solid Recovered Fuel from Landfills; and Pozzolan + Calcium Hydroxide				
Rice husk, Solid waste from refuse such as plastic waste, garden waste, wood, tissues, cardboard and paper.	AFs: 0% – 5%	AFs: 13%	Not Stated	[192]
Solid Recycled Fuel contains about 60% of plastic and about 40% of fibrous mixture of materials.	Not Stated	SRF: 5.5% (early scenario); 6.2% (near-term scenario); 6.3% (future scenario)	CO_2: 1.6% (early scenario); 1.5% (near-term scenario); 1.4% (future scenario). SO_2: 21% (early scenario); 19% (near-term scenario); 44% (future scenario). NO_x: 20% increment (early scenario); 24% increment (near-term scenario); 16% increment (future scenario).	[193]

Pozzolan and Calcium hydroxide	15%, 20% and 25%	15%	31%	[194]
Use of Recycled Cement				
Hardened waste cement	RC – Complete replacement	30% – 40%	80%	[155]
Waste or Recycled Cement	RC – Complete replacement	Not Stated	RC–450°C: 94% RC–800°C: 76%	[195]

Just like the use of various waste or recycled materials as a substitution material for the manufacturing process of cement gave considerably good percentage reduction of the consumption of energy and CO_2 emission reduction, a study which focused on use of other materials has been explored with success recorded. In 2014, Atmaca & Yumrutaş [158] in a study, aimed to investigate the specific consumption of energy in a rotary kiln which is used in the manufacturing process of a cement in the cement industry. To achieve this aim, supplementary materials such as alumina and magnesia spinel were used for the preparation of the clinker. Although the replacement percentage was not reported, it was gathered that, using these materials led to the energy consumption reduction of 7.27% during the process of clinker production. Although the percentage of the CO_2 emission reduction was not specifically stated, it was reported that a corresponding decrease of 1,614,480 kg of CO_2 emission was recorded [158]. The researchers then concluded that, the ability to minimize heat loss through insulation and the reduction of temperature of the outlet gases by an effective transfer of heat within the unit, as well as minimizing the leakage of steam and air through sealing, would greatly impact the reduction of the consumption of energy. Notwithstanding, the researchers concluded that the need for advanced studies involving the various parameters that may affect the optimal system performance, which could help to enhance the reduction of energy consumption in the clinker manufacturing process, is crucial and very urgent. Hence more research is encouraged.

3.4. Conclusion

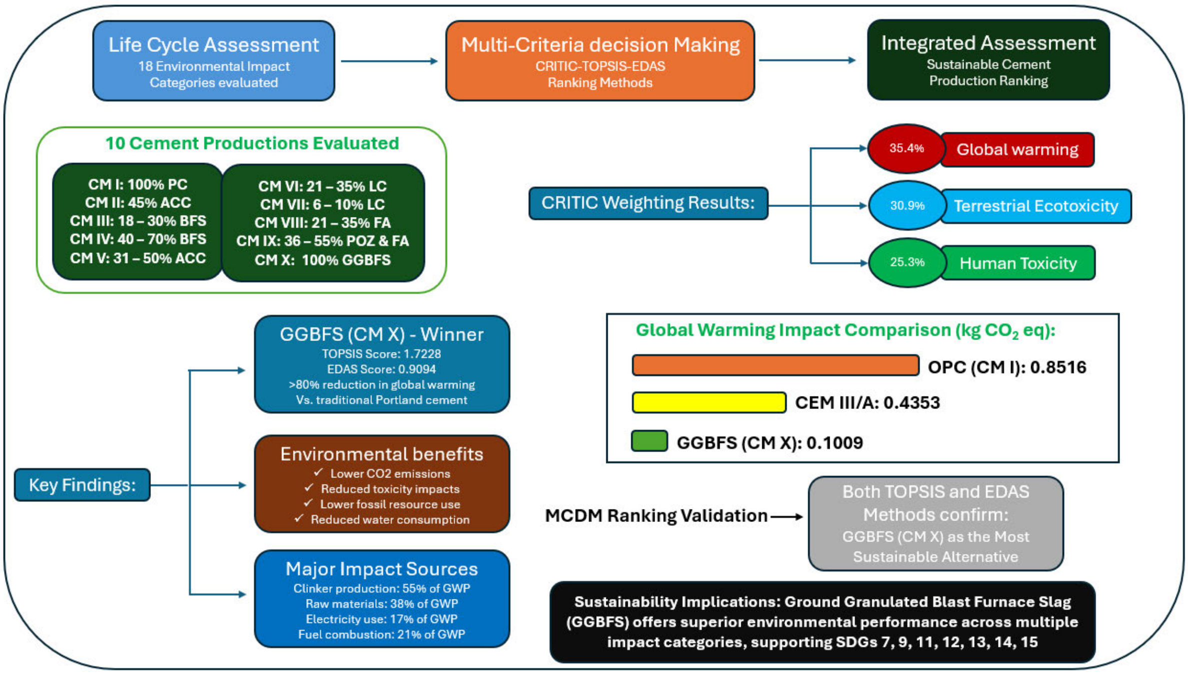
Cement manufacturing process is known to consume energy intensively as well as emit extensively, GHGs such as CO_2, which continues to become a source of concern. The use of traditional raw materials of natural origin such as fossil fuels, limestone, cannot be sustained owing to their constant depletion and the length of time in which it takes to renew these materials, and in some cases, the materials are non-renewable. The use of supplementary materials such as waste or recycled materials and other materials has shown to be a possible solution to this problem, and this can be observed from the various studies that have explored their use as a substitution material at different levels of substitution, with various successes recorded. Therefore, the long-awaited approach for the reduction of intensive energy consumption and CO_2 emission could just be the application of these materials as a substitute for the raw materials used in the manufacturing processes of cement in the cement industry.

CHAPTER 4

COMPARATIVE ANALYSIS OF CEMENT PRODUCTION METHODS USING A LIFE CYCLE ASSESSMENT AND A MULTICRITERIA DECISION-MAKING APPROACH

This chapter presents a comparative study to give insight on the most sustainable cement production process with the most reduced environmental impacts. Manufacturing cement has a major impact on climate change, resource depletion, and pollution. Selecting sustainable cement alternatives is vital but requires difficult trade-offs between numerous variables. This chapter carried out an LCA to quantitatively evaluate the environmental effects of 10 different methods of cement production across 18 distinct impact categories. The objective of this study is to determine the most environmentally beneficial way of cement manufacturing by employing an integrated Life Cycle Assessment-Multi-Criteria Decision-Making technique. The content of this study was published in sustainability and co-authored by Olubayo Moses Babatunde and Oludolapo Akanni Olanrewaju [201].

GRAPHICAL ABSTRACT



4.1. Introduction.

The construction industry is essential to global development, however, its contribution to pollution, resource depletion, and greenhouse gas emissions made it a major negative influence on the environment [202]. This is due to globalization and industrialization. The building industry urgently must transition to sustainable practices as urbanization picks up speed [203]. First, the building industry consumes a significant number of natural resources, including minerals, water, and wood [204]. Deforestation, habitat destruction, and soil degradation are caused by the unsustainable extraction and use of natural resources [205]. Accepting sustainable substitutes, including repurposed materials and resources obtained ethically, can lessen these negative impacts while fostering ecosystem health and biodiversity [206]. Secondly, a significant portion of carbon emissions are caused by the construction sector [207]. Conventional building techniques mostly rely on energy-intensive operations, such as the manufacturing of cement, which contributes significantly to global Carbon dioxide (CO_2) emissions [162, 208]. The sector's carbon footprint can be significantly decreased by using renewable energy sources, energy-efficient technologies, and eco-friendly materials [209]. Using sustainable building methods increases a facility's energy efficiency and lowers operating costs over time for both owners and inhabitants [210]. Employing green building standards, guarantees that buildings are planned and built with an emphasis on environmental performance, water efficiency, and energy conservation [211]. Promoting a sustainable environment in the building industry is essential to reducing environmental deterioration [212]. The construction sector can simultaneously meet the increasing demand for infrastructure expansion and promote a healthy planet by implementing energy-efficient technologies, green building standards, and eco-friendly materials [213].

The sustainable environment is greatly impacted by cement manufacture, which also contributes to a number of environmental problems [214]. The large carbon footprint connected to the production of cement is one of the main issues. CO_2 is released during the high-temperature calcination of limestone to produce clinker, a crucial component of cement [129]. Cement manufacture is a significant source of greenhouse gas emissions since this process is responsible for a significant amount of the industry's emissions [215]. In addition, the extraction of raw materials like clay and limestone from the ground can result in habitat degradation, soil erosion, and biodiversity loss [216]. The process of extraction damages ecosystems and depletes natural resources, which affects the equilibrium of the environment as a whole [217]. Adding to energy use and air pollution is the transportation of both raw materials and completed cement products [140]. The cement industry has been investigating substitute materials, such as supplementary cementitious materials (SCMs) like fly ash and slag, which can partially replace conventional clinker [218], in order to address these issues and move toward a more sustainable future. Research is being done to investigate new production technologies including carbon capture and utilization (CCU) in an effort to reduce CO_2 emissions from cement plants [219].

Cement production has a significant environmental impact, mostly because of its resource-intensive nature and high carbon emissions [97]. To create a cement industry that is more environmentally friendly and sustainable, sustainable practices in the sector include investing in technologies that lower carbon emissions, embracing alternative resources, and increasing production efficiency. The process of calcining limestone at a high temperature to create clinker is the primary cause of excess CO_2 emissions from the cement industry [194]. This technique adds significantly to the industry's large carbon footprint by releasing a large amount of carbon dioxide. Beyond its manufacturing, cement-related CO_2 emissions have a significant impact on global greenhouse gas levels, which in turn affects climate change [220]. Achieving sustainability goals requires addressing this surplus CO_2, which is why the industry is investigating new materials, creative production techniques, and carbon capture strategies to lessen the impact on the environment.

Cement production uses a lot of energy, making up a sizable amount of all industrial energy used worldwide [140]. The calcination of raw materials and other high-temperature clinker production processes are the main source of energy requirement [221]. The industry uses a lot of energy for the transportation, blending, and grinding of both raw materials and completed cement [140]. The sector is embracing alternate fuels, renewable energy sources, and energy-efficient technologies to improve sustainability. These steps are intended to lessen the energy consumption of cement production's negative environmental effects while fostering a more efficient and sustainable sector of the economy.

For the construction sector to have a steady and dependable supply of this necessary building material, cement production must be ongoing. The fundamental component of concrete, a vital building material used worldwide, is cement. Production remains uninterrupted, allowing for the timely completion of infrastructure projects and maintaining development timetables. The need for cement in the construction sector highlights the financial significance of its ongoing production, which affects the development of infrastructure, employment generation, and economic growth. The importance of continuous production in maintaining the construction industry is further highlighted by the fact that a stable supply of cement is essential to fulfilling the growing demand for infrastructure, housing, and commercial space globally [222].

The manufacturing of cement is responsible for around 7% of CO_2 emissions worldwide [152]. When limestone is heated to a high temperature and converted into a clinker, CO_2 is released during the process. Cement manufacture emits between 0.73 to 0.99 tonne of CO_2 per tonne of cement [162]. The processes in the high-temperature kiln require significant energy inputs. To minimize CO_2 emissions and lower energy consumption, as well as to expand the use of supplemental materials and efficient technology, the cement production industry is striving toward sustainability. Based on the above discussion, there is a need to consider an environmentally friendly way of cement production hence the need for the study. The following section reviews the various techniques from technologies, models, and policies among others that scholars have investigated to mitigate the emissions emanating from the production of cement. The Methodology section presents the integration of LCA and MCDM and the result and discussion section explain the findings of this study.

4.2. Literature Review

Several studies show that the manufacture of cement has a substantial carbon impact. Carbon dioxide is released during the calcination of limestone, which is the process used to produce clinker, the main component of cement [223]. Global anthropogenic CO_2 emissions from cement production are estimated to be between 5 and 7%, based on research published [21]. Researchers have looked for substitute materials and technological advancements to lessen cement production's negative environmental effects. The potential for SCMs such as fly ash and slag to partially replace conventional clinker in cement manufacturing is being researched [224]. Furthermore, scholars are exploring CCU technology as a means of reducing carbon dioxide emissions associated with the production of cement [219]. Evaluating the viability of using CCU to absorb and use CO_2 emissions from cement factories was researched [225]. By converting pollutants into useful products, this strategy seeks to promote economic and environmental sustainability.

Specialty cements provide alternate options to traditional Portland cement, although their general application is limited. Magnesium oxide cement is suitable for specific applications; nevertheless, their higher prices prevent widespread replacement of steel-reinforced concrete on a large scale [226]. Calcium aluminate cements offer regulated solidification but require improvements in performance [227]. The durability of sustainable foam concrete using additional cement varies [228]. Current research is primarily concerned with enhancing the sustainability of Portland cement by exploring supplementary materials, alternative cements, and new technologies. The aim is to minimize environmental consequences while meeting the growing demands for infrastructure. Scrivener et al [229], emphasizes how critical it is to use creative solutions to produce cement in a way that is more environmentally friendly and sustainable. According to studies, replacing conventional clinker with additional cementitious materials such as fly ash and slag is recommended [230]. The use of blast furnace slag (18–30%) and other alternative elements (18–30%) to reduce environmental effects is highlighted in [231]. Juenger and Siddique [232] highlighted the advantages of using additional cementitious materials in construction. These substitutes improve the longevity of concrete while simultaneously lowering CO_2 emissions. Diversifying alternatives such as fly ash and silica fumes are investigated in studies conducted by [233]. Dixon et al. [234] acknowledged the good benefits of the environment, but also mentioned problems such as material unpredictability. The available research highlights the possibility of strategically incorporating alternate elements into cement manufacture to improve its sustainability. Research has shown that altering the way cement is made, especially by adding a large amount of blast furnace slag (40–70%), can significantly lessen the environmental effect [235]. Research demonstrates the advantages of greater blast furnace slag percentage concrete for the environment and better performance [236]. This strategy tackles the issue of resource depletion in addition to reducing carbon emissions. The industry's demonstrated commitment to environmental responsibility is demonstrated by the growing emphasis on blast furnace slag as a significant substitute component, which portends a positive move toward more environmentally friendly cement production methods. An effective strategy for minimizing environmental impact is demonstrated by research on changing cement manufacturing with blast furnace slag (31–50%) and other alternative elements (31–50%) [237]. Gartner and Sui [238] provide evidence that combining limestone with conventional clinker may have benefits. This strategy tackles resource conservation issues in addition to lowering carbon emissions.

In establishing the most preferred environmentally friendly method for cement production, it is essential to consider various environmental aspects involved in its production. Usually, when selecting or ranking the most preferred alternatives based on multiple criteria, MCDM offers a robust approach. Another important method in assessing the most preferred environmentally friendly cement production approach is LCA; it offers an approach evaluating various environmental impacts in the production of cement. From the foregoing, there are several reasons why it is crucial to integrate MCDM tools and the LCA approaches in cement manufacturing studies [239]. These reasons all work together to provide a more thorough and reliable sustainability assessment. LCA offers a thorough grasp of the environmental effects connected to every step of the cement production process, from the extraction of raw materials to end-of-life concerns [240]. A comprehensive assessment of the life cycle environmental footprint is ensured by integrating LCA, making it possible to pinpoint problem areas and opportunities for development [241]. A flexible framework that can adjust to shifting circumstances and preferences over time is frequently offered by MCDM approach [242]. MCDM considers a number of elements, including social, economic, and environmental aspects [243]. Using a holistic approach guarantees that decisions are made considering the larger sustainability context rather than just one aspect. MCDM assists in evaluating trade-offs and synergies between various variables, guiding decision-makers through the challenges of striking a balance between conflicting goals in the production of building materials [244].

With regards to the literature on MCDM and cement manufacturing, various studies have been conducted. These included a study that proposed the selection of the most appropriate method for designing concrete mixes and determining the mix parameters that have the greatest impact on the quality of sustainable concrete [245]. Gökcekuş et al [246] evaluated these approaches - MCDM, specifically the Fuzzy Preference Ranking Organization Method for Enrichment Evaluation (F-PROMETHEE), for material homogeneity, dust emission, manufacturing cost, capital cost, fuel consumption, quality, and CO_2 emission. The dry method's reduced carbon dioxide emissions, fuel consumption, production costs, and processing time stand out. Furthermore, Marinelli and Janardhanan [247] examined cement production's environmental impact, notably in India, the second-largest producer. To reduce energy-intensive operations and global warming, it stressed the importance of green practices. Also, Bathrinath et al. [248] conducted an analysis of the elements that impact the quality and quantity of the cement manufacturing industry. The study utilized the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to investigate the interconnections between eighteen manufacturing parameters. The findings emphasized that capital investment, quality control, and machinery/equipment maintenance have a significant impact on cement output. These insights are helpful for industrial management to enhance both the quality and quantity of production

Considering the preceding discourse, it is imperative to examine a method of cement production that is ecologically friendly; this is the focus of this present study. The study uses LCA and MCDM for the selection and ranking of cement manufacturing methods based on environmental impacts.

4.3. Methodology

The research utilizes a methodological framework that combines LCA and MCDM. This integration allows for the incorporation of LCA's environmental perspectives into the decision-making capabilities of MCDM. The integration of these methodologies allows decision-makers to comprehensively evaluate possibilities, considering the environmental consequences alongside several parameters that contribute to the cement manufacturing process. The integration of LCA with MCDM enables decision-makers to make educated and equitable decisions that include various dimensions, including environmental, economic, social, and technological aspects. This integration contributes to the promotion of sustainability and responsible use of resources.

There are various justifications for the use of an integrated technique that incorporates LCA and MCDM. This technique effectively improves the methodological rigor, comprehensiveness, and practicality in the evaluation and ranking of various energy systems [249]. The utilization of LCA is strategically implemented owing to its intrinsic capability to provide a full assessment of the environmental impact over the complete life cycle of the cement production, encompassing activities ranging from the extraction of raw materials to the disposal stage [250]. The adoption of an inclusive method guarantees a comprehensive analysis of all aspects pertaining to environmental effect, hence avoiding the risk of overlooking interrelated stages and latent consequences. On the other hand, the incorporation of MCDM offers a solution to the inherent intricacy of cement production evaluations by offering a systematic framework for concurrently evaluating many criteria [251]. This methodology allows for the incorporation of both quantitative and qualitative data, hence permitting comprehensive comparisons of different alternatives.

Together, LCA and MCDM create a powerful decision-making tool that makes the most of both the quantitative accuracy of LCA and the subjective attribute evaluation of MCDM. This method acknowledges the difficulties in precisely measuring some characteristics while emphasizing their importance. In addition, the chosen technique guarantees that the method is transparent and reproducible by utilizing the widely accepted methodologies of both LCA and MCDM. The implementation of a systematic method in the assessment process increases transparency, allowing for the verification of findings and providing validity and dependability to the generated conclusions.

4.3.1. Integrating MCDM into LCA for Cement Production Assessment

This work selects and assesses the most preferred cement production processes by combining MCDM and LCA approaches. Through the life cycle stages, LCA offers quantitative environmental impact data after which the MCDM is used to compare alternatives systematically using both complimentary criteria and sustainability indicators from LCA. To rank alternatives according to their sustainability performance across a variety of factors, the MCDM employs the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Evaluation Based on Distance from Average Solution (EDAS) methods. By calculating the degree of conflict between each pair of criteria, CRITIC (Criteria Importance Through Intercriteria Correlation) establishes the weights of the criteria. This reduces the allowance for subjectivity in the process of weighting. The MCDM incorporates LCA impact categories such as human toxicity, photochemical oxidant formation, global warming potential, depletion of abiotic resources, acidification, eutrophication, and ozone depletion to rank the cement production alternatives. The study offers a comprehensive assessment of sustainability by combining MCDM's structured comparison using EDAS and TOPSIS weighted CRITIC with LCA's rigorous environmental impact data. The integrated strategy identifies the cement manufacturing method that is most favourable in terms of environmental objectives (Figure 4.1).

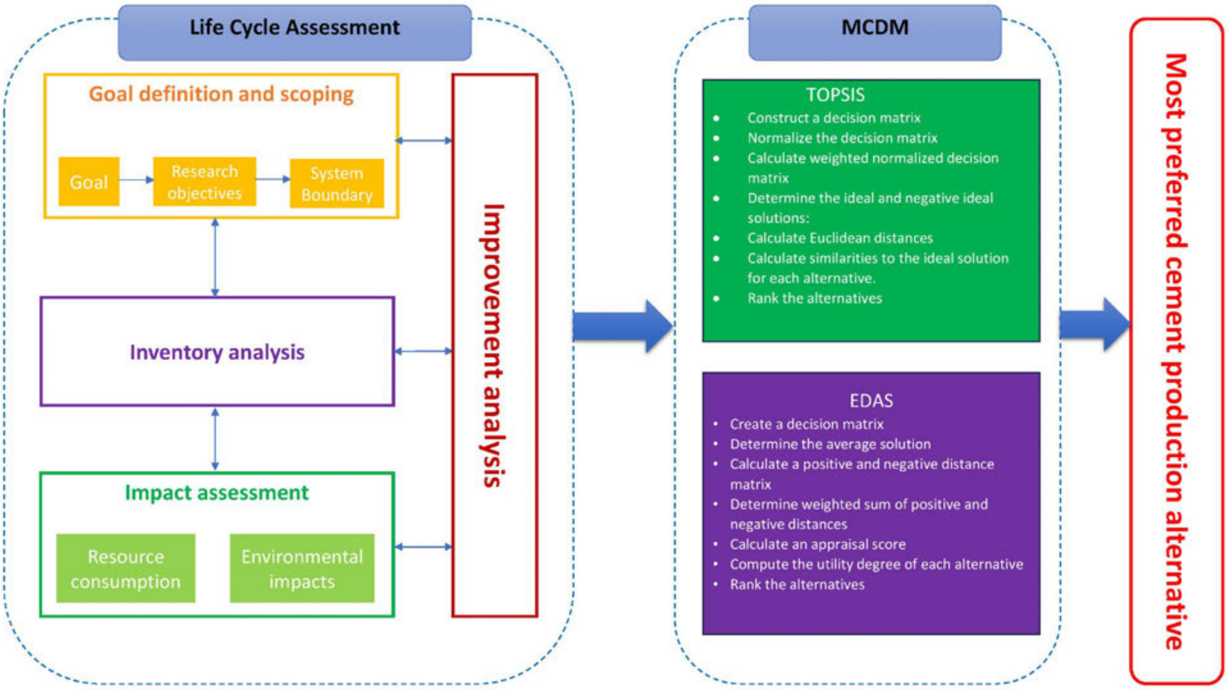


Figure 4.1. Proposed methodology for selecting the most preferred Cement production method.

4.3.2. LCA Assessment

LCA functions on the core idea of aggregating inputs and outputs related with the environmental, economic, and social characteristics of a product, goods, or services throughout their lifespan [252]. Because trade-offs between impacts in different categories often emerge when evaluating multiple scenarios, the interpretation of LCA data adds a layer of complexity to the analysis. This complexity is amplified by conflicting outcomes, providing difficulties in decision-making. There are two main ways to deal with this complexity: the first involves giving weight to and combining LCA results for each effect category into a single scoring indicator, while the second involves treating each impact category independently. The second method proposes using a limited number of impact categories to simplify the analysis of results. This analytical approach evaluates all potential methods of cement production and provides quantitative data regarding their impact on the environment. It is the process of analysing a product from beginning to end, from the extraction of raw materials to its use, operation, end-of-life treatment, recycling, and disposal. This strategy, sometimes referred to as "cradle-to-grave," is divided into four stages, namely goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [253, 254].

4.3.3. Goal and scope definition

The goal of this LCA study is to analyse and compare the environmental impacts associated with various methods of cement manufacturing. The current research attempts to evaluate five distinct production methods encompassing the entire process from raw material extraction to the final stage of cement grinding. The functional unit is operationally defined as the production of 1kg of cement. The analysis of each process is conducted with a focus on its ability to deliver the intended functional result. The system boundaries comprise all stages of the life cycle, including the purchase of raw materials, the manufacturing of clinker, the grinding of cement, transportation processes, and the end-of-life phase. The process of raw material extraction encompasses many activities such as limestone quarrying, shale mining, clay excavation, and the acquisition of any other necessary mineral inputs. The manufacturing of clinker encompasses a comprehensive range of thermal processes and associated emissions. The process of cement grinding involves the utilization of supplementary ingredients and milling operations to attain the desired result. The transportation choices and distances are provided for each stage. The concept of end-of-life encompasses the various outcomes associated with the reuse, recycling, and disposal of cement.

The analysis employs a "cradle-to-gate" methodology, encompassing the assessment of environmental implications from the acquisition of raw materials to the final stage of cement manufacturing. This LCA will measure environmental impacts to assist in the selection of sustainable processes by conducting a comprehensive analysis of the various cement production techniques throughout the major life cycle stages, from extraction to grinding.

4.3.4. Life cycle inventory analysis

For each cement production process, information on all material and energy inputs, emissions, wastes, and other environmental outputs must be gathered for the life cycle inventory study. Resources and pollutants related to the extraction of raw materials, the manufacturing of clinkers, the grinding of cement, the transportation process, and the disposal or recycling at the end of the product's life are included in this stage. Data on mineral inputs such as limestone, shale, clay, and gypsum, their extraction processes, and transportation to the plant are acquired for the raw material acquisition phase. All thermal processes and kiln types involved in the manufacturing of clinker also have their inputs and emissions quantified. Inventory of milling techniques, electricity consumption, and any blending components is part of the cement grinding stage. Transportation inventories consider several factors such as the mode of transportation, the distance travelled, and the energy consumption associated with each step of the life cycle. End-of-life inventories consider several factors, such as recycling, reuse, and disposal. The data used in this study comes from industry reports, ecoinvent and other commercial LCA databases, and earlier life cycle assessments of cement production. The functional unit of 1 kg of cement produced serves as the basis for standardizing all material and energy amounts, waste outputs, and emissions. This provides a comprehensive list of environmental flows, enabling effect analysis. Inventory analysis offers a comprehensive data platform for evaluating and contrasting the sustainability of each process since it encompasses all important life cycle stages of the cement manufacturing process.

4.3.5. Life cycle impact Assessment

An essential phase in the "cradle-to-grave" life cycle study of cement manufacturing is the Impact Assessment phase. This step includes a detailed evaluation and calculation of the possible environmental effect related to the life cycle inventory information that was acquired in earlier stages. It comprises several effect categories, including the possibility for eutrophication, acidification, and global warming, that are pertinent to the cement producing industry. For this study, the midpoint impact assessment method is used. This method is unique because it can precisely describe impact groups. This lets us understand the environmental effects of cement production in a more complex way. During the characterization process, SimaPro 9.2 is used. This is a high-tech tool designed for life cycle assessment. The present study employed this methodology to reveal the complex environmental impact of cement production by delineating and quantifying its effects across significant domains, so adding to a comprehensive comprehension of the intrinsic sustainability characteristics associated with this industrial procedure.

4.3.6. Interpretation.

The "cradle-to-grave" life cycle analysis's Interpretation step is crucial to the manufacturing of cement. It carefully examines the most important discoveries, explores the risks and constraints related to the production of cement, and comes to some insightful conclusions. It offers a comprehensive grasp of the social, economic, and environmental ramifications unique to cement production in addition to summarizing the findings. This stage provides strategic insights for raising the overall sustainability profile of cement production while acknowledging uncertainty and pointing out possible areas for development. Essentially, the Interpretation phase acts as a pivot, extracting significant learnings that guide choices and future thinking regarding environmentally friendly cement manufacturing.

4.3.7. Multicriteria Decision making Approach

The MCDM method is a strategic decision-making approach. It requires evaluating options using several criteria at the same time, taking both quantitative and qualitative factors into account. MCDM weighs multiple variables using a systematic framework, allowing for more meaningful comparisons, and supporting decision-makers in picking the optimal alternative.

This method addresses the complexity of decision-making head-on by providing a logical framework for reconciling competing considerations. In areas such as project selection, resource allocation, and environmental management, it encourages transparency and objectivity, allowing for more nuanced negotiations. To make judgments that consider the needs of all parties involved, MCDM is important.

Several MCDM methods, such as the Analytic Hierarchy Process (AHP), TOPSIS, the Elimination and Choice Expressing Reality (ELECTRE), and the Weighted Sum Model (WSM), provide diverse approaches for complex decision analysis [255]. For example, AHP hierarchically builds decision issues and prioritizes criteria; TOPSIS evaluates alternatives based on their proximity to an ideal solution; ELECTRE manages qualitative preferences; and WSM aggregates criteria with set weights. When deciding on the best approach, decision-makers should match the method's strengths to the unique decision environment. These methodologies, whether used for project selection, environmental management, or resource allocation, allow for a systematic evaluation of alternatives, ensuring informed and objective decision-making.

For this study the TOPSIS and EDAS MCDM methods were used in ranking cement production alternatives. TOPSIS assesses alternatives according to how close they are to the best option; it is therefore a good fit for addressing choice issues involving several criteria. When ranking alternatives based on their overall performance, it offers a clear-cut and intuitive method that works well. TOPSIS is most effective in scenarios where decision-makers need to make unambiguous choices between criteria and alternatives. Conversely, EDAS is chosen because of its resilience in handling ambiguous and imprecise information. EDAS computes the Euclidean distance between each alternative and the average solution by employing a distance-based methodology. Consequently, it facilitates a more flexible and adaptable approach to decision-making, which is particularly advantageous in circumstances involving ambiguous or variable data. Choosing the evaluation criteria for a decision-making problem is the initial phase in the MCDM. Subsequently, a decision-making matrix (Equation 4.1) is constructed utilizing the chosen criteria.

$$X_{ij} = [x_{11}\ x_{12}\ \dots\ x_{1m}\ x_{12}\ x_{22}\ \dots\ x_{2m}\ \vdots\ \vdots\ \vdots\ \vdots\ x_{n1}\ x_{n2}\ \dots\ x_{nm}] \qquad 4.1$$

Where X_{ij} is the score of the i^{th} alternative with respect to the j^{th} criteria. n is the number of alternatives and m is the number of criterial

4.3.8. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) Method

The TOPSIS methodology encompasses a set of sequential procedures aimed at evaluating and prioritizing options by measuring their relative closeness to the ideal solution [251]. The steps involved in the implementation process are as follows:

Normalization of Decision Matrix: A decision matrix R is created by transforming the initial decision matrix X into a normalized version. All the matrix's elements are divided in this process by the square root of the sum of the squares of the relevant column as presented in equation 4.2.

$$R_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} X^2\, ij}} \qquad 4.2$$

Weighted Normalized Decision Matrix: By multiplying the normalized decision matrix R by the weight vector W, the weighted normalized decision matrix V is generated (equation 4.3).

$$V_{ij} = R_{ij} \times W_j \qquad 4.3$$

Determine the Positive-Ideal and Negative-Ideal Solutions: For each criterion (A_j), identify the maximum and minimum values across all alternatives (equation 4.4).

$$A_j^+ = max(V_{ij}), A_j^- = min(V_{ij}), \tag{4.4}$$

Distance Calculation: Calculate the Euclidean distance (D^+) from each alternative to the ideal positive solution and (D^-) to the negative ideal solution (equation 4.5).

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (V_{ij} - A_j^+)^2}, \quad D_i^- = \sqrt{\sum_{j=1}^{n} (V_{ij} - A_j^-)^2}, \tag{4.5}$$

Calculate the Relative Closeness to the Ideal Solution: Determine the relative closeness (C_i) of each alternative to the ideal solution (equation 4.6).

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{4.6}$$

Ranking: The options should be ranked according to their respective similarity scores. The alternative that achieves the highest similarity score is assigned the highest rank, signifying its status as the most favoured answer.

4.3.9. Evaluation based on Distance from Average Solution (EDAS).

EDAS is a MCDM method that ranks alternatives across criteria based on their distances from the average solution [256]. It entails calculating an appraisal score and utility degree for each choice by determining weighted positive and negative distances from the average answer. EDAS's strengths are its own computational burden, simplicity, and ability to consider both beneficial and non-beneficial factors. EDAS minimizes subjectivity in selecting optimal values for each criterion by comparing alternatives to a mean value. The utility index also makes it possible to create a comprehensive final ranking with minimal effort. One potential drawback is that individual criteria have been replaced by an overall average. Changing the relative importance of criteria can also have a significant impact on rankings. In general, EDAS offers a MCDM technique that is comparatively easy and suitable for problems involving both positive and negative factors. By employing an average solution, presumptions regarding the definition of ideal values are mitigated. However, exclusive reliance on the mean may fail to consider possible outliers in performance. EDAS provides a straightforward yet resilient methodology for evaluating and prioritizing alternatives according to a variety of criteria, including both favourable and unfavourable variables.

Step 1: Determine each criterion's average solution

$$\text{AV} = [AV_J]_{1\times m} \tag{4.7}$$

Step 2: Calculate the positive distance from average (PDA) and the negative distance from average (NDA) (equation 4.8- equation 4.11).

if $j-th$ criterion is beneficial,

$$PDA_{ij} = \frac{max\,(0,\ \ (X_{ij} - AV_j))}{AV_j} \tag{4.8}$$

if $j-th$ criterion is non-beneficial,

$$PDA_{ij} = \frac{max\,(0,\ \ (AV_j - X_{ij}))}{AV_j} \tag{4.9}$$

if $j-th$ criterion is beneficial,

$$NDA_{ij} = \frac{max\,(0,\ \ (AV_j - X_{ij}))}{AV_j} \tag{4.10}$$

if $j-th$ criterion is non-beneficial,

$$NDA_{ij} = \frac{max\,(0,\ \ (X_{ij} - AV_j))}{AV_j} \tag{4.11}$$

where PDA_{ij} and NDA_{ij} represent the positive and negative distance of the $i-th$ alternative from the average solution in terms of $j-th$ criterion.

Step 3: Generate the alternatives' weighted sum of *PDA* and *NDA* (equation 4.12 and 4.13).

$$SP_i = \sum_{j=1}^{m} w_j PDA_{ij} \quad 4.12$$

$$SN_i = \sum_{j=1}^{m} w_j NDA_{ij} \quad 4.13$$

where wj stands for criterion *j* weight.

Step 4: Normalize the alternatives' SP and *SN* values (equation 4.14 and 4.15).

$$NSP_i = \frac{SP_i}{max_i(SP_i)} \quad 4.14$$

$$NSN_i = \frac{SN_i}{max_i(SN_i)} \quad 4.15$$

Step 5: Determine the alternatives' appraisal score (*AS*) (equation 4.16)

$$AS_i = \frac{NSP_i + NSN_i)}{2} \quad 4.16$$

4.4. Result and Discussion

This section presents the results of the analyses. This includes the LCA, the weight of the criteria, the MCDM and the mid-point characterization. The MCDM approach's criteria selection was an in-depth process aimed at capturing the various environmental and health implications connected with various cement production technologies. The criteria were chosen for their direct relation to sustainability goals as well as their capacity to capture the entire cement life cycle, from raw material extraction to manufacture and eventual usage. The criteria are outputs from the LCA process.

4.4.1. Results

4.4.1.1 LCA results: Midpoint Characterization results of all production processes

LCA was conducted to evaluate and compare the environmental impacts of 10 distinct types of cement across 18 different categories. The utilization of Ordinary Portland cement is associated with significant negative effects on the environment in various areas, including but not limited to global warming, toxicity, and resource consumption. Cement alternatives that incorporate a higher proportion of blast furnace slag, such as CEM III/A, have reduced negative effects in terms of global warming potential, carcinogenic toxicity, and fossil resource scarcity. The reduction of certain impacts was observed with the increase in limestone content in CEM II/A-L. The utilization of fly ash cement CEM IV/A and pozzolan-fly ash cement CEM IV/B has been found to result in noteworthy reductions in global warming potential, toxicity levels, and the consumption of fossil resources. Nevertheless, GGBFS emerged as the most favourable alternative in terms of minimal consequences over a wide range of categories. The product exhibited superior performance in terms of global warming potential, ozone depletion potential, toxicity, fossil resource utilization, and water consumption.

The LCA provides a quantitative analysis of the environmental advantages associated with cement substitutes that use higher proportions of slag, fly ash, and limestone in comparison to conventional Portland cement. In particular, the utilization of slag cement has been identified as a highly efficient approach for mitigating the adverse effects across several categories. This finding provides evidence for the adoption of environmentally friendly cement alternatives to enhance sustainability.

Weight of criteria

The CRITIC technique is used to assign weight to each environmental impact criterion to determine the preferred method of producing cement. With a significant weight of 35.4% (Figure 4.2), global warming is unquestionably the most important criterion. This is logical considering that cement production contributes to approximately 8% of worldwide CO_2 emissions. Direct greenhouse gas emissions result from the calcination process, while indirect emissions result from the combustion of fossil fuels for kiln heating. Consequently, to minimize carbon footprint and maximize energy efficiency, the manufacturing process must be optimized. This may encompass the implementation of carbon capture and storage, alternative fuels such as biomass or refuse materials, lower-temperature kilns, and innovative technologies like fly ash optimization. Terrestrial ecotoxicity is assigned the second-highest weight of 30.9. The cement manufacturing process has the potential to discharge hazardous pollutants, such as furnace dust particulate matter, heavy metals, and dioxins, into the surrounding environment. These have the potential to cause soil contamination and damage terrestrial species via bioaccumulation throughout the food chain. When controlling emissions, the cement production methods should avoid facilities located near sensitive ecological areas and employ dust collectors, filters, and scrubbers. To reduce ground-level concentrations and disperse emissions over a larger area, cement kilns might be required to employ higher towers.

The weight assigned to human non-carcinogenic toxicity is approximately 25.3, indicating its significant importance in the context being discussed. Cement operations emit respiratory irritants such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter, which might potentially endanger the health of local communities. The methodology should aim to reduce exposure by implementing emission control systems, as previously indicated, and by strategically locating plants at a distance from densely inhabited regions. In addition to being dissipated into adjacent areas, waste heat can also be effectively recovered and utilized for beneficial purposes. Although cement is significantly dependent on mineral inputs, the assigned weight of 0.29 for mineral scarcity suggests that this issue is of relatively lower concern. Nevertheless, it is possible that the approach might potentially prioritize manufacturing techniques that optimize the integration of supplemental cementitious materials such as fly ash and slag, hence reducing the dependence on newly extracted limestone from quarries.

Fossil resource scarcity is assigned a moderate priority, accounting for 2.76% of the overall weight. Cement kilns are significant consumers of coal and other fossil fuels. The implementation of lower-carbon alternative fuels, such as specific waste materials or biomass, has the potential to gradually mitigate the depletion of fossil resources. Nevertheless, the utilization of fuel is an inherent aspect of pyro-processing techniques, hence constraining the availability of alternate options. Impacts such as ozone depletion, water consumption, marine ecotoxicity, and usage of mineral resources are significantly less important considerations when choosing cement production techniques because they have relatively low weights. Priorities should continue to be set on minimizing the negative effects of greenhouse gases, risks to human health, and harm that toxic emissions cause to terrestrial ecosystems. The optimal approach would use the most advanced technology to reduce hazardous and particle emissions while simultaneously drastically reducing CO_2 emissions.

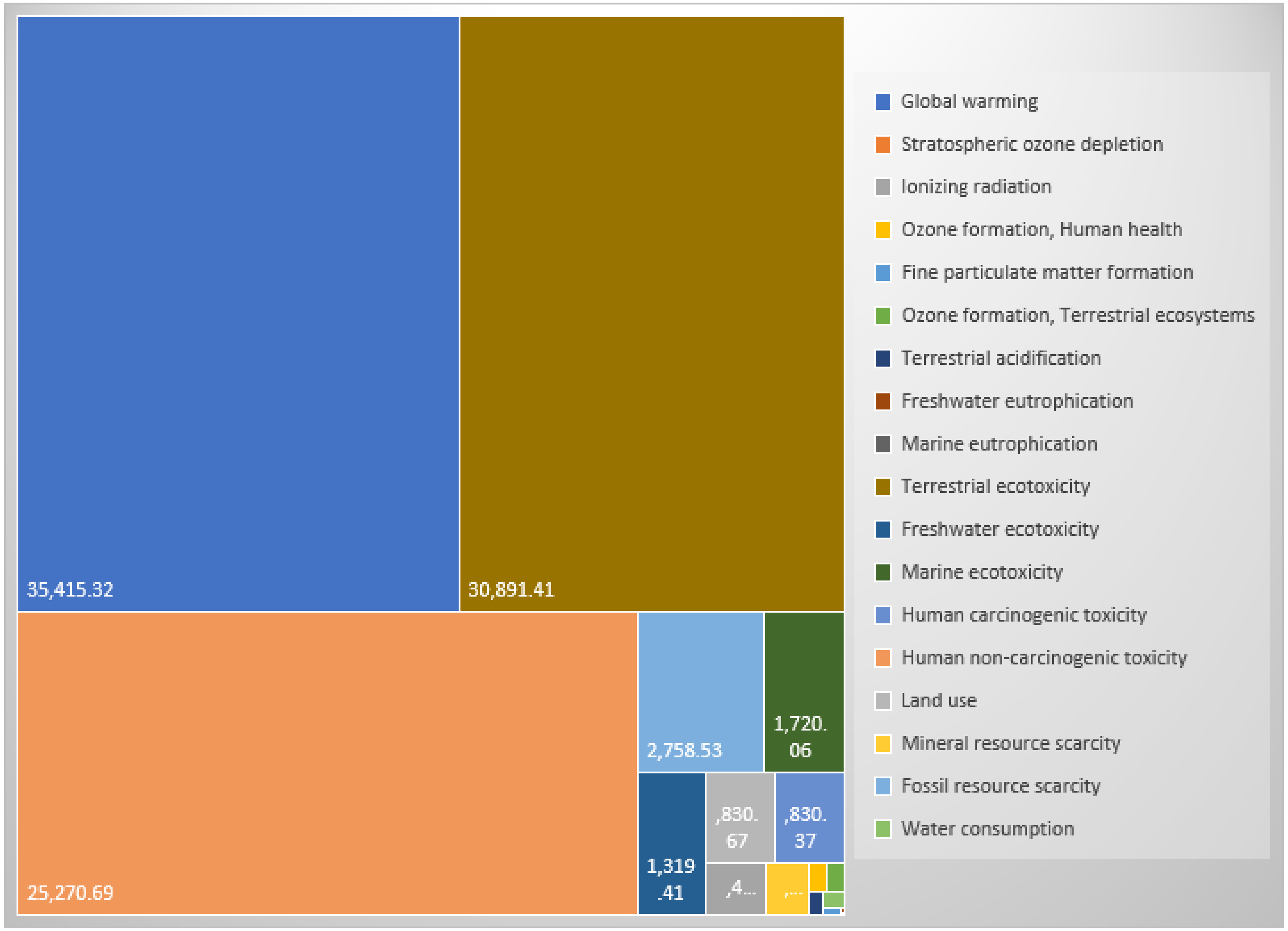


Figure 4.2. Weight contribution of each environmental impact criteria.

Table 4.1. Results of Life Cycle assessment

Impact category	Unit	CM 1	CM2	CM3	CM4	CM5	CM6	CM 7	CM8	CM9	CM10
Fine particulate matter formation	kg PM2.5 eq	0.00054	0.00042	0.00043	0.00045	0.00039	0.00048	0.00059	0.00044	0.00045	0.00019
Fossil resource scarcity	kg oil eq	0.07881	0.06017	0.05802	0.06266	0.05145	0.06767	0.08488	0.06196	0.06247	0.02076
Freshwater ecotoxicity	kg 1,4-DCB	0.00893	0.00946	0.01165	0.01627	0.01232	0.00697	0.00742	0.00662	0.00711	0.02148
Freshwater eutrophication	kg P eq	0.00009	0.00007	0.00007	0.00008	0.00007	0.00008	0.0001	0.00008	0.00007	0.00005
Global warming	kg CO2 eq	0.8516	0.55978	0.53205	0.55376	0.43525	0.67726	0.83768	0.60719	0.58763	0.10087

Human carcinogenic toxicity	kg 1,4-DCB	0.01437	0.01509	0.01567	0.02112	0.01583	0.01249	0.01486	0.01123	0.01391	0.02213
Human non-carcinogenic toxicity	kg 1,4-DCB	0.25982	0.24304	0.29774	0.39562	0.30486	0.19769	0.23665	0.18481	0.19629	0.48882
Ionizing radiation	kBq Co-60 eq	0.00721	0.00843	0.00616	0.01154	0.00577	0.00905	0.01179	0.00941	0.00555	0.00298
Land use	m2a crop eq	0.01592	0.02228	0.01634	0.02025	0.01617	0.02183	0.02425	0.01603	0.01748	0.00665
Marine ecotoxicity	kg 1,4-DCB	0.01205	0.01267	0.01558	0.02175	0.01644	0.00941	0.01016	0.00889	0.00955	0.02837
Marine eutrophication	kg N eq	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
Mineral resource scarcity	kg Cu eq	0.00339	0.00415	0.00307	0.00431	0.00295	0.00252	0.00304	0.00224	0.00586	0.00466

Ozone formation, Human health	kg NOx eq	0.00165	0.00118	0.00111	0.00114	0.00094	0.0014	0.00169	0.00124	0.00128	0.00025
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.00166	0.00119	0.00112	0.00116	0.00095	0.00141	0.0017	0.00125	0.00129	0.00026
Stratospheric ozone depletion	kg CFC11 eq	0	0	0	0	0	0	0	0	0	0
Terrestrial acidification	kg SO2 eq	0.00139	0.00103	0.00102	0.0011	0.00089	0.00119	0.00145	0.00107	0.00108	0.00036
Terrestrial ecotoxicity	kg 1,4-DCB	0.41804	0.55775	0.58726	0.88496	0.6294	0.45152	0.52567	0.37455	0.41454	0.61552
Water consumption	m3	0.00151	0.00127	0.00128	0.00193	0.00123	0.00123	0.00168	0.00119	0.00096	0.00148

4.4.1.2 MCDM results

Table 4.1 consists of the outputs from the LCA for the various cement production alternatives considered and the results from the CRITIC weighing method. The criteria weights obtained from the CRITIC technique as displayed in appendix (chapter 4, Table S1) shows that there are eighteen criteria that indicate various impact categories on the environment and human health. Given the large amount of greenhouse gas emissions associated with the manufacture of cement, global warming has the largest weight (35%), suggesting that it should be taken into consideration when choosing the optimal method for producing cement. Since the production process might release heavy metals and harmful contaminants, the next highest levels are for terrestrial ecotoxicity and human non-carcinogenic toxicity, at 30% and 25%, respectively. The weights of the other criteria are comparatively lower. The raw performance data for each of the 10 production methods (CM1 to CM10) across all 18 criteria is also shown in Table S1. A broad range of impact scores is observed, which correspond to variations in the ways the approaches influence each category.

Subsequently, the raw performance data for each approach was subjected to normalization, resulting in a scale ranging from 0 to 1 (Appendix; chapter 4, Table S2). This facilitated a fair and balanced comparison across various criteria. The normalized ratings provide a measure of relative performance for each impact. The criteria weights are incorporated into the normalized decision matrix by multiplying the normalized matrix by the weights to obtain the values in Appendix (chapter 4, Table S3). The weighted normalized matrix incorporates the variations in impact alongside the relative significance of each category. Factors such as global warming and toxicity are accorded greater significance. For every manufacturing option, Table S4 lists the ideal best, and worst solutions. The lowest weighted normalized score for each criterion represents the ideal best value, while the highest weighted score represents the ideal worst. This establishes the two extreme points of reference. Finally, the closeness coefficients used to rank the production alternatives are evaluated and presented in Appendix (Chapter 4, Table S5). This coefficient reflects the proximity every cement production technique is to the best and worst solution. The highest rating of 1.7228 for CM10 indicates that it is the closest to ideal (Table 4.2). The coefficient of 0.510 for CM4 indicates that it is the furthest away from the optimum solution.

Table 4. 2. Results of the MCDM analyses.

Cement production alternative	EDAS		TOPSIS	
	Appraisal score (Asi)	Rank	Relative closeness (Ci)	Rank
CM 1	0.4362	3	0.8314	8
CM2	0.0891	10	1.2235	5
CM3	0.1108	9	1.1064	7
CM4	0.5199	2	0.5103	10
CM5	0.2605	8	1.3342	4
CM6	0.3304	6	1.1756	6
CM 7	0.3775	4	0.7595	9
CM8	0.3460	5	1.5131	2
CM9	0.2722	7	1.4988	3
CM10	0.9094	1	1.7228	1

To validate the results of the TOPSIS method, another MCDM approach was implemented. The EDAS method was used in ranking the cement production alternatives to obtain the most and least preferred alternative. The study results obtained from the EDAS method reveal some noteworthy observations when compared to the prior TOPSIS ranking. The top-ranked option produced by the EDAS technique is CM10, which is the cement production method also favoured by TOPSIS. This supports CM10's position as the best option. The least favoured cement production approach for EDAS is CM2. Unlike the most preferred alternative that is consistent across both MCDM methods, the least and the intermediate choices exhibit variations in rankings between the two methodologies. As an illustration, CM4 holds the second position according to the EDAS ranking (Figure 4.3), although it is placed tenth according to the TOPSIS ranking. According to the rankings provided by EDAS, CM3 is ranked 9th, whereas according to TOPSIS, it is ranked 7th. Having the same alternatives as the best options, on the other hand, provides essential validation between the two MCDM approaches. Because TOPSIS and EDAS use different mathematical computations, having them arrive at the same most preferred cement manufacturing processes confirms the robustness of those choices as preferred solutions.

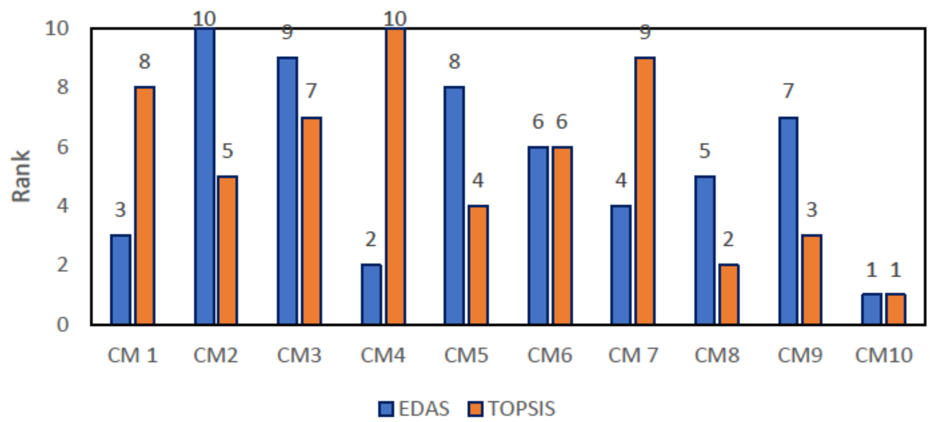


Figure 4.3. Comparison between EDAS and TOPSIS.

4.4.1.3 LCA results: analysis of GGBFS based on five production stages

This section presents the midpoint characterization of the most preferred cement production method- GGBFS. The findings from the midpoint characterization indicate that the primary factor responsible for global warming impacts is clinker production, which accounts for 55% of these impacts. This can be attributed to the release of CO_2 emissions during the calcination process (Figure 4.4). The production of raw materials is a significant contributor to various environmental issues. It is responsible for a considerable portion of global warming emissions (38%), as well as being the main cause of stratospheric ozone depletion (45%), ionizing radiation (95%), ozone formation with adverse effects on human health (47%), the formation of particulate matter (55%), terrestrial acidification (50%), eutrophication in freshwater and marine ecosystems (99-100%), impacts on ecotoxicity (55-91%), land use (48.6%), and water consumption (100%). The aforementioned factors can be ascribed to quarrying operations, the transportation of materials, and the release of particulate matter into the atmosphere. The utilization of electricity makes a substantial contribution to several environmental issues, including global warming (17%), ozone depletion (23%), ozone formation and its influence on human health (18%), particulate matter (17%), acidification (17%), and ecotoxicity consequences (ranging from 17% to 36.8%). These environmental concerns arise from the emissions resulting from the combustion of fossil fuels in the generation of electricity.

The process of fuel combustion is responsible for various environmental and health impacts. Global warming is primarily driven by fuel combustion, accounting for 21% of its contribution. Additionally, fuel combustion contributes to the formation of ozone, which has adverse effects on human health, accounting for 22% of its formation. Particulate matter, another consequence of fuel combustion, contributes to air pollution and accounts for 21% of its generation. Acidification, which has detrimental effects on ecosystems, is also caused by fuel combustion and accounts for 21% of its occurrence. Furthermore, fuel combustion leads to ecotoxicity, with a range of 14.6% to 18% contribution. Lastly, the combustion emissions of CO_2, NO_x, SO_2, VOCs, and other pollutants from fuel combustion contribute to the depletion of fossil resources, accounting for 100% of their scarcity. Transportation exerts comparatively lesser impact across many categories by means of emissions. Overall, the environmental consequences of cement are mostly attributed to many factors such as clinker production, power consumption, fuel combustion, raw material acquisition, and transportation. Among these factors, clinker and raw materials emerge as the primary sources of environmental impact across most categories.

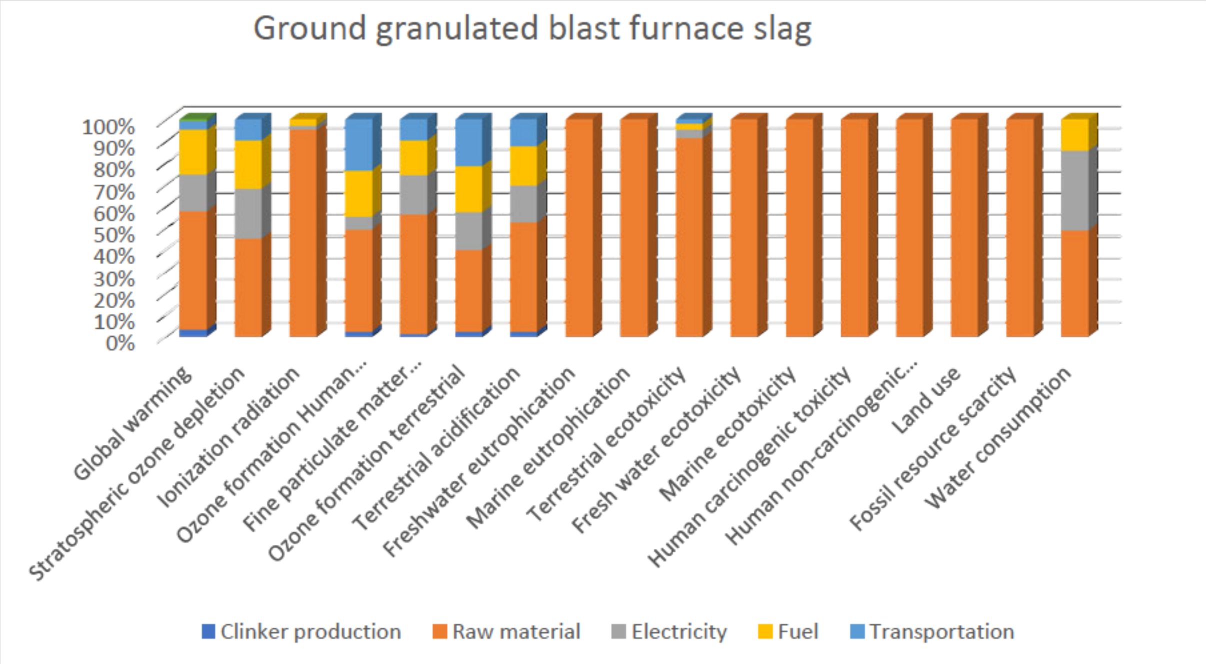


Figure 4.4. Mid-point Characterization of GGBFS.

4.4.2. Discussion

The importance of selecting environmentally sustainable cement alternatives, optimizing manufacturing processes, and prioritizing factors such as global warming, terrestrial ecotoxicity, and human health in the goal of sustainable cement production is underscored by the analysis of life cycle assessment (LCA) and weight analysis.

The life cycle assessment (LCA) was used to investigate and compare the environmental effects of ten different cement production methods across 18 different categories. It was discovered that regular Portland cement had the most negative effects on the environment, including resource use, toxicity, and global warming. Cement substitutes with a higher blast furnace slag concentration, like CEM III/A, had less of an adverse impact on the potential for global warming, carcinogenic toxicity, and the scarcity of fossil fuels. Likewise, there were notable decreases in several environmental consequences for fly ash cement (CEM IV/A) and pozzolan-fly ash cement (CEM IV/B). Nevertheless, GGBFS has emerged as the most favourable option because of its superior performance in various categories, such as global warming potential, ozone depletion potential, toxicity, fossil resource utilization, and water consumption. The life cycle assessment offers a quantitative examination of the benefits cement alternatives have for the environment. The application of slag cement is emphasized as a productive strategy for reducing negative impacts. The adoption of environmentally friendly cement substitutes to improve sustainability is supported by this research.

The environmental impact criteria were weighted using the CRITIC approach, and the results indicate that 35.4% of the weights go to global warming. Considering that the production of cement accounts for around 8% of global CO_2 emissions, it is imperative to optimize the manufacturing process. The weight allocated to terrestrial ecotoxicity, which is the second highest at 30.9%, underscores the importance of managing and regulating the release of hazardous pollutants in cement manufacturing processes to prevent soil contamination. The significance of reducing the release of respiratory irritants during cement activities to safeguard nearby communities is shown by the human non-carcinogenic toxicity, which has an estimated weight of 25.3%. While the issue of limited fossil resources is of considerable importance, the primary emphasis is placed on mitigating the adverse impacts of greenhouse gases, potential dangers to human health, and damage to terrestrial ecosystems.

The results of the MCDM analysis demonstrate the prioritization of different alternatives for cement production using two separate methodologies: the EDAS and TOPSIS. The rankings provided useful information regarding the applicability and preference of each option, assisting decision-makers in the selection of the most environmentally friendly and health-conscious method to cement manufacturing. Based on the TOPSIS technique, it can be observed that CM10 stands out as the highest-ranked alternative, with an appraisal score of 0.9094. This score highlights its exceptional performance across the assessed parameters. The EDAS approach further supports the consistency observed, as it likewise identifies CM10 as the most beneficial alternative, which is in line with the findings obtained from the TOPSIS analysis. The presence of inconsistencies in the least and intermediate rankings (such as CM1-CM9) between the TOPSIS and EDAS methods sheds light on the intricate decision-making process involved in cement production. Although the high level of agreement observed in the top-ranking alternative (CM10) instil confidence in its superiority. It is important to recognize the nuanced nature of decision-making in this industry. The evaluation of these variations can provide useful insights into the peculiar factors that may vary in significance between techniques, thereby assisting stakeholders in making informed decisions that are customized to their objectives.

Regarding the environmental effects of using GGBFS the primary technique identified as the most preferred for producing cement—the midway characterization results provide a thorough insight. Clinker production is the largest contribution to the effects of global warming, accounting for a substantial 55% of the total. To lessen the overall carbon footprint of cement manufacturing, it is imperative to control emissions during the calcination process. This finding has implications for optimizing clinker production, such as using new methods or substitute materials to significantly lessen cement's environmental impact. The production of raw materials has been identified as a significant factor in several environmental problems. Of particular concern is its significant contribution to global warming emissions, accounting for 38% of such emissions. This raises questions about the long-term environmental viability of activities related to quarrying and transporting raw materials. Additionally, the substantial impact on stratospheric ozone depletion (45%) and ionizing radiation (95%) emphasizes the necessity of adopting sustainable approaches to raw material extraction. These findings underscore the importance of responsible sourcing and minimizing the ecological impact associated with the acquisition of raw materials.

The utilization of electricity is recognized as a substantial factor in various environmental issues, such as the exacerbation of global warming, the depletion of the ozone layer, the generation of particulate matter, the acidification of ecosystems, and the occurrence of ecotoxicity. The results underscore the imperative of shifting towards renewable energy sources in the cement manufacturing sector to mitigate the environmental repercussions associated with power usage. The use of sustainable energy practices has the potential to significantly decrease the overall environmental effect and improve the ecological profile of the industry. The combustion of fuel has been recognized as a significant factor in both environmental and health impacts. The critical nature of transitioning to cleaner and more sustainable energy sources is underscored by the significant contributions of fuel combustion to global warming (21%), ozone formation (22%), particulate matter generation (21%), acidification (21%), ecotoxicity (14.6-18%), and fossil resource scarcity (100%) all of which have adverse health effects. These negative effects can be substantially mitigated through the adoption of sophisticated combustion technologies or the transition to alternative fuels. Although transportation has a relatively small effect in many respects, it continues to be a significant contributor to environmental impacts. The comprehensive analysis underscores that, within the multitude of factors that influence the environment, clinker production and the procurement of raw materials emerge as principal contributors. This highlights the importance of implementing focused interventions during these stages of cement manufacturing to attain considerable advancements in environmental sustainability.

Overall. the results of the midpoint characterization highlight the intricate nature of the environmental consequences linked to the manufacturing of cement. It is imperative to prioritize the adoption of sustainable practices in raw material extraction, optimize clinker production, and transition to renewable energy sources to address the identified key contributors and improve the environmental performance of the cement industry. These insights provide significant guidance for stakeholders and decision-makers who are attempting to reconcile the increasing need for cement with objectives related to environmental sustainability.

4.4.3 Interconnection with sustainable development goals

The findings of the study have important implications for specific Sustainable Development Goals (SDGs), providing insights into the environmental impact of various cement production technologies and contributing to larger global sustainability targets. The findings emphasize the necessity for a shift to renewable energy sources in cement production in the context of SDG 7 (Affordable and Clean Energy). To promote innovation and sustainable industrialization, recommendations for streamlining production procedures and switching to substitute materials are in line with SDG 9 (Industry, Innovation, and Infrastructure). Sustainable Cities and Communities (SDG 11) is supported by cement's important role in urban infrastructure and the focus on environmentally suitable alternatives. SDG 12 (Responsible Consumption and Production) is directly addressed by the study's recommendation for responsible sourcing and consumption. Given the emphasis on global warming and carbon footprint reduction, the study directly contributes to SDG 13 (Climate Action) while recognizing the impact of raw material exploitation on both terrestrial and aquatic ecosystems corresponds with SDGs 14 and 15 (Life Below Water and Life on Land). In addition, SDG 17

(Partnerships for the Goals) is reflected in the study's suggestion that stakeholders work together. The study calls for a more comprehensive strategy that considers the interdependence of environmental, social, and economic factors in a larger framework. Policymakers, industry leaders, and stakeholders working towards a sustainable and resilient future in the construction and allied industries will benefit from the practical blueprint it offers for bringing the cement industry in line with global sustainability goals. By employing the best practices, the cement industry can support climate action, environmental preservation, social well-being, and responsible growth in line with sustainability goals.

4.5. Conclusion

This study showcases the significance of employing an integrated Life Cycle Assessment (LCA) and Multi-Criteria Decision Making (MCDM) approach to conduct an in-depth analysis of the sustainability aspects associated with various ways of cement manufacturing. The Life Cycle Assessment (LCA) offers a comprehensive and rigorous quantitative evaluation of ten different alternatives, considering their performance across eighteen distinct impact categories. This study facilitates a thorough benchmarking process, allowing for extensive comparisons and assessments. In the context of decision-making, MCDM techniques are employed to methodically rank options according to their sustainability performance.

The key findings of the study indicate that the mixing of slag, fly ash, and limestone with Ordinary Portland Cement yields several advantages compared to the use of pure cement. These benefits include the reduction of various environmental impacts, such as global warming potential and toxicity. According to the MCDM ranking, GGBFS emerges as the most favourable alternative, exhibiting a significant reduction of more than 80% in global warming impacts compared to traditional cement. The evaluation of the situation also highlights clinker production and raw material sources as significant areas of concern.

Nevertheless, it is important to acknowledge the presence of certain constraints. The utilization of secondary data in the LCA methodology is a potential limitation as it may overlook regional disparities in technology, energy sources, and transportation. Future studies can mitigate this limitation by conducting sensitivity analyses based on different regions and using more localized data. Such sensitivity analysis may be conducted considering regional disparities in technology, energy sources, and transportation. The enhancement of generalizability could be achieved by using the framework in various geographical contexts. The MCDM framework excludes social and economic factors, prioritizing exclusively environmental indicators. A comprehensive sustainability viewpoint could provide enhanced guidance for decision-making. Furthermore, the application of uncertainty analysis can serve to enhance the evaluation of the reliability and stability of the MCDM rankings. Future research should include primary data gathering, application in diverse geographies, integration of social and economic issues, and uncertainty analysis to overcome these limitations. A localized approach to criterion weighting could involve government and industry stakeholders. Additional cement substitutes like silica fumes or magnesium oxides could be assessed by more LCA research. Endpoint modelling has the potential to offer valuable insights focused on damage-oriented assessment.

This present study is based on quantitative data obtained from the LCA; however, future may combine both quantitative and qualitative data through stakeholder participation in decision-making. This should include community representatives, environmentalists, and industry professionals who can confirm results and offer suggestions. It is crucial to address potential trade-offs and consider technical, policy, financial constraints as well as environmental favourability. Examining new technology in the cement industry may help address recognized environmental issues. Also, comparisons with present benchmarks or norms will improve the study's context and advance knowledge of sustainable cement production techniques.

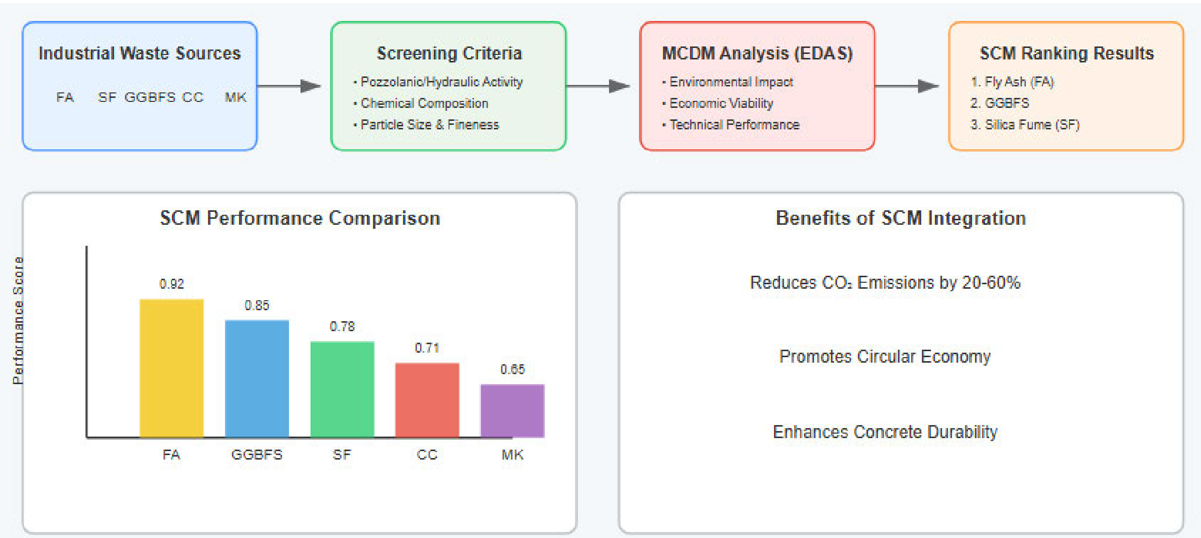
However, this work provides substantial contributions. The study showcases a rigorous and reproducible approach that aligns with ISO requirements for evaluating the sustainability of cement. Additionally, it emphasizes potential avenues for enhancing sustainability in this industry. The LCA-MCDM approach combines robust life cycle inventory data with a transparent multi-criteria decision analysis. The results of the study provide practical remedies for reducing the significant environmental impact and harmful effects of cement, hence facilitating advancements in sustainable manufacturing practices. Through careful utilization and subsequent refinement, the concept offers significant utility in the context of evidence-based cement selection. Industry practitioners must consider the unique qualities and requirements of each project while deciding on the most suitable mix proportions of GGBFS in concrete. Policy makers should implement rigorous quality control mechanisms to assure the consistency and reliability of GGBFS, to retain the intended performance characteristics of the concrete.

CHAPTER 5

TRANSFORMING INDUSTRIAL WASTE INTO LOW-CARBON CEMENT: A MULTI-CRITERIA ASSESSMENT OF SUPPLEMENTARY CEMENTITIOUS MATERIALS FOR SUSTAINABLE CONCRETE DESIGN.

This chapter presents a review that critically evaluates 27 agro-industrial and industrial by-products incorporating robust multi-criteria framework, with each alternative is assessed across regulatory, environmental, economic, and technical dimensions. The objective of this study is to investigate the potential of industrial waste as supplementary cementitious materials (SCMs) and assess their applicability in achieving cleaner and more sustainable cement production processes. The content of this study has been partially published at the IEEM 2024 conference proceeding and co-authored by Oludolapo Akanni Olanrewaju [257, 258]. An article from this chapter is under review at journal of material research and technology.

GRAPHICAL ABSTRACT



5. 1 Introduction

Cement production is paramount for modern-day infrastructure advancement, serving as the backbone of the global construction sector. However, it is one of the major carbon-intensive industries, contributing approximately 7–8% of CO_2 emissions [213, 229] These emissions are mainly from: (i) the chemical decomposition of limestone ($CaCO_3$) into lime (CaO) and CO_2 during clinker production (≈60%), and (ii) the burning of fossil fuels to sustain kiln temperatures above 1450 °C (≈40%) [259, 260]. The energy required to produce one ton of ordinary Portland cement (OPC) is between 3.0 and 6.0 GJ, contingent to the efficiency of the kiln and fuel type [261]. Despite evolutions such as dry-process kilns, the industry continues to greatly depend on non-renewable fuels, aggravating both emissions and resource depletion [21]. In 2020, the global demand for cement was approximately 4.2 billion tonnes and is expected to rise steadily, considering the swift urbanization in developing economies [262, 263]. Without generic innovation, annual CO_2 emissions from the construction sector is forecasted to exceed 2.34 billion tonnes by 2050 [213]. In addition, cement production cause land degradation through the extraction of raw material thereby releasing pollutants like NO_x, SO_2, and particulate matter, which have severe health and ecological implications [122]. Technological advances, such as alternative fuels, carbon capture and storage (CCS), and high efficiency kilns, presents partial mitigation but encounter scalability, cost, and regulatory hurdles [229, 263].

Reducing the environmental impact of cement, transformational changes in both material usage and process design are important. One of the most efficient strategies is reducing the content of clinker via the use of supplementary cementitious materials (SCMs), especially those obtained from industrial waste. SCMs can both serve as partial replacement clinker and/ alternative binder; this way significantly reducing both CO_2 emissions and energy consumption, while presenting a practicable end-use pathway for industrial by-products.

Industries such as energy, metallurgy, and manufacturing in the global space produce large amount of solid waste which are often difficult to manage and hazardous. China for example produced over 3.3 billion tonnes of industrial waste in 2019, which includes metallurgical slags, fly ash, and red mud [264]. Most of this waste remains unused, leading to GHG emissions, land and water pollution, and ecological hazards. Yet, many industrial by-products have physicochemical properties and are rich in SiO_2, Al_2O_3, CaO, and Fe_2O_3 which make them appropriate for cementitious applications [265, 266].

Environmental guidelines and sustainability agendas now motivate industries to decrease waste generation thereby encouraging circular economy practices [238]. Incorporating industrial waste into cement kilns be it as alternative fuels or SCMs helps reduce the use of virgin raw material which aligns with Sustainable Development Goal 12 (Responsible Consumption and Production) [264, 267]. Established SCMs such as fly ash and ground granulated blast furnace slag (GGBFS) improve concrete strength, durability, and chemical resistance [232], while activating cost savings through carbon credits, reduced energy use, and landfill avoidance [268]. The concept of industrial interdependence where waste from one industry becomes the starting material for another embodies circular economy vision [269]. Nevertheless, the complete deployment faces challenges which is not limited to logistical obstacles, lack of regulatory co-ordination, variation in waste composition, and inadequate performance-based standards [270]. Overcoming these limitations requires process engineering, harmonized advances in material science, and policy development. Particularly in emerging regions, valorising industrial waste for cement production presents double benefits: addressing waste management gaps and supporting inexpensive infrastructure development using locally available materials [264].

SCMs have become principal to the strategy of reducing the embodied carbon of concrete. SCMs offer improved mechanical performance and durability while reducing environmental effect especially those derived from natural sources or industrial residues such as GGBFS, fly ash, silica fume, and calcined clays, [232, 267]. Considering that clinker contributes more than

90% of CO_2 emissions in OPC production, substituting it with SCMs at ranges of 20–70% can significantly reduce the carbon footprint without compromising functionality [229, 238].

Fly ash and GGBFS are widely standardized because of their well-defined pozzolanic and hydraulic properties. Fly ash reacts with calcium hydroxide to form calcium silicate hydrate (C–S–H), contributing to long-lasting strength and durability [265]. GGBFS forms compact microstructures when activated, improving resistance to sulphates, chloride ingress and alkali–silica reaction [266]. Silica fume, a material with high surface area, improves impermeability and compressive strength, particularly in high-performance concrete [271].

Considering sustainability, SCMs offer triple-bottom-line benefits. Several life cycle assessment (LCA) studies report considerable reductions in energy use, global warming potential (GWP), and natural resource depletion compared to OPC [213, 272-276]. Economically, using local industrial by-products reduces production costs as much as opens opportunities for green jobs in recycling, sustainable construction and quality testing [269]. However, their cost-effectiveness varies from region to region because it is subject to processing, transport, and supply-demand dynamics [277].

Despite substantial research on specific SCMs, few studies critically assess them combining multi-criteria framework that considers environmental impact, technical performance, regulatory compatibility and economic viability. This review intends to bridge that gap by systematically investigating industrial waste-derived SCMs for sustainable concrete design. Through a critical fusion of existing literature and policy, the emphasizes key opportunities and trade-offs in advancing low-carbon, resource-efficient cementitious materials.

While prior literature has explored the environmental and performance characteristics of various SCMs including fly ash, GGBFS, silica fume, and metakaolin, the integration of Multi-Criteria Decision-Making (MCDM) frameworks to holistically evaluate a broader spectrum of SCMs remains scarce. Recent systematic reviews in construction and circular economy contexts emphasize that although methods like AHP, TOPSIS, PROMETHEE, and EDAS are applied, there is still a gap in combining these tools for SCM assessment, particularly with underutilized waste-derived materials [278-280] Moreover, hybrid MCDM frameworks such as COPRAS, SWARA, fuzzy-TOPSIS, and emerging EDAS variants have been shown to offer more robust and nuanced decision support capabilities, yet have rarely been applied to SCM selection [280, 281].

5.2. Contribution to Knowledge

This study significantly promotes current understanding in the field of sustainable cement production by developing a detailed, multi-criteria framework for assessing supplementary cementitious materials (SCMs) derived from agro-industrial/ industrial waste. Unlike previous studies that assess a limited set of materials or lack profound expert judgment, this research adopts a data-driven and systematic approach. It combines key assessment qualities like technical performance, environmental impact, chemical composition, economic viability, and regulatory compliance into a unified scoring matrix. The application of advanced decision-making tools, which includes life cycle assessment (LCA) and the EDAS (Evaluation based on Distance from Average Solution) technique, presents a replicable and more objective methodology for ranking SCMs. This robust approach supports material selection that is not only performance-driven but also economically and environmentally practicable.

Moreover, the study contributes to knowledge by assessing and exploring a wide range spectrum of both emerging and established industrial by-products including under-researched materials such as aspiration dust, Napier grass ash and bagasse ash. This wider scope addresses regional variability and improves the potential for localized SCM sourcing, especially in developing environments. The findings are directly aligned with global sustainability goals, advancing circular economy practices by valorising industrial waste and over dependence on reducing clinkers. By presenting a replicable model that bridges policy relevance, environmental sustainability, and material science, this research offers a practical roadmap for future implementation and innovation of low-carbon cement technologies.

Unlike existing reviews that focus on traditional SCMs, this study includes emerging waste-derived SCMs like Napier grass ash, eggshell powder, and sugarcane bagasse ash. Evidence of their potential pozzolanic properties has been demonstrated (e.g., Napier grass ash exhibits ≥ 85 % lime consumption and improved compressive strength at 20 % replacement) [282, 283]. Also, hybrid MCDM approach anchored in EDAS is applied in this study, offering enhanced discrimination and sensitivity compared to single-method strategies (e.g., AHP or TOPSIS alone) [280, 284, 285]. In addition, this study establishes a clearly defined scoring framework, grounded in quantitative LCA, mechanical performance, economic feasibility, and supply prognostics supported by primary data from literature and standard thereby addressing the subjectivity issues in prior works. This work integrates analysis of regional resource availability, techno-economic risks (e.g., fly ash decline, geopolymer scale-up), and climate/market adaptation strategies, representing a first in SCM studies.

5.3 Mapping Industrial Waste and its Characteristics

The generation of industrial waste is increasingly becoming a major environmental concern that requires urgent mitigation due to the pace of global industrialization. These wastes vary in their composition, geographic distribution, disposal practices, and volume thereby posing different levels of environmental and health threats. Beyond prevalent waste management issues known, some industrial residuals present unique prospects for valorisation in the construction sector specifically as potential supplementary cementitious materials (SCMs) or alternative raw materials. For example, mineral-rich wastes like fly ash, blast furnace slag, red mud, and iron ore tailings are well known for their latent hydraulic or pozzolanic properties and high content of reactive oxides such as Al_2O_3, SiO_2, and CaO [265, 266]. There is a need to understand the global industrial sources, generation trends, and current disposal challenges of such wastes to assess their viability in sustainable cement design. Table 5.1 offers a combined overview of the major types of industrial waste that exist in the built environment. It details their primary origin, geographic prevalence, and the environmental management concerns associated with each of them; this serves as the foundation for evaluating their sustainability and technical applicability potential in concrete production systems.

Table 5.1. General overview of the different industrial waste.

Waste Type	Global Availability & Key Regions	Primary Sources	Current Disposal Issues	References
Mining Waste	~1.4 billion tonnes/year of iron ore tailings; major producers include Brazil, China, and Australia.	Iron ore, coal, and other mineral extraction activities.	Tailings often stored in dams; risk of dam failures and toxic leachate contaminating water bodies.	[286]
Fly Ash & Slag	Significant quantities from coal-fired power plants and steel, especially in the U.S., China, and India.	Combustion of coal in thermal power plants.	Contains heavy metals; improper disposal leads to air and water pollution; limited recycling in construction.	[287]

Chemical Waste	Global widespread; significant in chemical manufacturing hubs like the U.S., Germany, and China.	Chemical manufacturing, pharmaceuticals, and laboratories.	Hazardous nature; challenges in treatment and disposal; risk of soil and water contamination.	[288]
E-Waste	Electronic wastes also known as e-waste. Over 70% of global ends up in China; significant amounts also in India and Nigeria.	Disposed electronic devices/parts from consumers and industries.	Laid-back recycling leads to environmental pollution and health hazards; lack of proper infrastructure.	[289]
Textile Waste	countries with large textile industries are the major contributors. These countries include Bangladesh, India, and China.	Textile and dyeing industry.	Wastewater contains dyes and chemicals; solid waste disposal issues; informal recycling.	[290]

Paper Mill Waste	Abundant in countries with large paper industries like the U.S., Canada, and Finland.	Pulp and paper manufacturing industries.	Sludge disposal challenges; chemical residues in wastewater; air emissions.	[291]
Plastic Waste	Plastic waste is a global issue; prominent producers include the U.S., China, and European countries.	Plastic manufacturing and packaging industries.	Non-biodegradable nature; accumulation in landfills and oceans; recycling challenges.	[292]
Radioactive Waste	Produced in countries with nuclear power plants and medical facilities; notable producers include the U.S., France, and Russia.	Nuclear power generation, medical isotope production, and research laboratories.	Long-term storage challenges; risk of radiation leaking; high cost of disposal.	[293]
Biomedical Waste	Abundant in countries with large healthcare sectors like the U.S., India, and China.	Hospitals, clinics, and pharmaceutical industries.	Risk of infection; improper disposal leads to environmental pollution;	[294]

			need for specialized treatment.	
Construction Debris	High volumes globally; especially in fast growing regions like Asia and the Middle East.	Construction, renovation, and demolition activities.	Large volumes; limited recycling; most times ends up in landfills; potential for hazardous materials.	[295]
Hazardous Waste	High in Asia-Pacific, North America, and Europe due to rapid industrialization and legacy adulteration.	Chemical manufacturing, metal processing, electronics industry.	Improper disposal leads to soil and groundwater contamination, health risks, and illegal dumping.	[296]
Industrial Sludge	Predominant in industrialized countries; increasing in Asia and Latin America.	Wastewater treatment, metal processing, mining.	Landfilling raises environmental issues; drying and incineration are energy intensive.	[297].

Asbestos Waste	persistent in Russia, China, India, Brazil; legacy waste in many banned countries.	Construction, shipbuilding, automotive industries.	Hazardous to health when airborne; disposal requires strict handling and encapsulation.	[298]
Food Processing Waste	Globally generated, particularly high in North America and Europe; significant production losses in developing regions.	Food and beverage industry, agriculture.	Causes methane emissions in landfills; underused in bioenergy or composting.	[299].
Packaging Waste	High volumes in EU, North America; rapid growth in Asia-Pacific.	Manufacturing, retail, logistics.	Plastic-based materials resist degradation; recycling rates are low; leads to aquatic pollution.	[300]

The information presented in Table 5.1 highlights the diversity, scale, and environmental importance of industrial waste streams arising from key sectors such as metallurgy, energy, chemicals, construction and mining. These wastes differ not only in geographic distribution and volume but also in their chemical composition and management issues. Mining activities, especially iron ore abstraction, generate vast number of tailings, which, if not properly managed, will result in disastrous long-term contamination of aquatic environments and failures of containment systems. Likewise, coal combustion residuals like fly ash and boiler slag are produced in large amount and contain minute quantity of metals that pose environmental hazards when disposed inappropriately. Although such materials have shown potential as SCMs, there are still irregularities in their utilization due to issues that include: logistical constraints, variable quality and limited recycling infrastructure. The treatment practice of waste from chemical and pharmaceutical industries is more complex and pose continuous dangers to groundwater and soil. While the prompt turnover of electronic devices has increased the generation of e-waste, significant amount is exported to regions lacking adequate recycling infrastructure thereby compounding ecological and human health risks. Textile, paper, and food processing industries also contribute considerably to solid and liquid waste with high or chemical and organic loadings whereas construction and demolition activities continue to produce vast volumes of inert debris, much of which ends up in landfills. Within this wide-ranging waste, specific waste types like fly ash, red mud, blast furnace slag, and mine tailings are of special interest due to their mineralogical compatibility with cementitious formulations. These materials are rich in aluminosilicates and have calcium-bearing phases which offer viable pathways to reduce clinker demand and thereby mitigate CO_2 emissions and high energy consumption in cement production (Juenger & Siddique, 2015; Gartner & Sui, 2018). While fly ash and slags have established partial incorporation in commercial concrete systems, the valorisation of other industrial residues such as red mud and tailings is still evolving and being supported by innovations in activation chemistry and geopolymer synthesis [264, 287]. However, effective integration of these waste materials requires careful assessment of their long-term performance, environmental safety, and phase stability. Concerns such as lack of harmonized standards, heavy metal leaching, and heterogeneity in composition continue to be significant barriers [286, 301]. Addressing these concerns calls for a structured framework that accounts for material reactivity, local waste availability, regulatory alignment and processing needs. This will be essential for both resource efficiency and emission reduction goals. It will also support the alignment of waste management strategies with broader sustainability and circular economy principles.

5.4. Screening SCMs from the Industrial Waste Pool

The transition toward sustainable concrete design necessitates the strategic valorisation of industrial by-products as viable supplementary cementitious materials (SCMs). In response to the environmental burden of clinker production and industrial waste accumulation, the integration of industrial by-products, agricultural residues, and engineered pozzolan SCMs offers a dual environmental benefit: reducing landfill pressures and lowering the carbon footprint of cementitious systems [213, 268]. However, the applicability of these materials is not universal and varies significantly depending on their chemical composition, reactivity, processing requirements, and regional availability.

This section outlines a two-stage systematic screening process designed to identify and characterize industrial by-products, agricultural residues, and engineered pozzolan with potential SCM applications. While most materials considered in this study originate from industrial and agricultural residues (e.g., fly ash, rice husk ash, red mud), some—such as calcined clay and metakaolin are not waste materials but rather engineered pozzolans derived from thermally activated natural clays. Their inclusion is justified due to their high performance, emerging availability in developing markets, and increasing relevance in low-carbon cement strategies such as LC3 (limestone calcined clay cement) systems [302]. This is further classified in Table 5.2. In this study, the term "Geopolymer Binders" refers to alkali-activated materials produced from industrial by-products such as fly ash, GGBFS, or metakaolin. While geopolymers are often studied as alternative complete binders (not just SCMs), their inclusion here reflects their SCM-like use in blended systems or partial replacement scenarios in emerging low-carbon technologies.

Geopolymers are not a singular material, but rather a class of binders whose performance, cost, and CO_2 footprint depend heavily on precursor and activator type [33]. As such, their origin is categorized separately in Table 5.2 and Appendix (chapter 5), with caution applied to their comparability against traditional SCMs.

The first stage involves an extensive classification of materials based on their source, availability, prevalent region, and disposal challenges. Table 5.2 presents this classification, which includes both well-established SCMs such as fly ash, silica fume, ground granulated blast furnace slag (GGBFS), and metakaolin, as well as emerging materials like red mud, biomass ash, waste glass powder, and ceramic dust [265, 303]. Each material is assigned to one of three categories based on existing literature: Established SCMs (already broadly adopted and standardized), Promising SCMs (have potential but limited standardization or application), and Exploratory SCMs (under research, with preliminary feasibility).

Table 5.2. Emerging industrial by-products, agricultural residues, and engineered pozzolan SCMs.

S/N	Material	SCM Classification	Global Availability & Key Regions	Primary Sources	Current Disposal Issues	Material origin	References
1	Fly Ash (FA)	Established	~750 million tonnes annually; major producers: China, India, USA	Coal-fired power plants	Landfill disposal; heavy metal contamination	Industrial by-product	[304]
2	Ground Granulated Blast Furnace Slag (GGBFS)	Established	~300–360 million tonnes annually; major producers: China, India, USA	Steel and iron industries	Underutilized; landfill accumulation	Industrial by-product	[304]
3	Silica Fume (SF)	Established	~1.5 million tonnes annually; produced in silicon-producing countries	Silicon and Ferrosilicon industries	Inhalation risk; ultrafine particle disposal	Industrial by-product	[304]
4	Red Mud (Bauxite Residue)	Promising	~170 million tonnes annually; major producers: Australia, China, Brazil	Alumina production	Highly alkaline; pond storage risks	Industrial by-product	[305]
5	Rice Husk Ash (RHA)	Established	~70 million tonnes annually; producers: China, India, SE Asia	Rice milling	Open burning; air pollution	Industrial by-product	[306]
6	Palm Oil Fuel Ash (POFA)	Established	~7 million tonnes annually; major producers: Malaysia, 7Indonesia, T8hailand	Palm oil mills	Groundwater contamination; poor awareness of reuse potential	Industrial by-product	[304]

7	Bottom Ash (BA)	Promising	~1934 million tonnes annually; major producers: USA, EU	Coal-fired power plants	Groundwater leaching; low reuse rates	Industrial by-product	[304]
8	Waste Glass Powder (WGP)	Promising	~11.5 million tonnes in USA; higher globally	Post-consumer glass	Alkali-silica reaction; landfill dumping	Industrial by-product	[307]
9	Marble Dust Waste (MDW)	Exploratory	Significant in India, Italy, Turkey	Marble cutting and polishing	Dust pollution; underutilized	Industrial by-product	[308]
10	Flue Gas Desulfurization Gypsum (FGDG)	Exploratory	~30 million tonnes annually in the USA	Coal power with desulfurization units	Leaching risks; storage problems	Industrial by-product	[308]
11	Ceramic Dust Waste (CDW)	Promising	High in China, India, Spain	Ceramic tile manufacturing	Landfill disposal; reuse unexplored	Industrial by-product	[308]
12	Napier Grass Ash (NGA)	Exploratory	Biomass-producing countries	Biomass combustion	Underutilization; disposal in landfills	Agricultural residue	[309]
13	Biomass Ash	Promising	Regions using biomass energy (e.g., Brazil, India)	Biomass combustion	Heavy metal leaching; landfill disposal	Agricultural residue	[310]
14	Calcined Clay	Established	Abundant in India, Brazil, Africa	Calcined kaolinitic clay	Mining and energy-intensive processing	Engineered pozzolan	[311]
15	Aspiration Dust	Exploratory	Found in industrial processing zones	Dust from industrial collectors	Inhalation hazard; fine particle management	Industrial by-product	[312]
16	Bagasse Ash	Promising	Common in Brazil, India, Thailand	Sugarcane processing	Groundwater pollution risk; landfill accumulation	Agricultural residue	[313]
17	Boiler Slag	Promising	Found in thermal power regions (e.g., China, USA)	Coal-fired boilers	Contains heavy metals; poor reuse	Industrial by-product	[314]
18	Egg Shells	Promising	Global; large poultry-producing nations	Poultry processing	Odor; organic contamination risk	Agricultural residue	[315]
19	Metakaolin (MK)	Established	Global (especially	Calcined kaolinite clay	Calcination emissions	Engineered pozzolan	[316]

			where kaolin clay is found)				
20	Copper Slags	Exploratory	Common in Chile, India, China	Copper smelting	Heavy metal leaching	Industrial by-product	[317]
21	Other Non-Ferrous Slags	Exploratory	Countries with base metal smelting (e.g., Canada, China)	Zinc, lead, aluminum, nickel smelting	Toxic metal leaching; landfill accumulation	Industrial by-product	[318]
22	Lead/Zinc Slags	Exploratory	Common in China, Australia, USA	Lead and zinc smelters	Toxicity; environmental contamination risks	Industrial by-product	[319]
23	Blast Furnace Dust	Promising	Major steel-producing nations (e.g., China, India, Germany)	Steel production	Airborne hazard; landfill accumulation	Industrial By-product	[320]
24	Steel Slag	Promising	~200 million tonnes annually; found globally	Steel plants	Heavy metal leaching; landfill dumping	Industrial by-product	[321]
25	Geopolymer Binders	Established	Dependent on industrial waste supply (FA, GGBFS, MK)	Fly ash, slag, metakaolin	Early-stage adoption; production variability	Engineered binder (Composite of by-products)	[322]
26	Oil-Based Mud	Exploratory	Oil-producing regions (e.g., Middle East, USA, Russia)	Drilling waste from oil rigs	Hydrocarbon contamination; classified hazardous waste	Industrial by-product	[323]
27	Kaolinitic Waste	Promising	Found in mining countries like Brazil, USA, UK	Kaolin mining	Dust pollution; poor valorization	Industrial by-product	[324]

The second stage of screening involves the evaluation of these materials based on critical cementitious performance indicators. The identification and qualification of potential SCMs from industrial by-products, agricultural residues, and processed natural materials rely on a comprehensive set of performance and sustainability indicators. Each criterion plays a distinct role in determining whether a material is technically viable, environmentally beneficial, and practically implementable in cementitious systems. The screening criteria are elaborated below:

5.4.1. Pozzolanic or Latent Hydraulic Activity

Pozzolanic activity describes the ability of siliceous or aluminosilicate materials to chemically react with calcium hydroxide (Ca $(OH)_2$) in the presence of water, to form cementitious compounds mainly calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H). These compounds contribute significantly to the long-term mechanical strength, impermeability and durability of concrete. In contrast, latent hydraulic activity refers to the innate ability of certain materials (e.g. GGBFS) to harden in the presence of water but also requires activation through the alkaline environment of cement paste. The pozzolanicity or hydraulicity of a material can be determined through standardized methods such as the Chapelle test Strength Activity Index (SAI) or Frattini test in accordance with ASTM C618. Materials like silica fume, Class F fly ash, and rice husk ash exhibit pronounced pozzolanic properties, while metakaolin, GGBFS and calcined clays display latent hydraulic or combined pozzolanic-hydraulic behavior [265, 325].

5.4.2. Oxide Composition (SiO_2, Al_2O_3, CaO)

The chemical composition of an SCM, especially the proportions of aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), and calcium oxide (CaO), plays a key role in its reactivity and compatibility with the traditional Portland cement. These oxides contribute to the formation of C–S–H, C–A–H, and other useful hydration compounds that influence the durability and compressive strength of concrete. For example, a high content of reactive silica and alumina improves pozzolanic activity, whereas a balanced combination with calcium oxide can promote early-age strength development through latent hydraulic reactions. Fly ash general contains

40–60% SiO_2 and 20–30% Al_2O_3, while GGBFS is rich in CaO (30–50%), making both highly recommended SCMs when combined with Portland cement [232].

5.4.3. Fineness (Particle Size Distribution and Surface Area)

The fineness of an SCM calculated in terms of particle size distribution (PSD) and specific surface area (e.g., Blaine fineness or BET surface area) directly impacts its reactivity, water demand, and ability to fill voids in cementitious matrices. The finer the particles, the larger the surface area for reaction thereby giving more room for packing denser binder matrix, which contributes to lower porosity and enhanced mechanical strength. For example, silica fume, with a particle size less than 1 μm and surface area over 20,000 m^2/kg, is highly reactive and improves both strength and durability in high-performance concretes. In contrast, coarser materials such as bottom ash require mechanical grinding to reach optimal fineness. Target fineness values for SCMs are typically >300 m^2/kg for Blaine fineness, depending on the type of material [271, 326].

5.4.4. Compatibility with Cement Chemistry

A suitable SCM must integrate efficiently with the hydration kinetics and chemical equilibrium of ordinary Portland cement (OPC) without activating undesirable reactions. Incompatibility may lead to reduced strength gain, delayed setting, or even issues related to expansion. One prevalent concern is the alkali-silica reaction (ASR), where amorphous silica in some SCMs (e.g., waste glass powder) reacts with alkalis from cement, forming expansive gels that damage concrete. Therefore, pre-treatment or particle size control may be required to mitigate ASR hazards. Compatibility can also be influenced by the SCM's chloride and sulfate contents, which can affect durability and reinforcement corrosion. Proper chemical and mineralogical characterization ensure that the SCM does not interfere with OPC hydration or compromise structural integrity [266, 302].

5.4.5. Availability and consistency

For real-world and commercial-scale use, SCMs is expected to be available in significant quantities and display relatively stable composition across production batches. Availability is influenced by logistical feasibility, industrial activity levels, and regional distribution. A good example is fly ash; it is abundantly available in coal-dependent countries like China, India, and the United States, but its availability is declining with the transition away from coal-fired power. Consistency, particularly in oxide composition and fineness, is critical for predictable performance. SCMs from uncontrolled processes (e.g., biomass ash or red mud) often show high variability, requiring pre-treatment, blending, or quality monitoring protocols [268, 326].

5.4.6. Environmental and economic benefits

SCMs must provide net environmental benefits over traditional Portland cement by reducing greenhouse gas emissions, conserving raw materials, and minimizing solid waste accumulation. Life cycle assessment (LCA) tools have consistently shown that the partial replacement of clinker with SCMs can reduce embodied CO_2 by 20–60%, depending on the substitution rate and material type [213]. For instance, using GGBFS or fly ash can offset energy-intensive clinker production, while also diverting industrial waste from landfills. From an economic standpoint, SCMs sourced as industrial by-products are often less costly than Portland cement and can contribute to financial savings in waste management and production. However, economic feasibility is region-specific and depends on collection, processing, transportation, and market demand [238].

5.4.7. Regulatory and standards compliance

To ensure safe and durable application in concrete, SCMs must meet regulatory specifications defined by international and national standards. These standards cover loss on ignition (LOI), chemical composition, fineness, pozzolanic activity, and performance metrics such as strength development and durability. Widely adopted standards include ASTM C618 (for fly ash and natural pozzolans), ASTM C989 (for GGBFS), and EN 197-1 (for common cements incorporating SCMs). Materials not yet covered by these standards (e.g., red mud, waste glass powder) require robust research facts and performance testing to support their acceptance. Regulatory acceptance is crucial for market penetration and for meeting construction code requirements in infrastructure projects [160, 266]. Table 5.3 presents a summary of standards available around the world focusing on SCMs.

Table 5.3. Summary of international standards governing SCMs.

Standard Code	Region	SCMs Covered	Key Criteria
ASTM C618	USA/Global	Fly Ash, Natural Pozzolan	$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$, LOI $\leq 6\%$, Strength Activity Index $\geq 75\%$
ASTM C989	USA	GGBFS	Chemical limits, fineness, activity index
ASTM C1240	USA	Silica Fume	$SiO_2 \geq 85\%$, specific surface $\geq$ 15,000 m^2/kg

EN 197-1	Europe	Multiple SCMs (FA, GGBFS, pozzolans)	Strength classes, durability, chemical constraints
IS 3812	India	Fly Ash	Pozzolanic activity, particle size, LOI
BS 8615	UK	Natural Pozzolans	Reactivity, durability, consistency
NBR 12653	Brazil	Pozzolans (Rice Husk Ash, Metakaolin)	Pozzolanic index ≥ 75%, moisture & loss on ignition limits

This comprehensive two-phased screening design helps to distinguish SCMs that are immediately applicable from those that necessitate further investigation or process optimization. It forms the groundwork for the multi-criteria assessment presented in the subsequent section, where SCMs are critically evaluated for their potential contribution to sustainable, low-carbon concrete technologies. Table 5.4 presents the result of SCM suitability scoring matrix. Each material is rated across the seven SCM selection criteria, with scores from 1 (lowest) to 10 (highest). The Scoring framework is presented in Appendix (chapter 5) in supplementary material.

Table 5.4. SCM Suitability Scoring Matrix.

S/N	Waste Material	Pozzolanic / Hydraulic Reactivity	$SiO_2/Al_2O_3/CaO$ Content	Fineness	Cement Compatibility	Availability & Consistency	Environmental Benefit	Standards Compliance	Total /70
1	Fly Ash (FA)	9	9	8	9	10	10	9	64
2	GGBFS	9	9	7	9	9	9	9	61
3	Silica Fume (SF)	10	10	10	8	6	8	8	60
4	Red Mud	5	6	6	5	9	7	3	41
5	Rice Husk Ash (RHA)	8	9	6	8	8	9	7	54
6	Palm Oil Fuel Ash (POFA)	7	8	7	7	7	6	6	48
7	Bottom Ash (BA)	5	6	5	6	8	7	5	42

8	Waste Glass Powder (WGP)	7	8	7	3	7	8	5	45
9	Marble Dust Waste (MDW)	3	3	6	6	7	6	4	36
10	FGDG	6	7	6	7	7	7	6	46
11	Ceramic Dust Waste (CDW)	4	6	3	6	6	3	4	32
12	Napier Grass Ash (NGA)	6	7	7	6	3	8	4	41
13	Biomass Ash	6	7	6	6	6	8	5	44
14	Calcined Clay	9	9	8	9	8	8	9	60

15	Aspiration Dust	4	5	5	5	6	6	3	34
16	Bagasse Ash	7	8	6	7	6	9	6	49
17	Boiler Slag	5	6	3	6	7	7	4	39
18	Egg Shells	3	3	4	4	6	3	2	25
19	Metakaolin (MK)	10	10	9	9	8	9	9	64
20	Copper Slags	6	7	6	6	3	7	5	40
21	Other Non-Ferrous Slags	5	6	5	5	6	6	4	37
22	Lead/Zinc Slags	4	5	4	4	5	5	3	30
23	Blast Furnace Dust	5	6	5	5	6	6	4	37
24	Steel Slag	7	8	7	7	8	8	6	51

25	Geopolymer Binders	9	9	8	9	7	9	7	58
26	Oil-Based Mud	3	4	4	3	5	5	2	26
27	Kaolinitic Waste	8	9	7	8	7	8	7	54

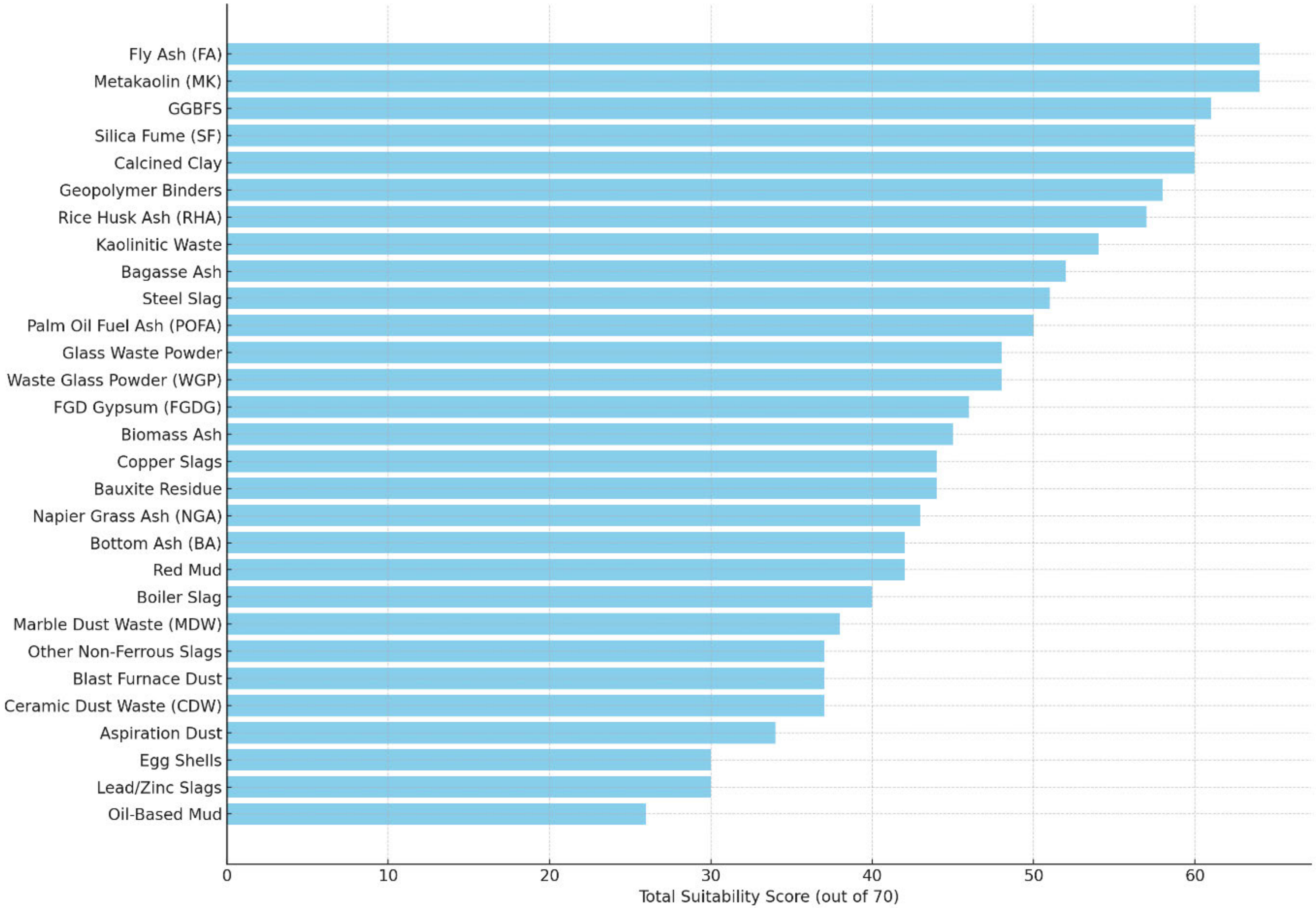


Figure 5.1. Pictorial representation of SCM suitability Scoring Matrix.

The result shows a definite hierarchy among the screened SCMs, reflecting distinctions in pozzolanic activity, physical characteristics, chemical composition, and environmental performance. Based on cumulative scores, the materials are classified into four categories: Top performers (≥60), high Suitability (50–59), moderate Suitability (40–49), and low Suitability (<40). These groupings presented by Table 5.4 and illustrated in Figure 5.1, are summarized below.

5.4.8 Top Performers (Scores ≥ 60)

- Fly Ash (64) and Metakaolin (64) rank highest due to their high pozzolanic reactivity, fine particle size, and extensive field performance. They both meet ASTM C618 standards and substantially reduce CO_2 emissions [327, 328]. Metakaolin is gotten from calcined kaolinite clay; it enhances early strength, durability, and chloride resistance [329, 330].
- GGBFS (61) (Ground Granulated Blast Furnace Slag) is a latent hydraulic binder known for its long-term strength gain and durability benefits. It is widely available and used in sustainable concrete systems [331, 332].
- Calcined Clay (60) and Silica Fume (60) are high-reactivity SCMs. Calcined clay, especially kaolinitic varieties, provides exceptional pozzolanic activity and is promising for low-carbon cements [333]. Silica fume, though less available, offers high strength and low permeability in small dosages [325].

5.4.9 High Suitability (Scores 50–59)

These SCMs exhibit strong potential but may require further optimization or standardization for broader adoption.

- Geopolymer Binders (58) and Rice Husk Ash (57) are innovative and emerging SCMs. Geopolymers are synthesized from aluminosilicate-rich wastes under alkaline activation. Its present full cement replacement prospective and outstanding mechanical properties [334, 335]. Rice husk ash, when properly calcined, contains amorphous silica and exhibits strong pozzolanic activity [336].
- Kaolinitic Waste (54) and Bagasse Ash (52) perform well due to favourable mineralogy. Bagasse ash is a sugar industry byproduct that requires fine grinding but enhances strength and durability [337].
- Steel Slag (51) and Palm Oil Fuel Ash (50) show good chemical composition and environmental benefits. Nonetheless, both require further processing like grinding and stabilization to address free lime and improve fineness [338, 339].

5.4.10 Moderate Suitability (Scores 40–49)

SCMs in this tier possess partial pozzolanic properties or compositional advantages but face constraints in reactivity, variability, or environmental risk.

- Waste Glass Powder (48) and/ Glass Waste Powder (48) contain amorphous silica but are susceptible to alkali-silica reaction unless finely ground. When processed correctly, they can improve durability and reduce permeability [340].
- FGD Gypsum (46) and Biomass Ash (45) offer decent pozzolanic reactivity. Biomass ashes vary substantially in composition depending on feedstock and combustion method [336, 337].
- Bauxite Residue (44) and Copper Slag (44) possess alumina and iron oxides but may introduce impurities or heavy metals that require treatment [317, 341].
- Napier Grass Ash (43) and Bottom Ash (42) can serve as regional SCMs when finely processed but show slower pozzolanic activity compared to fly ash [342, 343].

5.4.11 Low Suitability (Scores < 40)

These materials generally exhibit poor reactivity, inconsistent quality, or elevated environmental risks, limiting their application as active SCMs.

- Boiler Slag (40) and Ceramic Dust Waste (37) contain silica and calcium but possess poor reactivity and it is not consistent in supply [314, 344].
- Aspiration Dust (34), Lead/Zinc Slags (30), and Oil-Based Mud (26) have reduced reactive phases and often contain toxic elements, restricting their safe application in cement [345-347].
- Eggshells (30) are composed mainly of calcium carbonate and lack pozzolanic phases, making them more appropriate as fillers than active SCMs [315].

Although both materials originate from the steel industry, GGBFS is a latent hydraulic material formed during iron production and is widely accepted as a high-performance SCM. In contrast, steel slag is a by-product of steel refining, often containing free lime (CaO), periclase (MgO), and unreacted oxides, which can cause volumetric instability unless treated. GGBFS has broader global standardization (ASTM C989), whereas steel slag's use in cement is still under research due to variability and leaching risks [348]. This ranking incorporates technical, environmental, and practical potentials. Top-tier SCMs like Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume (SF), Metakaolin (MK), and Calcined Clay demonstrate superior pozzolanic or latent hydraulic reactivity, rich reactive silica and alumina content, and adequate fineness which are the major characteristics for strength development and improved durability in cementitious systems [268, 349]. For instance, FA and GGBFS are greatly used due to their favourable particle size distribution and long-term availability from coal combustion and iron production, respectively, which make them reliable SCMs [350]. Silica Fume, despite lower availability, ranks high due to its ultrafine particles and extremely high SiO_2 content, significantly enhancing strength and durability [351]. Metakaolin and

Calcined Clay also have significant score as they offer high pozzolanic activity and comply with global standards such as ASTM C618 and EN 197-1 [311]. Environmental benefits were also a key consideration; high-ranking materials often deter substantial waste streams from landfills while reducing CO_2 emissions by replacing clinker, thus encouraging circular economy goals [213]. Standards compliance further strengthens the ranking, as materials that meet ASTM, BS EN, or local regulatory criteria are more possible for large-scale implementation. Lower-ranking materials may still be feasible in specific environments or regions but necessitate further development to meet performance and safety benchmarks. Materials like Rice Husk Ash (RHA) and Palm Oil Fuel Ash (POFA) demonstrate strong potential due to their extraordinary amorphous silica content and environmental benefits derived from agricultural waste valorization, though variability in combustion methods may impact consistency [352, 353]. Conversely, materials such as Red Mud, Bottom Ash, and Bauxite Residue are limited by lower reactivity, higher content of heavy metal, or alkali concerns, which may hamper their performance and acceptance in standard cement formulations [354, 355]. Similarly, waste glass powder and steel slag are not so promising due to reasonable pozzolanic properties but require careful preprocessing to mitigate alkali-silica reaction [356]. Ultimately, this multi-criteria assessment aligns with sustainable construction goals and global efforts to reduce the carbon footprint of the cement industry [229].

5.5. Performance and Sustainability Review of Top-Ranked SCMs

A thorough analysis of five leading SCMs from the suitability scoring matrix which are Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume (SF), Calcined Clay (CC), and Metakaolin (MK) is presented in this section. The focus is on their performance in concrete integration, sustainability capabilities, and major challenges. The Life cycle assessment (LCA) perspective is also considered to compare environmental impacts, alongside recent case studies that illustrate real-life applications and innovations.

5.5.1 Fly Ash (FA)

5.5.1.1 Performance and Sustainability Characteristics

Fly ash (FA) is a fine powdery material derived from the flue gases of coal-fired thermal power plants. Classified as either Class F or Class C under ASTM C618, its composition and performance are dependent on the coal origin and combustion conditions [357]. Class F fly ash is gotten from bituminous and anthracite coal that contains high concentrations of silica (SiO_2) and alumina (Al_2O_3) which offers strong pozzolanic activity. Class C fly ash is generated from lignite or sub-bituminous coal and contains large quantities of calcium oxide (CaO) and exhibits both pozzolanic and latent hydraulic properties. The smooth texture and spherical shape of fly ash particles help to reduce water demand, improve workability, and enhance packing density in fresh concrete. These rheological benefits translate to improved resistance to sulphate attack, lower permeability, and mitigation of alkali–silica reaction (ASR) [350]. Fly ash also enhances the durability and long-term compressive strength of concrete. However, its moderately slow pozzolanic reaction may result in reduced early-age strength development thereby requiring optimization in mix design or the integration of more reactive SCMs, such as silica fume or metakaolin [350].

In terms of sustainability, fly ash significantly contributes to reducing the environmental footprint of concrete. Substituting 15–35% of clinker with FA can reduce CO_2 emissions by up to 30% when compared to traditional Portland cement systems [358]. This makes it a vital contributor to climate mitigation strategies in the construction sector most especially in regions with abundant coal power infrastructure.

5.5.1.2 Life Cycle Assessment (LCA) and Environmental Impact

Life cycle assessment (LCA) is a systematic framework for quantifying the environmental impacts of materials across their life cycle from extraction to end-of-life. In the context of cement and concrete, LCA studies constantly identify FA as one of the most environmentally advantageous SCMs due to its by-product nature and low processing requirements [359] .

Unlike Portland clinkers, which require high energy approximately 1450°C of calcination, fly ash does not require high thermal treatment. When compared to Portland cement, its collection, drying, and classification require minute energy inputs, generating a GWP as low as 6–200 kg CO_2-eq/ton, depending on local energy mixes and processing conditions [263, 359]. Meanwhile, ordinary Portland cement (OPC) has a GWP of approximately 850–900 kg CO_2-eq/ton. When integrated into concrete at a 30% replacement, FA can reduce the embodied carbon of concrete mixtures by over 20–30% [263]. Beyond GWP, LCA studies also report reduced cumulative energy demand (CED), acidification potential (AP), and eutrophication potential (EP) when fly ash is used in blended cements [360]. When incorporation FA, there is no need of extraction virgin resources and minor thermal processing hence the reduction. Furthermore, the use of FA addresses end-of-pipe waste challenges, diverting tons of ash from landfills annually and promoting a circular economy practice in the construction and power sectors [359].

A comparative study by Chen et al. (2011) [263] realized that of the prevalent SCMs utilized, fly ash had the lowest environmental impact per functional unit of blended concrete, outperforming GGBFS, silica fume, and natural pozzolans under similar mix design conditions. However, regional variability in fly ash composition, quality and availability can influence LCA results. For instance, in countries with a declining coal usage or cleaner electricity grid, the marginal advantage of using fly ash may reduce due to decreased availability and increased transport burdens [360].

Evolving dynamic LCA models have started to incorporate future scenarios, evaluating the impact of decreasing fly ash supply on the sustainability of cement systems. These analyses emphasize the importance of integrating mineral extraction technologies and exploring hybrid SCM blends to maintain the environmental benefits of fly ash even under restrained supply chains [360].

Overall, fly ash contributes significantly to reducing the life cycle impacts of concrete, specifically in terms of resource depletion and climate change. When assessed under cradle-to-grave or cradle-to-gate scenarios, it is used in cementitious systems that support both carbon neutrality goals and waste valorization strategies, aligning with global sustainability frameworks such as the UN SDGs and EU Green Deal.

5.5.1.3 Challenges and Mitigation Strategies

Though fly ash has several advantages, some limitations must be addressed to ensure the continuous use of fly ash in cement and concrete systems. To start with, global availability is declining due to the ongoing transition from coal to renewable energy sources. This reduction is particularly obvious in Europe and North America, where coal plants are being decommissioned. Also, the physical and chemical properties of fly ash affect consistency in its performance and can vary significantly depending on the source. Unclassified or low-quality FA may contain high degrees of coarse particles, unburnt carbon, or sulphates, leading to poor reactivity or undesirable effects on air entrainment in concrete [350].

To mitigate these limitations, a range of mineral extraction and processing strategies have been developed. These include classification systems to ensure chemical conformity, electrostatic or magnetic separation to eliminate carbon and enhance fineness and blending with other SCMs to improve overall performance. Moreover, mechanical and chemical activation techniques have shown promising improvement in the reactivity of low-quality fly ashes, thereby expanding the usable supply [361].

5.5.1.4 Field Applications and Case Studies

Several large-scale infrastructure projects have established the practical viability of fly ash as an SCM in various contexts. In India, the Delhi Metro Rail Corporation (DMRC) utilized high volumes of fly ash in its concrete mix designs for underground structures and tunnel linings. This enabled a 25% reduction in cement use, improved control overheats of hydration, and enhanced crack resistance in mass pours [362]. In the United States, the construction of the Hoover Dam Bypass Bridge integrated Class F fly ash to improve sulfate resilience and reduce permeability, considering the aggressive environmental exposure of the structure [363]. Likewise, in China's South–North Water Transfer Project, high-volume fly ash concrete (HVFAC) was successfully deployed to achieve low heat generation and long-term durability over extensive service life expectations [364]. These projects highlight the technical robustness, scalability, and sustainability potential of fly ash in diverse climatic and structural conditions.

Fly ash remains one of the most technically viable and environmentally favorable SCMs in global construction practice. Its established performance in improving durability, strength, and sustainability is supported by years of empirical data and standards adoption. Nonetheless, future applications will depend on enhanced mineral extraction technologies, quality control, and the development of alternative SCMs in regions where fly ash availability is declining. By integrating fly ash thoughtfully into blended cement systems, the cement industry can continue to advance toward low-carbon, circular economy resource-efficient construction paradigms.

5.5.2 Ground Granulated Blast Furnace Slag (GGBFS)

5.5.2.1 Performance and Sustainability Characteristics

Ground granulated blast furnace slag (GGBFS) is a by-product of the iron and steel industry, formed when molten blast furnace slag is rapidly quenched with water to produce a glassy, granular material that is then dried and ground into a fine powder. GGBFS is commonly categorized into grade 80, 100, or 120 based on its relative strength performance; it is classified under ASTM C989 [365]. The chemical composition of GGBFS is dominated by silica (SiO_2), calcium oxide (CaO), magnesia (MgO) alumina (Al_2O_3), which allow latent hydraulic properties. When activated by the alkaline environment of Portland cement, GGBFS exhibits both pozzolanic and cementitious reactions, improving the long-term durability and strength of concrete [349]. Usually, the particle morphology of GGBFS is fine and angular which improves packing density and reduces the water-to-cement ratio needed for desired workability. Concrete incorporating GGBFS demonstrates superior resilience to chloride ingress, sulfate attack, and alkali–silica reaction (ASR), making it a good fit for marine and chemically aggressive environments [366]. Although early-age strength development may be slower than ordinary OPC, GGBFS concrete shows continuous strength gain over time due to its continuous hydration processes [349]. The integration of GGBFS is also known to reduce the heat hydration, mitigating thermal cracking in mass concrete structures [367].

As regards sustainability, GGBFS significantly reduces the environmental problem of concrete production. As an industrial by-product, it eliminates the need for additional raw material mining and high-temperature processing. Substituting 40–50% of OPC with GGBFS can reduce CO_2 emissions by up to 30–40% [229]. The GWP of GGBFS is reported to be approximately 60–250 kg CO_2-equivalent per ton, significantly lower than the 850–900 kg CO_2-equivalent per ton for OPC clinker [229, 358]. Additionally, GGBFS utilization supports circular economy objectives by valorizing metallurgical waste and reducing landfill demand.

5.5.2.2 Life Cycle Assessment (LCA) and Environmental Impact

In most LCA studies GGBFS is seen as a low-impact SCM because it requires low processing energy unlike clinker production, which involves energy in the calcination process. GGBFS production involves quenching and grinding, which are substantially less carbon intensive. Its GWP ranges from 60–250 kg CO_2-eq/ton, depending on grinding energy, electricity source, and location [229, 263]. When used at 40–50% substitution levels in concrete, GGBFS can reduce the embodied carbon of concrete by approximately 25–40% [358]. In addition to lower GWP, LCA analyses highlight reductions in CED, photochemical ozone creation potential (POCP) and AP when GGBFS is used in blended cements [263]. A comparative LCA conducted by Habert et al. (2011) revealed that GGBFS had the second-lowest environmental impact among key SCMs, slightly higher than fly ash but significantly lower than silica fumes and natural pozzolans considering their equivalent performance criteria [358].

GGBFS also solves the problem of resource depletion by reducing the demand for limestone, clay, and other primary cement raw materials. Moreover, it addresses the disposal issues in the iron and steel industry, aligning with global waste valorization and industrial symbiosis frameworks such as the United Nations SDGs and the European Union's Green Deal [229]. While Although GGBFS' availability is more geographically restrained than fly ash, especially in non-industrialized regions, emerging logistics and grinding companies are increasing its market reach.

5.5.2.3 Challenges and Mitigation Strategies

Although GGBFS have several enticing attributes, some shortfalls restrict its widespread adoption. Firstly, its availability is a function of existence and large-scale blast furnace operation in countries transitioning away from traditional steelmaking to electric arc furnace (EAF) technologies, there is decline in the supply [368]. Secondly, variations in slag composition due to different metallurgical processes can impact reactivity and strength development [349]. For example, high MgO content or low glass content can unfavorably affect hydraulic behavior. To address these limitations, advanced characterization methods such as X-ray fluorescence (XRF) and scanning electron microscopy (SEM) are employed to guarantee quality control and reactivity estimation. In addition, hybrid binders blending GGBFS with other SCMs like fly ash or limestone are being adopted to counterbalance performance inconsistencies and widen its applicability in diverse climatic and structural settings [238]. Innovative alkali-activated slag systems (AAS) are also gaining traction, presenting a pathway to clinker-free binders in high-performance, low-carbon applications [265].

5.5.2.4 Field Applications and Case Studies

GGBFS has been successfully employed in several landmark infrastructure projects globally, underlining its technical viability and environmental value. In the UK, the channel tunnel rail link vastly used GGBFS-based concrete to meet stringent sustainability and durability criteria under marine exposure conditions [358]. Also, the Burj Khalifa in Dubai incorporated GGBFS in its concrete mixes to enhance long-term strength in the region with hot climate and reduce heat hydration [262]. In South Africa, the Gautrain rapid rail link project used GGBFS because of its reduced carbon footprint and sulfate resistance which aligns with the sustainable infrastructure agenda [229]. These case studies show that GGBFS is reliable across a wide range of structural requirements and environmental exposures. With appropriate quality control, mix design, and supply chain planning, it is a robust SCM alternative that balances resource efficiency goals and global decarbonization in the built environment. As the cement industry adapts to low-carbon targets, the strategic use of standalone GGBFS or hybrid blends will remain vital to evolving sustainable concrete technologies.

5.5.3 Silica Fume (SF)

5.5.3.1 Performance and Sustainability Characteristics

Silica fume (SF) also known as microsilica, is an ultrafine non-crystalline by-product generated during the production of silicon and ferrosilicon alloys in electric arc furnaces. SF contain over 85–95% amorphous silicon dioxide (SiO_2) and it's distinguished by high surface area, unusually fine particle size about 100 times smaller than tradition Portland cement grains, and high pozzolanic reactivity [369]. Also, it is classified under ASTM C1240 and highly efficient SCM alternative combined in small amounts (5–10% by weight of cement) [268]. The physical and chemical properties of silica fume are the major factors for improvements in the durability and mechanical attributes of concrete when incorporated. Its ultrafine particles fill voids between cement grains, reducing porosity, improving dense packing, and refining the microstructure [370]. When combined with calcium hydroxide released during cement hydration, SF undergoes pozzolanic reactions to form additional calcium silicate hydrate (C–S–H gel) resulting to reduced permeability, enhanced compressive strength, and enhanced resistance to chemical attack and chloride ingress [366]. These characteristics make silica fume exceptionally valuable in high-performance concrete (HPC) applications, including bridge decks, precast elements, industrial floors, and marine structures.

Although SF is used in relatively small amounts when compared to other SCMs, it provides significant environmental advantages contribute to the durability of concrete. The production of silica fume process of does not emit CO_2 gas or require material extraction, as it is collected from the off gases of silicon smelting operations. The GWP of silica fume is estimated to range between 40 and 200 kg CO_2-eq per ton subject to purification processes and energy sources [229]. By allowing the production of durable, high-strength concrete with prolonged service life, SF contributes indirectly to resource conservation and reduced life cycle environmental impacts [358].

5.5.3.2 Life Cycle Assessment (LCA) and Environmental Impact

LCA studies indicate that silica fume shows relatively low environmental burdens, specifically in AP, GWP, and CED, when regularized to its functional contribution in concrete mixtures [229]. As a high-performance SCM derived from an existing industrial process, SF has a much lower GWP than Portland clinker (850–900 kg CO_2-eq/ton) and requires reduced processing beyond collection, packaging, and densification [229, 263]. In high-performance and ultra-high-performance concretes UHPC, SF is often used at 5–10% substitution levels, the marginal rise in material cost or energy input is offset by reduced maintenance requirements, enhanced structural longevity, and prolonged durability. In a study by Habert et al. (2011), LCA revealed that silica fume has a somewhat higher GWP per ton than fly ash or GGBFS, its excellent reactivity means that only little amount is needed to achieve comparable or superior performance, especially in durability-centred applications.

Also, the use of silica fume supports circular economy initiative by rerouting industrial emissions into productive use and improving concrete longevity, hence reducing the rate of reconstruction and repair. Nevertheless, LCA results are highly dependent on the regional factors such as the transportation in supply chains and the energy mix during silicon production. In some instances, the environmental values may be reduced by the high embodied energy associated with densification and long-distance hauling [263].

5.5.3.3 Challenges and mitigation strategies

Although excellent technical properties have been recorded, several challenges hinder the widespread adoption of SF. Its high specific surface area and exceptionally fine particle size increase water demand and reduce workability in fresh concrete. This can result in compaction challenges and poor rheology if there is no appropriate admixture management [370]. To address this, superplasticizer especially high-range water-reducing admixtures (HRWRAs) are usually used to sustain workability while preserving low water-to-cement ratios [268]. Another challenge is the limited and geographically uneven availability of high-quality SF. Since its retrieved during the production of silicon and ferrosilicon industries, supply depends on the regional presence of these industries. Furthermore, the cost of silica fume is higher than other SCMs due to logistics and densification particularly in regions without silicon sources [368]. Quality control is also important, as impurity degrees, variations in SiO_2 content, and densification methods can affect performance in concrete.

To address these challenges, ongoing research focuses on advancing alternative ultra-fine pozzolans (e.g., rice husk ash, nano-silica) and enhancing the processing and transportation of SF. Also, optimizing mix design with binary or ternary blends involving SF and other SCMs (e.g., fly ash, slag) can help workability, balance cost, and performance requirements [371].

5.5.3.4 Field Applications and Case Studies

SF has been utilized in high-performance infrastructure projects globally due to its ability to deliver superior strength and durability. One remarkable example is the Confederation Bridge in Canada, which used silica fume-modified concrete to achieve improved freeze-thaw resistance and extended service life under harsh marine conditions [367]. Also, the Øresund Tunnel between Denmark and Sweden incorporated SF to enhance durability and chloride resistance in the underwater concrete segments [372]. In the United States, SF has been broadly adopted in bridge decks and parking structures, where resistance to de-icing salts and freeze thaw cycles is critical [366]. The use of SF has also been demonstrated in the construction of industrial floors and precast elements in the Middle East, where low permeability and high early strength are vital under hot and harsh conditions [229].

These case studies demonstrate the efficiency of SF in demanding applications, especially where service life, strength, durability, and are of great importance. While cost and workability concerns remain, the strategic use of SF in specialized concrete formulations continues to advance the goals of sustainable, resilient, and long-lasting construction.

5.5.4 Calcined Clay

5.5.4.1 Performance and Sustainability Characteristics

Calcined clay, a thermally activated aluminosilicate material, is produced by heating kaolinitic clays ($Al_2Si_2O_5(OH)_4$) at temperatures ranging from 600°C to 850°C. This thermal process dehydroxylates the clay and results into a very reactive amorphous material that qualifies to be a SCM. More impure and abundant kaolinitic clays, like those used in the LC^3 (Limestone Calcined Clay Cement) system, are also gaining attention for wider applications [229]. Calcined clay contributes considerably to filler and pozzolanic effects in cement systems. When reacted with calcium hydroxide ($Ca(OH)_2$), CC forms hydrates like calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), thereby reducing porosity, improving mechanical strength and durability and enhancing the microstructure [373]. Also, the alumina content of CC plays a vital role in chloride ingress, which helps in improving resistance to corrosion of steel reinforcement in concrete structures [374]. When mixed with ground limestone in LC^3 formulations, the interactive effect is improved durability, strength development, and workability at substitution levels of up to 50% of Portland clinker [302].

CC offers major environmental benefits over Portland cement because of avoidance of decarbonation (unlike using limestone), large quantity of materials and its lower calcination temperature. The GWP of CC ranges from 300 to 500 kg CO_2-eq/ton which is lower than that of clinker (about 850–900 kg CO_2-eq/ton) [213]. In LC^3 systems, clinker substitution levels of up to 50% can lead to CO_2 emission reductions of 30–40%, alongside significant reductions in resource consumption and embodied energy [375]. Also, CC does not require industrial by-products, making them especially suitable in regions where fly ash or slag is lacking.

5.5.4.2 Life Cycle Assessment (LCA) and Environmental Impact

LCA studies particularly in LC^3 formulations recognize CC a low-impact alternative to Portland cement. The main environmental benefits are elimination of CO_2 emissions from limestone decarbonation and reduced calcination temperature (between 200–300°C lower) [213]. In addition, kaolinitic clays are broadly available in many regions, and their mining and milling process is minimal compared to that of limestone and clay for clinker production. LCA comparisons reveal that substituting 50% of clinker with a blend of 30% CC and 15–20% limestone can lower the GWP of cement by up to 40%, while still maintaining expected durability and mechanical performance [375, 376]. These systems also result in reduced particulate matter formation, AP and CED [377]. Moreover, the international energy agency and United nations environment programme have highlighted LC^3 as a vital advancement for reducing emissions in developing economies, particularly where SCM alternatives like slag or fly ash are scarce [160]. However, the composition of clay varies from region to region; this is sole based on the logistics and the energy sources used during calcination which can in turn have effect on the overall environmental savings. For instance, low-kaolinite content clays may require further mineral extraction to attain desired reactivity, increasing material and energy inputs [378]. Regardless of these challenges, dynamic LCA models confirm that CC-based systems maintain robust environmental advantages under a varied condition, particularly when incorporated with waste-heat recovery or renewable energy systems during calcination [376].

5.5.4.3 Challenges and Mitigation Strategies

Although CCs present favourable performance and sustainability benefits, it also has numerous limitations that must be addressed before large scale adoption. One of those major challenges is the variation in the kaolinitic content across diverse clay deposits. Impure or non-kaolinitic may present reduced reactivity, requiring blending strategies or further mineral processing to meet performance requirements [373]. Furthermore, the effective adoption of CC necessitates controlled thermal activation, typically in flash or rotary kiln, which this infrastructure is not available in many regions. The increased water demand and reduce workability associated with some CC is another limitation. This is mainly because of their high specific surface area and angular particle shape. To address this, additives like superplasticizers are often used in mix designs, especially in high-performance concrete applications [379]. Also, enhancing blending and fineness with other SCMs like slag or limestone can help increase rheology and performance consistency. The need for new processing infrastructure like dedicated calcination unit can impose financial and logistical limitations, specifically in low-income regions. However, retrofitting current kilns or co-processing with other materials like clay-limestone systems offers an economically viable strategy. Performance-based specifications and standardization efforts will also be crucial to foster consumer confidence and broader implementation [378].

5.5.4.4 Field Applications and Case Studies.

The LC^3 project was initiated by École Polytechnique Fédérale de Lausanne (EPFL) and led industrial-scale and pilot demonstrations of calcined clay-based cements in Cuba, India, and several African countries. In India, the use of LC^3 cement in residential and infrastructure construction has demonstrated 30–40% reductions in CO_2 emissions without reducing durability or strength [6]. In Cuba, national-scale trials exhibited the feasibility of using local clays and limestone to produce LC^3 cement that meets EN standards, promoting the transition away from clinker-intensive production [9]. In Kenya, the Savannah Cement Company financed the development of clay-based cements using locally obtained materials. Preliminary results from infrastructure and housing projects indicate lower CO_2 emission, higher affordability, and compatibility with existing construction practices [12]. These case studies emphasize the utilization of CC not only as a low-carbon SCM, but also to support climate resistance construction in the built environment, foster industrial symbiosis, and improve local resource utilization.

Overall, CC stands out as a technically feasible, environmentally stable and scalable alternative to Portland clinker. Its low processing requirements, abundant availability, and compatibility with other SCMs as a central player in the cement sector's decarbonization roadmap.

5.4.5 Metakaolin (MK)

5.4.5.1 Performance and Sustainability Characteristics

Metakaolin is an extremely reactive pozzolanic material obtained from the controlled thermal dehydroxylation of kaolinite clay ($Al_2Si_2O_5(OH)_4$) with high purity level usually at temperatures ranging from 650°C to 800°C [380]. This process produces an irregular amorphous aluminosilicate structure, which reacts effortlessly with calcium hydroxide in cement systems to form secondary calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H) [381]. When compared with other SCMs, metakaolin stands out for its high purity and reactivity. When integrated at 5–15% by weight of cement, it substantially improves durability, reduces porosity, and improves early-age strength by consuming portlandite ($Ca(OH)_2$) and polishing the pore structure [382]. In addition, metakaolin impacts chloride ion resistance and alkali binding, making it a good fit for marine and destructive chemical environments [383]. Its fine particle size and angular morphology can also serve as nucleation sites, accelerating hydration reactions and increasing packing density of the cement matrix [384].

Considering sustainability, metakaolin provides reasonable environmental benefits relative to other SCMs. Although it is a natural material that requires calcination, the process occurs at lower temperatures than Portland clinker production and avoids limestone decarbonation significantly reducing related CO_2 emissions [229]. The GWP of metakaolin ranges from 400 to 600 kg CO_2-eq/ton, based on processing efficiency and calcination energy sources [385]. Though its carbon footprint is more than that of fly ash or GGBFS, it remains significantly lower than Portland cement. It is exceptionally valuable in regions that does not have access to industrial byproducts.

5.4.5.2 Life Cycle Assessment (LCA) and Environmental Impact

A detailed life cycle assessment carried out by researchers at UC Berkeley revealed that the GWP of metakaolin production can range from about 46 kg CO_2-eq/ton (when utilizing waste wood as the energy source) to approximately 347 kg CO_2-eq/ton (when utilizing coal in conventional rotary kilns). This variation highlights the significant impact that processing technologies and energy sources can have on the environmental footprint of metakaolin production [385]. These benefits become more noticeable in concrete mixes that prioritize high performance or chemical resistance, where metakaolin offers better durability enhancements.

Metakaolin unlike slag or fly ash is produced exclusively for cementitious applications and thereby introduces some environmental trade-offs. The calcination process is less energy in tensive compared to the clinker production process, but it still contributes to GWP especially when fossil fuel is used. However, this challenge can be mitigated by using waste heat or renewable energy and also sourcing kaolin locally to reduce emissions from transportation [386].

In addition to lowering GWP, the use of metakaolin in concrete is guarantees improvements in eutrophication potential (EP) and AP. Also, it improves chemical stability of the matrix and reduced leaching of alkaline compounds [262, 387]. These qualities make metakaolin an important component in concrete design of long-term durability and environmentally sensitive applications.

5.4.5.3 Challenges and Mitigation Strategies

Despite strong technical features, metakaolin adoption is limited by several challenges. The number one limitation of metakaolin is cost; it requires high energy calcination of high-grade kaolinite, making it more expensive than every other SCMs [388]. This can affect its wide range adoption especially in low-cost or large-scale construction projects except performance requirements justify its inclusion.

Another barrier is its high surface area that demands larger quantity water demand and thereby reducing workability in fresh concrete mixes. The mitigation strategy for limitation is using additives, admixtures or combining metakaolin with other SCMs such as slag or fly ash to balance rheology and performance [384]. Incompatibility with certain admixtures, particularly superplasticizers, can also occur and must be assessed during mix design development. Also, metakaolin availability has geographical constrained due to the limited presence of kaolinitic clay deposits. Its production is not yet widely industrialized as that of GGBFS and fly ash. Setting up local processing infrastructure and incorporating metakaolin into performance-based standards can promote its broader application and market acceptance [389].

5.4.5.4 Field Applications and Case Studies

Metakaolin has been successfully employed in wide range of infrastructure and high-performance projects where chemical resistance, low permeability and early strength, are of utmost importance. By way of illustration, an high geothermal tunnel grouting projects that integrated metakaolin recorded improved impermeability of about 38.91% and resistance to chloride penetration of approximately 12.77% [390]. In the United States, parking structures and bridge decks have incorporated metakaolin to address improve freeze–thaw durability and ASR [391, 392]. In the United States, metakaolin has been progressively integrated as a SCM to improve the durability and performance of concrete in infrastructure projects. Its high pozzolanic reactivity impacts reduced permeability, improved resistance to chemical attacks and enhanced compressive and flexural strengths. State Departments of Transportation (DOTs) in Illinois, Iowa, and other states have adopted highly reactive metakaolin into concrete overlay designs to achieve these favourable benefits. Despite the reported positive results and broad utilization literature, there is need for to establish standardized usage limits across diverse concrete classes in comprehensive studies [393, 394]. In Brazil, metakaolin was blended with local pozzolanic materials to produce eco-efficient concrete for urban development; it yielded enhanced durability and strength-to-cement ratios and used in tropical exposure conditions [395]. These applications reveal the resourcefulness of metakaolin as a high-performance SCM and its ability to lower environmental footprint of concrete in specialized construction contexts. Overall, metakaolin remains one of the most effective engineered pozzolans for improving concrete performance. While its higher cost and environmental impact compared to industrial by-products limit its widespread adoption, targeted use in demanding applications ensures its continued relevance in sustainable construction. Table 5.5 presents a summary of the five alternatives.

Table 5.5. Summary of the comparative assessment of SCMs.

SCM	Strength Contribution	Durability	LCA GWP (kg CO_2-eq/ton)	Availability	Main Limitation	Usage Case study
Fly Ash	Abundant, good long-term strength, eco-friendly	High	50–200	Declining	Variable quality, slow early strength	Mass concrete, blended cements

SCM	Strength Contribution	Durability	LCA GWP (kg CO_2-eq/ton)	Availability	Main Limitation	Usage Case study
GGBFS	High durability, consistent quality	Very High	50–150	Regional	Alkali activation needed	Marine and sulfate-resistant concrete
Silica Fume	High strength, low permeability	Very High	90–200	Limited	Workability, handling. Expensive, densification issues	High-performance/ultra-high-strength concrete
Calcined Clay	Abundant clay sources, good reactivity	High	350–450	Broad	Calcination, purity. Moderate strength gain, variability in kaolinite.	Low-carbon cement blends (e.g., LC^3)
Metakaolin	Very high reactivity, improves durability	High	400–600	Niche	Expensive, energy-intensive processing.	Precast, white concrete, specialty applications

5.5 Multi-Criteria selection of SCMs for sustainable concrete applications.

SCMs act as a link between conventional cement manufacture and sustainable applications on the demand side of the construction industry [51, 224, 396]. As shown in Section 3, each of these SMCs has advantages and drawbacks, and therefore when choosing the most suitable SM for sustainable concretes, a tradeoff is inevitable. For a designer the best SCM is one which possesses high pozzolanic reactivity, favorable $SiO_2/Al_2O_3/CaO$ composition, appropriate fineness, compatible with and effective in cement, is available in abundance form mother nature, saves energy and the environment and is available relatively cheap. Also, the economic viability of SCMs is influenced by several factors including processing requirements, raw material cost, supply chain logistics, and regional infrastructure. Low-cost SCMs such as FA, GGBFS, and RHA typically benefit from large-scale industrial production, integration within existing supply networks, and established handling and blending practices, reducing additional infrastructure and transportation costs [213]. Transportation over long distances remain a cost constraint, reinforcing the advantage of sourcing SCMs near cement plants. Medium-cost SCMs, such as calcined clay and metakaolin, require thermal activation at ~700–900 °C, which, although lower than conventional cement production (~1,450 °C), still incurs substantial energy input and operating costs, especially for drying, dehydroxylation, and milling [397]. High-cost or limited-scale SCMs like silica fume and treated red mud face significant logistical and processing challenges, particularly where centralized processing infrastructure is lacking. Silica fume is expensive due to specialized handling and purification requirements, while treated red mud requires complex neutralization and moisture management systems, raising both operational and transport costs [302, 398]. Furthermore, regional variability significantly affects SCM pricing. While fly ash remains economical in regions with abundant coal-fired generation (e.g. China, India), its production is dwindling in Europe and North America due to coal plant retirements. As a result, local prices in those regions have risen, and supply risks have increased [399-402]. As a result, the economic scoring reflects not just base price but also the logistical and processing intensity required to make the material suitable for concrete blending.

It implies that a tradeoff is required between the design criteria in case SCMs are utilized for sustainable concrete development. For example, from Table 5.4, the best pozzolanic reactivity as well as chemical composition properties can be attributed to Metakaolin while it has one of the least economic feasibilities. Furthermore, a contrast between Fly Ash and GGBFS shows that despite similar pozzolanic/hydraulic reactivity scores, the global availability of Fly Ash is higher. In line with this, the efficiency of multi-criteria techniques should be implemented in choosing the best SCM for a sustainable concrete application.

There has been extensive studies using MCDM techniques in SCM selection. Ahmed et al. [2] developed an integrated DSS including OSM and AHP-TOPSIS for the initial short listing of SCMs based on their technical and cost related attributes and prioritizing the materials as per their potential sustainability. The study showed that siliceous industrial waste and industrial waste products from the agriculture sector were materials with the highest environmental sustainability when used in construction. Moro [403] performed comparison study about MCDM methods and Life Cycle Assessment (LCA) approaches for the concrete batch plant with conventional and recycled materials using (SCMs) and recycling aggregate. The research also showed that different MCDM techniques had acceptable differences in ranking concrete mixtures and that the ability to select item values for properties provided flexibility in weighting properties for different applications of concrete. On the other hand, various LCA techniques with durability included showed much larger spreads, highlighting the superior consistency of MCDM techniques in SCM selection. Álvarez-López et al. [404] utilized the Analytic hierarchy process for the selection of biomasses to the manufacture of SCMs in a case where expert assessments in varied industries were not ignored. Their approach differed in that they assessed not only technical feasibility of the biomasses but also their production rate, ash content from combustion and the logistics aspects of supplying concrete plants. Their findings showed that technical possibilities (characteristics of the concrete) were the highest weighted criteria, followed by the availability of the material and transportation qualities, the combustion process being the least important.

These studies exemplify how MCDM is essential in selecting the preferred SCMs. Although these studies provide valuable frameworks for multi-criteria perspective in SCM selection, many relied primarily on expert opinion rather than the inherent material characteristics. Moving forward, the methodologies applied by these studies and other Multi-Criteria Decision-Making (MCDM) approaches can be applied to the inherent characteristics of SCMs to identify the most preferred alternative for specific applications, considering regional availability of materials, specific performance requirements, and local environmental regulations.

This would include identifying the supplementary cementitious materials (SCMs), their characteristics (which can be obtained from their performance data or existing literature) and selecting the appropriate weighing and MCDM methods. This section presents an example of how an MCDM approach can be used to choose the preferred SCM alternative in sustainable concrete design. Based on the scoring matrix presented in Table 5.3, five top-performing SCMs were identified: Fly Ash (FA), Metakaolin (MK), Ground Granulated Blast Furnace Slag (GGBFS), Calcined Clay (CC), and Silica Fume (SF). These materials were evaluated across ten key criteria including durability, CO_2 reduction potential, cost and processing ease, standards compliance, availability, Alkali-silica reaction (ASR), carbon avoidance credit, ease of blending & use, and resource circularity impact. The result is summarized in Table 5.6 and Figure 5.2.

Table 5.6. Comprehensive multi-criteria evaluation of key SCMs.

SCM	Durability Enhancement	Environmental Impact (CO_2 Saving)	Economic Viability	Standards Compatibility	Global Availability	Long-Term Strength Gain	ASR Mitigation Potential	Carbon Avoidance Credit	Ease of Blending & Use	Resource Circularity Impact	Ref
Fly Ash	4	5	4	5	5	5	5	5	5	5	[26, 261, 367, 405-412]
GGBFS	5	5	4	5	3	4	4	4	4	4	[229, 396, 413-417]
Silica Fume	5	4	2	5	2	5	5	3	3	2	[232, 311, 369, 418-421]
Calcined Clay	4	4	5	3	4	3	2	3	3	4	[267, 302, 375, 422, 423]

Metakaolin	5	3	2	3	2	4	3	2	3	3	[349, 424-430]

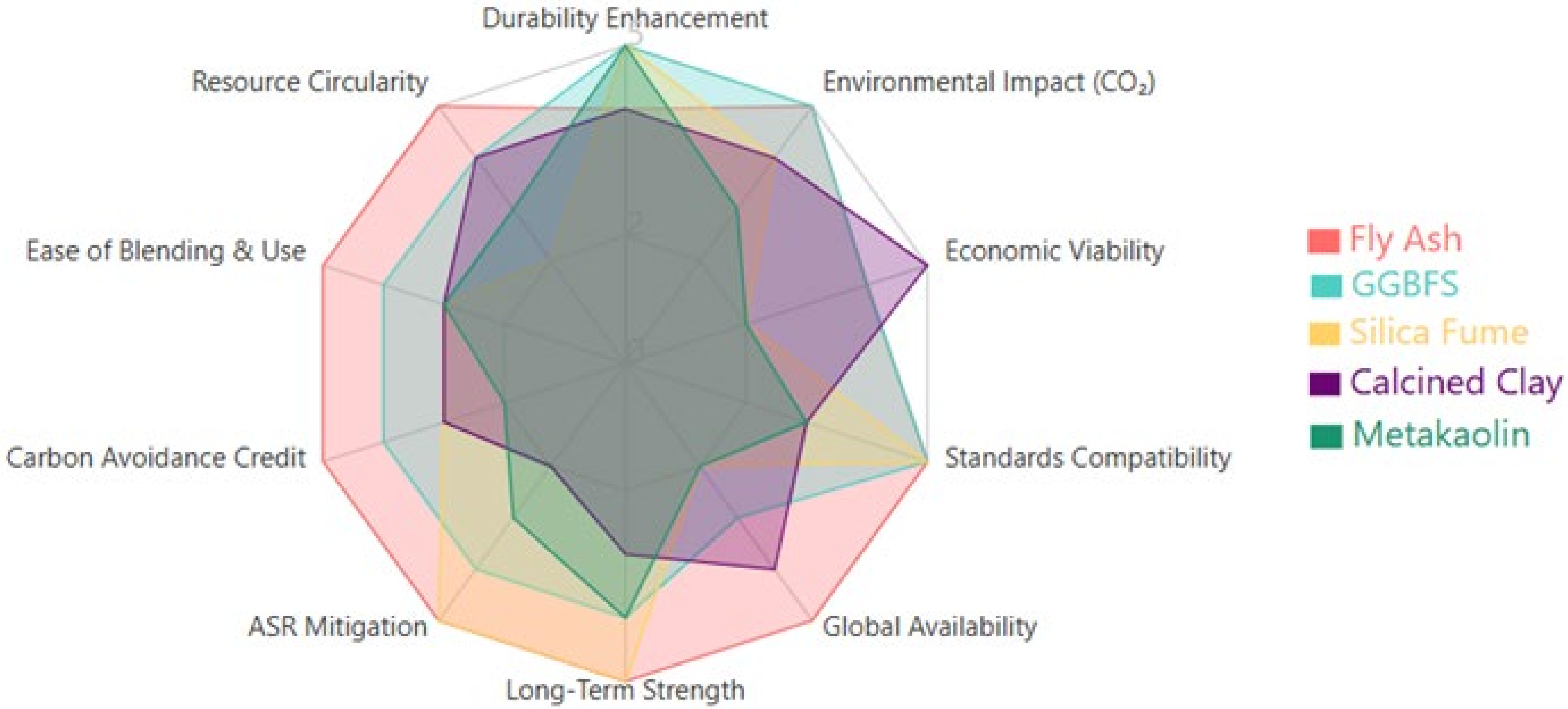


Figure 5.2. Radar chart of comparative Evaluation of SCMs

These criteria comprehensively address the chemical properties, technical performance, environmental impact, economic feasibility, and practical implementation aspects required for sustainable concrete design. Evaluation based on Distance from Average Solution (EDAS), an effective MCDM approach, can be applied to the ranking and selection process. EDAS can be implemented using 8 basic steps [431] as follows:

Step 1: Aggregation of the supplementary cementitious, i^{th} (known as alternatives) and the selected criteria j^{th} to form a decision-making matrix $X = \left[x_{ij}\right]_{m\times n}$. This takes the form of the expression presented in Eq. (5.1).

$$= \left[x_{ij}\right]_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdot\cdot & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \qquad 5.1$$

Where m is the number of SCM alternatives, and n is the number of evaluation criteria. For this case the decision-making matrix is presented as Equation 5.2.

$$= \left[x_{ij}\right]_{5\times 10} = \begin{bmatrix} 4 & 5 & 4 & 5 & 5 & 5 & 5 & 5 & 5 & 5 \\ 5 & 3 & 2 & 3 & 2 & 4 & 3 & 2 & 3 & 3 \\ 5 & 5 & 4 & 5 & 3 & 4 & 4 & 4 & 4 & 4 \\ 5 & 4 & 2 & 5 & 2 & 5 & 5 & 3 & 3 & 2 \\ 4 & 4 & 4 & 3 & 4 & 3 & 2 & 3 & 3 & 4 \end{bmatrix} \qquad 5.2$$

Step 2: Calculate the average (AV) for each criterion (Equation 5.3):

$$AV_j = \frac{\sum_{i=1}^{m} x_{ij}}{m} \quad 5.3$$

The resulting matrix is given in Equation 4

$$AV_j = [4.6 \quad 4.2 \quad 3.4 \quad 4.2 \quad 3.2 \quad 4.2 \quad 3.8 \quad 3.4 \quad 3.6 \quad 3.6] \quad 5.4$$

Step 3: Calculate Positive Distances from Average (PDA and Negative Distances from Average (NDA) using Equation 5.5 and 5.6 respectively

$$PDA_{ij} = \begin{cases} \max\left(0, \dfrac{x_{ij} - AV_j}{AV_j}\right) & B \\ \max\left(0, \dfrac{AV_j - x_{ij}}{AV_j}\right) & NB \end{cases} \quad 5.5$$

$$NDA_{ij} = \begin{cases} \max\left(0, \dfrac{AV_j - x_{ij}}{AV_j}\right) & B \\ \max\left(0, \dfrac{x_{ij} - AV_j}{AV_j}\right) & NB \end{cases} \quad 5.6$$

The implementation of the PDA_{ij} and av for this case results in the matrix presented in Equation 5.7 and 5.8 respectively.

$$PDA_{ij} = \begin{bmatrix} 0.000 & 0.190 & 0.176 & 0.190 & 0.563 & 0.190 & 0.3165 & 0.471 & 0.000 & 0.000 \\ 0.087 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.167 & 0.167 \\ 0.087 & 0.190 & 0.176 & 0.190 & 0.000 & 0.000 & 0.053 & 0.176 & 0.000 & 0.000 \\ 0.087 & 0.000 & 0.000 & 0.190 & 0.000 & 0.190 & 0.316 & 0.000 & 0.167 & 0.444 \\ 0.000 & 0.000 & 0.471 & 0.000 & 0.250 & 0.000 & 0.000 & 0.0003 & 0.167 & 0.000 \end{bmatrix} \quad 5.7$$

5.8

$$NDA_{ij} = \begin{bmatrix} 0.000 & 0.025 & 0.017 & 0.018 & 0.054 & 0.017 & 0.030 & 0.044 & 0.000 & 0.000 \\ 0.008 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.015 & 0.021 \\ 0.008 & 0.025 & 0.017 & 0.018 & 0.000 & 0.000 & 0.005 & 0.017 & 0.000 & 0.000 \\ 0.008 & 0.000 & 0.000 & 0.018 & 0.000 & 0.017 & 0.030 & 0.000 & 0.015 & 0.055 \\ 0.000 & 0.000 & 0.045 & 0.000 & 0.024 & 0.000 & 0.000 & 0.000 & 0.015 & 0.000 \end{bmatrix}$$

Step 4: Compute the Weighted Sum of PDA (Equation 5.9) and NDA (Equation 5.10)

$$SP_i = \sum_{j=1}^{n} (w_j \times PDA_{ij}) \qquad 5.9$$

$$SN_i = \sum_{j=1}^{n} (w_j \times NDA_{ij}) \qquad 5.10$$

The weights of the criteria are presented in Figure 3; it is obtained using the entropy method (Appendix: chapter 5). The result of the weighted Sum of PDA (Equation 5.9) and NDA (Equation 5.10) is as presented in equations 5.11 and 5.12.

$$SP_i = \begin{bmatrix} 0.205 \\ 0.044 \\ 0.089 \\ 0.143 \\ 0.085 \end{bmatrix} \qquad 5.11$$

$$SN_i = \begin{bmatrix} 0.0956 \\ 0.2026 \\ 0.0344 \\ 0.0933 \\ 0.1397 \end{bmatrix} \quad 5.12$$

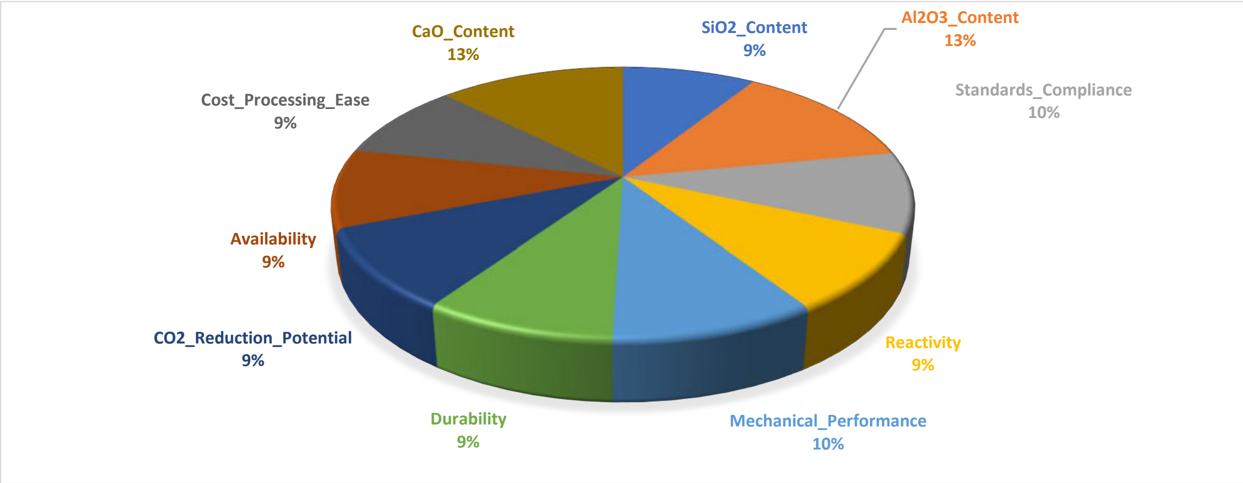


Figure 5.3. Weights of alternatives.

Step 5: Normalize SP_i and SN_i

$$NSP_i = \frac{SP_i}{\max(SP_i)} \quad 5.13$$

$$NSN_i = 1 - \frac{SN_i}{\max(SN_i)} \quad 5.14$$

The normalization of equations 5.13 and 5.14 results in equations 5.15 and 5.16.

$$NSP_i = \begin{bmatrix} 1.000 \\ 0.213 \\ 0.433 \\ 0.697 \\ 0.413 \end{bmatrix} \quad 5.15$$

$$NSN_i = \begin{bmatrix} 0.528 \\ 0.000 \\ 0.830 \\ 00.539 \\ 0.310 \end{bmatrix} \quad 5.16$$

Step 6: Compute the appraisal score (AS) for each alternative as presented in Equation 5.17

$$AS_i = \frac{NSP_i + NSN_i}{2} \quad 5.17$$

Resulting in the appraisal score (AS) shown in Equation 18.

$$AS_i = \begin{bmatrix} 0.764 \\ 0.107 \\ 0.631 \\ 0.618 \\ 0.362 \end{bmatrix} \qquad 5.18$$

The EDAS method revealed that Fly Ash is the most suitable SCM based on the ten criteria evaluated, significantly outperforming the other alternatives (Figure 5.4). GGBFS and Silica Fume showed comparable performance, ranking second and third respectively. Calcined Clay ranked fourth, while Metakaolin, despite its excellent pozzolanic properties, ranked last due to its performance across the weighted criteria set. This comprehensive evaluation provides concrete designers with a clear preference order for SCM selection based on a balanced assessment of chemical, technical, environmental, economic, and practical factors.

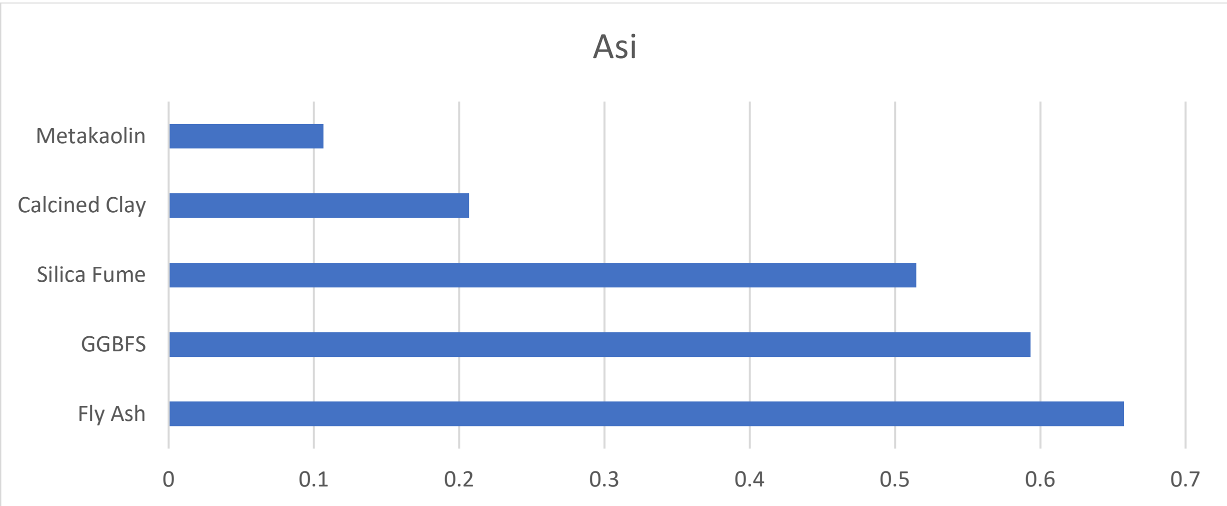


Figure 5.4. Ranking of the most suitable SCM.

5.6 Regional Availability, Supply Risks, and Adaptive Strategies for SCMs

The practical adoption of SCMs is highly region-dependent, influenced by industrial activity profiles, policy frameworks, logistical constraints, and resource distribution. While materials such as FA, GGBFS, and MK are technically proven, their regional availability presents a critical risk to large-scale deployment in the cement industry.

5.6.1 Decline in Fly Ash Availability

One major concern is the rapid decline in fly ash production in many regions due to the phase-out of coal-fired power plants. For instance, studies have shown that fly ash supply in the EU is projected to decline by over 70% by 2030 as member states transition to cleaner energy [224, 432, 433]. Similar trends are evident in North America and parts of Asia. Consequently, future SCM strategies must shift toward more abundant or locally sourced alternatives, including calcined clays, agricultural ashes, or mine tailings.

5.6.2 Regional Disparities in SCM Availability

In regions such as sub-Saharan Africa or Southeast Asia, access to industrial by-products like GGBFS or silica fume is limited due to the absence of steel or silicon industries at scale. However, these same regions generate large volumes of biomass waste, including rice husk ash, palm oil fuel ash, and bagasse ash, offering untapped SCM potential [434-436].

To address this, adaptive strategies should include:

- Localized SCM sourcing: Emphasizing regionally abundant residues (e.g., bagasse ash in Brazil, RHA in India, palm oil ash in Malaysia) to reduce dependence on imported SCMs.
- Waste valorization incentives: Promoting government-supported waste-to-resource frameworks to stimulate local SCM markets.
- Hybrid binder systems: Blending multiple SCMs (e.g., calcined clay + limestone + biomass ash) to compensate for limitations in single-source supply and ensure performance consistency [302].

5.6.3 Policy and Infrastructure Barriers

Adoption is also constrained by regulatory misalignment and infrastructure gaps. In many low- and middle-income regions, standards for alternative SCMs remain underdeveloped, preventing formal incorporation into structural codes. Moreover, pre-treatment and grinding facilities for SCM processing (e.g., for red mud or bottom ash) are largely lacking, even where raw materials are abundant.

These risks suggest the need for region-specific SCM roadmaps, which combine techno-economic evaluation with policy incentives, infrastructure investment, and long-term supply chain planning.

5.7. Conclusion

This research establishes the transformational potential of industrial waste valorisation in decarbonizing the cement sector. By integrating a comprehensive material screening process with an evidence-based MCDM framework (EDAS), a sound, data-driven ranking of SCM alternatives that goes beyond the conventional exclusive criterion assessments was provided. The MCDM analysis showed that Fly Ash outperforms all other alternatives across ten weighted criteria which are not limited to durability enhancement, CO_2 reduction potential, economic viability, and resource circularity: highlighting its exclusive ability to balance technical performance with environmental and cost concerns. GGBFS and SF emerged as strong runners-up, transcending in long-term strength and strong environment resilience, respectively. Although calcined clay and metakaolin, offer exceptional pozzolanic reactivity, they have the demerit of higher processing energy and cost requirements in the overall ranking.

Critically, the MCDM model reveals that no single SCM is globally optimal; each material's suitability is dependent on the context, local regulative frameworks, specific performance requirements and regional availability. By way of illustration, fly ash's global abundance and little or no additional processing demand make it a perfect primary SCM in coal-rich regions, whereas calcined clay may be ideal where kaolinite deposits and low-carbon calcination infrastructure coexist.

These findings corroborate the strategic value of incorporating decision-support tools into concrete mixture design, thereby enabling stakeholders to lucidly trade off competing objectives like early-age strength against lifecycle carbon footprint. Besides, the approach facilitates alignment with circular economy principles, incentivizing upstream waste producers (e.g., power plants, steel mills, rice mills) to see industrial by-products as valuable raw materials rather than disposal problems.

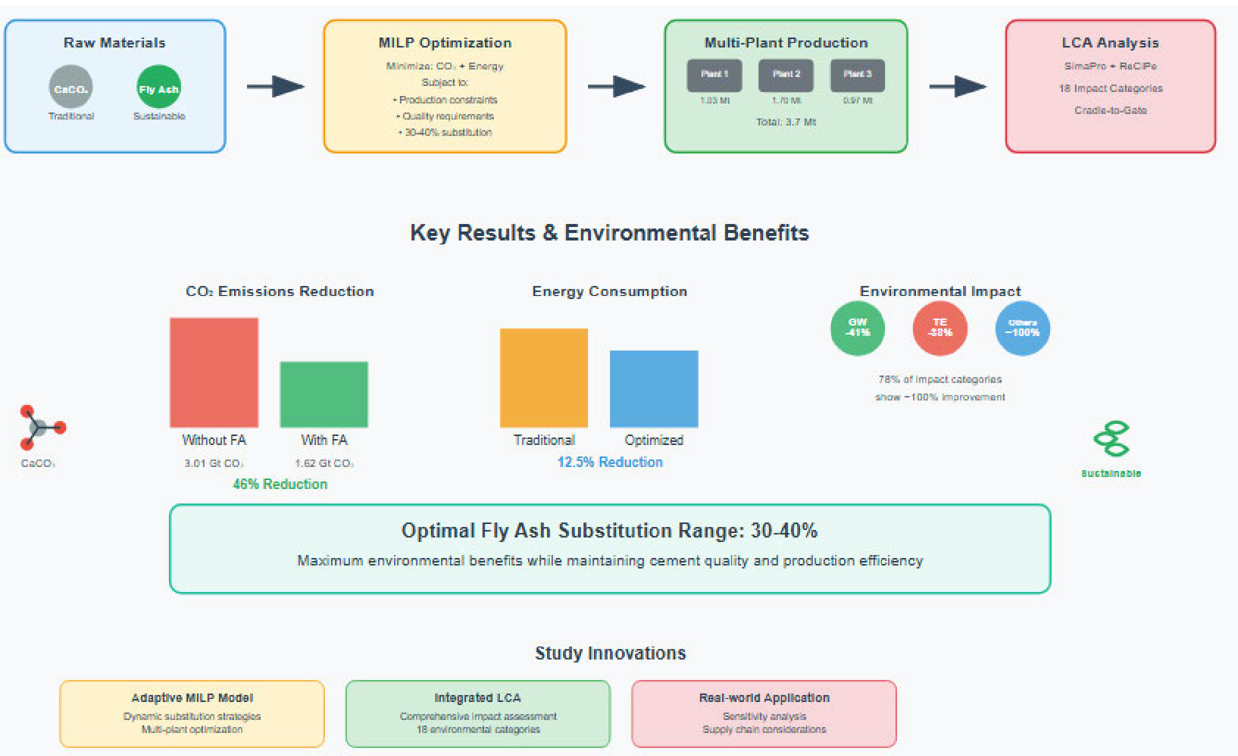
In considering the future, scaling this methodology will necessitate better data collection on standardized criteria weights adaptable to local contexts, emerging waste streams, and seamless incorporation with digital platforms (GIS, AI) for real-time SCM commendation. Policymakers and industry partners must collectively develop supportive standards and financial stimulants like carbon credits linked to MCDM-verified SCM utilization; to propel wider adoption. Finally, grafting MCDM-based SCM selection into industry practice can fast-track the transition to low-carbon concrete, reduced GHG emissions, producing resilient infrastructure, and a real circular economy in the built environment.

CHAPTER 6

MINIMIZING CARBON FOOTPRINT IN CEMENT PRODUCTION: A ROBUST MILP MODEL FOR ADAPTIVE FLY ASH SUBSTITUTION STRATEGIES

This chapter addresses the problem of emission and energy reduction by adapting fly ash substitution strategies by employing a Mixed-Integer Linear Programming (MILP) model. Also, LCA was carried out to know the environmental gains after applying the model. Cement production is responsible for approximately 7% of total global CO_2 emissions, primarily due to the calcination of calcium carbonate ($CaCO_3$) during the production of clinker. The goal is to minimize greenhouse gas emissions and energy consumption during cement production, meet production demands, and remain efficient. This chapter presents a systematic approach for the cement industry to achieve its environmental goals while meeting business needs. The content of this chapter is under review in the journal cleaner systems.

GRAPHICAL ABSTRACT



6.1 Introduction

Cement production is a core activity in the construction industry and is estimated to be between 4 and 4. 5 billion metric tons per year Mishra, et al. [437]. This process accounts for approximately 7% of the total CO_2 emissions released into the atmosphere each year, primarily due to the calcination of $CaCO_3$ to produce clinker, the primary ingredient of cement [438]. The high energy consumption during the production of clinker, makes cement manufacturing one of the largest sources of greenhouse gas emissions. The use of $CaCO_3$ with fly ash is an efficient strategy for reducing emissions. Fly ash is a byproduct of coal combustion. In its application, it addresses the issue of raw material needs while simultaneously reducing CO_2 emissions associated with clinker production, as suggested by Abdul-Wahab et al. It also enhances the durability and strength of concrete, making it a great candidate for SCMs. However, optimizing fly ash replacement involves many challenges, including meeting product performance standards and production targets. The cement industry faces a significant challenge: reducing emissions while improving production and financial performance. Today's production models do not account for real-life conditions, such as fluctuating demand, limited material availability, and stringent environmental constraints. It is almost impossible to meet such ambitious targets of emission reductions and, at the same time, ensure that production processes are efficient without adaptive solutions. This study develops an optimisation model that utilises fly ash to meet production goals while minimising greenhouse gas emissions, inputs, and energy. The model addresses significant challenges relevant to real-life situations, such as energy consumption, emission limits, and material availability for the cement industry, thereby providing a realistic approach. The study appraises: The objective of the study is to develop a proper Mixed-Integer Linear Programming (MILP) model that will help in the optimization of cement production; to incorporate various substitution rates of $CaCO_3$ with fly ash; to analyse their effects on emissions and energy consumption; to reduce the greenhouse gas emissions from cement production and at the same meet the operational constraints; and to check how well the model can respond to variations in conditions including demand

and supply of materials, and to carry out a LCA study to know the environmental gain of the optimal outcome of the model and other implications.

6.2 Literature Review

Cement production is one of the most significant contributors to world CO_2 emissions, which account for about 7% of total emissions [439]. Most of this is due to the calcination of $CaCO_3$ to produce clinker, which is a process that releases a lot of CO_2, as well as the energy-consuming kiln processes [440]. These pollutants must be addressed to reduce the building industry's environmental impact. Using fly ash as a substitute for $CaCO_3$ is a possible solution. Fly ash is a material obtained as a byproduct from coal power plants and can help reduce raw material consumption, CO_2 emissions and energy consumption [441]. Research shows fly ash can reduce emissions by 30% and increase concrete durability [442]. However, the quality of fly ash and the challenges in its transportation pose a barrier to utilisation [443]. Fly ash has pozzolanic properties, which makes it an efficient supplementary cementitious material because it increases the strength and durability of concrete [422]. It reacts with calcium hydroxide to form a denser structure less susceptible to chemical attack. Higher substitution levels enhance environmental performance but can hamper early strength development, a disadvantage in some applications [444]. Research on the use of $CaCO_3$ with fly ash has shown that partial replacement is beneficial. According to [445], the use of 30% to 40% of clinker with fly ash reduces the CO_2 emission by 25% without compromising the mechanical properties. Shaheen, et al. [446] also emphasized that the variation in the quality of fly ash available in different regions can affect its performance, highlighting the need for site-specific solutions. There are optimization methods, such as Mixed-Integer Linear Programming (MILP), that have been used to enhance efficiency in cement production. MILP models help in the effective management of resources, as well as minimize the costs and emissions [447]. Kantor, et al. [448] employed MILP to optimize the integration of intricate industrial systems, ranging from unit operations to processes, entire plants, and ultimately to exploring industrial symbiosis prospects among plants.

Nevertheless, these models are often based on certain assumptions that may not always be accurate, and they do not adapt to conditions such as fluctuations in demand and supply shortages. Other techniques, such as Genetic Algorithms (GA) and Neural Networks, focus on specific elements, such as optimizing clinker cooling or energy control [449]. However, the methodologies mentioned above are still limited by their ability to meet the requirements of MILP for large-scale production planning in terms of flexibility. This highlights the need for more sophisticated models that can handle changing conditions and are subject to real-life constraints. Life Cycle Assessment (LCA) is a technique that helps evaluate the environmental impact of cement production, from the acquisition of raw materials to the production process and waste management [240]. It determines the emissions of gases into the atmosphere, energy use, and resource utilization, and helps producers identify areas for improvement. The integration of LCA with optimisation models enhances the decision-making process by relating operational changes to long-term environmental gains [450]. Recent research combines life cycle assessment with optimisation models to improve cement production. Cadavid-Giraldo, et al. [451] combined LCA with MILP to assess the environmental impacts of using SCMs, including fly ash. However, such approaches are often inadequate for addressing the dynamics of operational conditions, such as fluctuating demand or changes in material supply. Even with the improvements made in cement production optimisation, there are still challenges. Few models consider the adaptive or the complex management strategies for substituting $CaCO_3$. Most research works are based on fixed substitution rates, which limit their applicability in practical scenarios. In addition, the use of MILP with LCA for the dynamic and multi-plant optimisation is not well explored. All these gaps are addressed in this study by developing a MILP model that extends the work on fly ash substitution while incorporating LCA. The model is flexible enough to accommodate various conditions and provide adequate measures for addressing the challenges of greenhouse gas emissions and energy consumption in cement production.

6.3 Methodology

This study employs a dual-method approach combining MILP and LCA to optimize cement production with minimal environmental impact. This integration addresses both ecological and operational objectives, allowing for data-driven, system-oriented decision-making in cement manufacturing.

6.3.1 Justification for Methodological Approach.

The cement industry presents a complex decision space involving multiple competing objectives: satisfying demand, minimizing emissions, managing limited resources (e.g., fly ash), and adhering to production constraints. MILP is a well-established operations research tool capable of optimizing such systems by modelling discrete and continuous decision variables under multiple linear constraints [452, 453]. MILP has formerly been used in energy systems [447], industrial symbiosis [451], and supply chain management for sustainable production [448].

Unlike heuristic or metaheuristic methods (e.g., genetic algorithms), MILP provides transparent constraint formulation and guaranteed optimality, which are important for policy-centred industrial optimization. Its adoption in cement production allows for precise modelling of plant-level substitution decisions, emissions, energy use and capacity constraints.

To Complement the MILP model, LCA is employed to estimate the environmental gains of optimized outcomes across multiple impact categories. LCA is a globally established method (ISO 14040/44) that evaluates the environmental impacts associated with all stages of a product's life as the name implies i.e. from raw material extraction to production (cradle-to-gate) [104]. Its combination with MILP helps measure whether optimised decisions yield meaningful improvements across categories like global warming, toxicity, resource depletion, and particulate formation etc. [454].

This integration has gotten limited but increasing use in sustainability-focused cement modelling [83, 450], but seldom in a multi-plant, flexible replacement context as demonstrated in this study.

6.3.2 Model Formulation

The purpose of the mathematical formulation is to minimize the total environmental impact, which includes emissions from raw materials and energy consumption. The notation used in the model is presented in Table 6.1 to make the analysis easier.

Table 6.1. Mathematical notation

Symbols	Description
x_{ij}	The amount of material i used in process j.
y_i	Binary decision variable indicating whether material i is used in the production process (1 if used, 0 otherwise).
p	Percentage of CaCO3 substitution with fly ash. This will vary from *10%* to *40%*.
C_{max}	Maximum production capacity for cement.
e_i	Emissions associated with material i per unit produced.
E_{max}	Maximum allowable total emissions
q_i	Cost of material i per unit.
Q_{max}	Total cost constraint.
e_{energy}	Emissions per unit of energy used in production.
E_{energy}	Total energy emissions
f_{ash}	The quality factor for fly ash, modelled as a variable impacting cement strength and production energy.

6.3.2.1 Objective function

The objective function is designed so that the raw materials, overall energy, environmental impact, and impact minimized substitution, including the quality emissions and cost of production, as shown in equation 6.1.

$$\boldsymbol{Minimize} = \sum_{j}\left(\sum_{i} \boldsymbol{e_i} \cdot \boldsymbol{x_{ij}} + \boldsymbol{e_{energy}} \cdot \boldsymbol{E_{energy}}\right) \tag{6.1}$$

The emission associated with using one unit of material i is represented as e_i; the quantity of material, i used in the process, j is represented as x_{ij}; the emission per unit of energy used in the production process is represented as e_{energy} and the total energy used in the production process is denoted as E_{energy}. The objective function, as described in equation (6.1), is built on two assumptions:

- All relevant emission sources are linearly proportional to the material or energy used.
- The environmental impact can be represented as a sum of the emissions from raw materials and energy use.

6.3.2.2 Model Constraints

The objective function described in Equation (6.1) is subject to material balance, production capacity, substitution, emission, energy use, cost, and quality constraints.

The material balance constraint is described mathematically in equation (6.2). The expression ensures that the total input materials are equal to the total cement output for each process.

$$\sum_{i} x_{ij} = Cement\ Output_j, \qquad \forall j \tag{6.2}$$

The production capacity constraint is described mathematically in equation (6.3). It ensures the total cement production cannot exceed the maximum production capacity.

$$\sum_{j} Cement\ Output_j \leq C_{max} \tag{6.3}$$

The constraint governs the percentage substitution of $CaCO_3$ with fly ash captured in equation (6.4)

$$xC_aC0_3, j = (1-p) \cdot Cement\ Output_j, \quad xFly\ Ash, j = p \cdot Cement\ Output_j,\ \forall j \tag{6.4}$$

Where p is varied between *0.10* and *0.4*.

The total emission from the production process must be within the maximum allowable emission.

$$\sum_{j}\left(\sum_{i} e_i \cdot x_{ij} + e_{energy} \cdot E_{energy}\right) \leq E_{max} \tag{6.5}$$

Since energy use must be within the maximum allowable energy consumption, equation (6.6) will help compensate for energy use constraints.

$$E_{energy} \leq Max\ Energy\ Use \tag{6.6}$$

The energy consumption will be a function of the quality of fly ash f_{ash} as lower quality fly ash most times requires energy processing: equation (6.7).

$$E_{energy} = \sum_{j}\left(b_{base\ energy} + b_{fly\ ash} \cdot f_{ash} \cdot x_{Fly\ Ash,j}\right) \tag{6.7}$$

Where $\boldsymbol{b_{base\ energy}}$ denotes the base energy required for production and $\boldsymbol{b_{fly\ ash}}$ is the additional energy required due to fly ash quality.

The constraints that ensure the total cost of material and energy does not exceed the maximum allowed cost are described mathematically in equation (6.8).

$$\sum_{j}\left(\sum_{i} q_i \cdot x_{ij} + q_{energy} \cdot E_{energy}\right) \leq Q_{max} \tag{6.8}$$

The quality constraints ensure that the cement meets minimum regulatory standards and is modelled, as shown in (6.9) by setting a lower bound on the cement's strength, which depends on the proportion and quality of fly ash.

$$Cement\ Strenght_j \geq Min\ Strenght, \quad \forall j \tag{6.9}$$

The strength can sometimes be a function of the quality factor f_{ash} and the proportion of fly ash in the mix. Mathematically, the quality of constraints that link the quality factor and the proportion of fly ash in the mix is described in equation (6.10).

$$Cement\ Strength_j = \alpha \cdot xCaC0_3, j + \beta \cdot f_{ash} \cdot xFly\ Ash, j, \qquad \forall j \qquad (6.10)$$

Where α and β coefficients represent CaC03 and fly ash's contributions to cement strength.

6.4 Data Collection

Data from credible sources were collected to ensure the accuracy and relevance of this study. CO_2 emission factors in kg/ton based on OPC benchmarks and energy use in MJ/ton, which reduced linearly with substitution based on empirical estimates. These were calculated and estimated using data available in an avalanche of scientific, articles, literatures and publication [21, 455-465]. Research and case studies in regions where cementitious materials, such as fly ash, are commonly incorporated indicate the fly ash savings, representing the reduction in CO_2 emissions in kg per tonne of substitution [145, 466-471]. These studies provided reasonable comparisons for assessing the environmental benefits of fly ash use. A simulation-based analysis was conducted to evaluate the performance of fly ash-based concrete with replacement levels ranging from 15% to 50%. production capacity and fly ash compatibility were varied across three plants; an estimated production capacity was calculated for each plant and total output of 3.7 million tons assessed across all plants. The model was solved under real-life constraints including energy limits, cost considerations, and regulatory emissions thresholds. The key data used in the model are reported in Tables 6.2 and 6.3.

Table 6.2. Simulation data without fly ash replacement [21, 145, 455-458, 466-468]

Plant	Cement Production (tonne)	CO_2 Emission Factor (kg/ton)	Energy Use (MJ/ton)
Plant1	1,032,967	750	3,783
Plant2	1,700,000	800	3,500
Plant3	1,000,000	900	4,000

Table 6.3: Simulation Data with Fly Ash Replacement[456, 461-463, 465, 470-472]

Plant	Substitution Levels	CO_2 Emission Factor (kg/ton)	Energy Use (MJ/ton)
Plant1	0.15, 0.20, 0.30, 0.40, 0.50	405.0	2,458.95
Plant2	0.21, 0.25, 0.30, 0.35	432.0	2,642.5
Plant3	0.15, 0.20, 0.30, 0.40	486.0	2,880

6.5 Mathematical Programming Model Justification and Solver Selection

6.5.1 Rationale for Using Mixed-Integer Linear Programming (MILP)

To address the growing need for sustainable cement production while considering both environmental constraints and operational efficiencies, this study adopted a Mixed-Integer Linear Programming (MILP) framework for optimizing production across multiple cement plants. MILP is particularly well-suited for modelling problems that involve both discrete and continuous decision variables, making it ideal for industrial applications that require on/off decisions (e.g., plant operation or fly ash substitution levels) alongside continuous variables like production quantities or emissions levels [453].

The choice of MILP is underpinned by its ability to handle multi-objective trade-offs, capacity limitations, and policy constraints in a unified structure. In the context of this thesis, MILP was crucial for representing the integrated decision-making process involving the allocation of fly ash as a SCM, while concurrently minimizing CO_2 emissions and energy consumption. These goals are consistent with the United Nations Sustainable Development Goal 12 on responsible consumption and production, and Goal 13 on climate action [452].

MILP is a well-established method in energy systems modelling, supply chain optimization, and environmental planning due to its flexibility and precision in formulating real-world constraints and objectives in linear forms [473-475]. Furthermore, it allows for scenario-based sensitivity analysis, which is instrumental in evaluating policy impacts and environmental trade-offs in industrial systems [476, 477].

6.5.2 Objectives and Model Fit

The MILP model was designed to optimize the allocation of cement production among three facilities, incorporating varying levels of fly ash substitution, while minimizing the environmental footprint. The primary objectives were:

- Minimize CO_2 emissions (kg/ton)
- Reduce energy consumption (MJ/ton)
- Satisfy regional production demand under uncertainty (80%-120% of baseline)
- Account for availability of SCMs such as fly ash (50%-150% of baseline)

MILP's capability to model such multi-facility, resource-constrained systems with binary and continuous variables made it superior to alternative techniques such as heuristic approaches, which often lack guarantees of optimality or purely linear programming, which cannot accommodate discrete operational decisions.

6.5.3 Why Gurobi Optimizer?

The Gurobi Optimizer was selected as the primary solver due to its state-of-the-art computational performance, robustness, and scalability. Gurobi has consistently outperformed other solvers in benchmark studies for MILP problems across multiple domains, including logistics, energy, and environmental systems [478, 479].

Key features of Gurobi that justified its selection include:

- Advanced MILP algorithms, including Branch-and-Bound, Cutting Planes, and Heuristics.
- Parallel computing support, which drastically reduces computation time for large-scale problems.
- Automatic presolve and model reformulation, which improves convergence efficiency.
- High precision with tenable gap tolerances, critical for environmental decision models requiring exact trade-off calculations.

The model was implemented on a PC with Intel Core i7 processor, 16 GB RAM, and 64-bit OS. Gurobi version 9.5 was deployed with a 600-second time limit per iteration, and a gap tolerance of 0.001, to ensure accurate results within reasonable computational time.

6.5.4 Solver Implementation and Model Execution

The optimization model determined the cement output of each facility under different fly ash substitution scenarios. Input parameters were derived from scholarly literature, published industrial studies and LCA databases. The MILP model incorporated constraints related to:

- Production capacities
- Regional demand
- Availability of fly ash
- Operational feasibility (binary decision for plant operation)

By using Gurobi's multi-threaded capabilities, the model distributed computation across CPU cores, which significantly reduced solution times and enabled real-time sensitivity analysis. The results proffer invaluable insights into how trade-offs between fly ash substitution, CO_2 reduction, and energy consumption could be balanced for sustainable production planning. The MILP-Gurobi framework hence offers a rigorous yet practical decision-support tool for cleaner cement production.

Figure 6.1 illustrates the MILP-based optimization procedure for reducing CO_2 emissions and energy consumption in cement manufacturing. This arrangement facilitates the import of data and thorough

LCA. Every plant's production and environmental indicators align with SimaPro's input criteria, enabling the evaluation of trade-offs and confirmation of the sustainability advantages of the optimal cement manufacturing model using ecoinvent database. This integration helps link LCA with optimization, supporting improved decision-making in sustainable production.

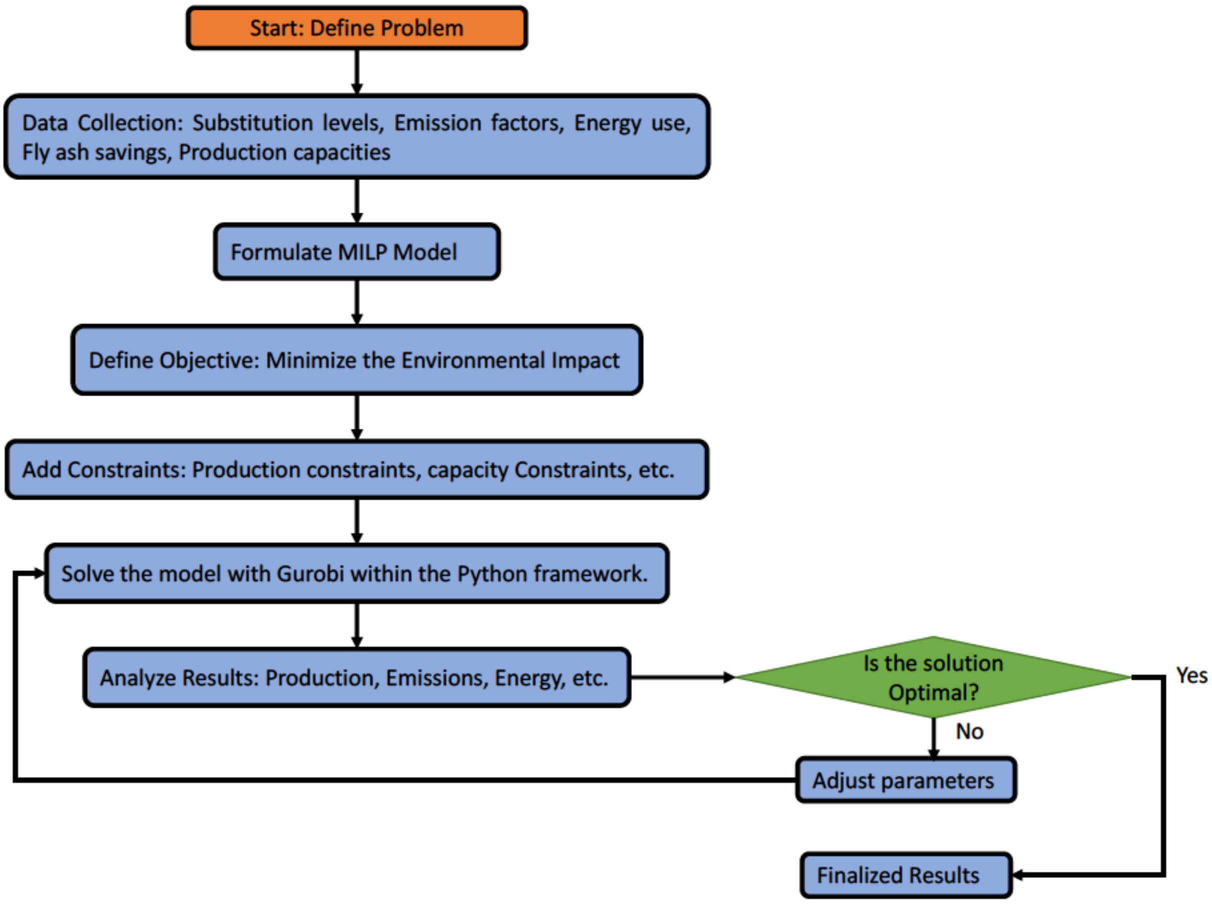


Figure 6.1. Optimization flowchart for minimizing carbon footprint in cement production

6.5.5 Sensitivity Analysis

A secondary model (no substitution scenario) was employed to benchmark performance. Emission factors were varied between 900 and 1200 kg CO_2/ton to simulate market and policy-induced uncertainties (e.g., carbon taxation, unavailability of fly ash). The sensitivity plots showed the robustness of MILP optimization under changing environmental penalties.

6.5.6 Life Cycle Assessment (LCA).

LCA was conducted using SimaPro 9.1.1 and the ecoinvent v3.6 database. The ReCiPe 2016 midpoint (H) method was used to assess 18 impact categories which are not limited to Global Warming (GW), Terrestrial Ecotoxicity (TE), and resource depletion. A cradle-to-gate boundary was selected, covering raw material extraction through cement production. The functional unit was 1 ton of cement, allowing for direct comparison between OPC and Pozzolanic Cement (PC) with 30–40% fly ash replacement.

Incorporation with MILP was achieved by importing optimized plant-level outputs (production volume, substitution level, energy use) into ecoinvent database in the SimaPro's LCI interface. This facilitated the calculation of environmental impacts associated with each scenario. Similar methods have been used in recent LCA-integrated optimization studies in cement [201, 249, 451], although this work is among the first to combine adaptive multi-plant substitution with full LCA-based environmental impact quantification.

6.6. Results and Interpretation.

The optimization model was solved for two primary scenarios: (1) Conventional OPC production without substitution, and (2) Optimized production incorporating adaptive fly ash substitution. Both scenarios satisfied the total demand of 3.7 million tons while observing all plant-level capacity constraints. Outputs are presented below and analysed in terms of substitution efficiency, emissions, and energy consumption.

6.6.1 Optimized Fly Ash Substitution Strategy

Table 6.4 and Table 6.5 summarizes the optimized production outcome and associated environmental impacts under the fly ash substitution and OPC production without substitution scenario respectively. The model allocated production strategically, favouring plants with higher substitution potential and lower emissions-to-energy ratios.

Table 6.4. Optimized production levels with Fly ash replacement.

Plant	Cement Output (tons)	Energy Use (MJ)	CO_2 Emissions (kg)
Plant 1	1,032,967	2.54×10^9	4.18×10^8

Plant	Cement Output (tons)	Energy Use (MJ)	CO_2 Emissions (kg)
Plant 2	1,700,000	4.49×10^9	7.34×10^8
Plant 3	967,033	2.79×10^9	4.69×10^8

The model allocated production strategically, favouring plants with higher substitution potential and lower emissions-to-energy ratios. These results show a 46.2% reduction in CO_2 emissions and a 28.3% reduction in energy consumption compared to the no-substitution scenario.

Table 6.5. Optimized production levels without Fly ash replacement.

Plant	Cement output (tons)	Energy Use (MJ)	CO_2 Emissions (Kg)
Plant1	1032967.0	3.9×10^9	7.74×10^8
Plant2	1700000.0	5.95×10^9	1.36×10^9
Plant3	967033.0	3.87×10^9	8.7×10^8

In the no-substitution output, the total CO_2 emissions was almost 3.01×10^9 kg, and energy consumption exceeded 1.37×10^{10} MJ (as seen in Table 6.5). Figure 6.2 compares the performance of the two scenarios. EUO and EUP are energy use (MJ) of OPC and PC respectively and CO_2O and CO_2P are CO_2 emissions (Kg) of OPC and PC respectively. The blended fly ash scenario (PC) shows reduced CO_2 emission of about 1.38 billion kg energy savings of approximately 3.9 billion which reflects improved energy efficiency per ton of cement. Plant 2, which supported a maximum 35% fly ash substitution, contributed the maximum production volume and highest emissions savings.

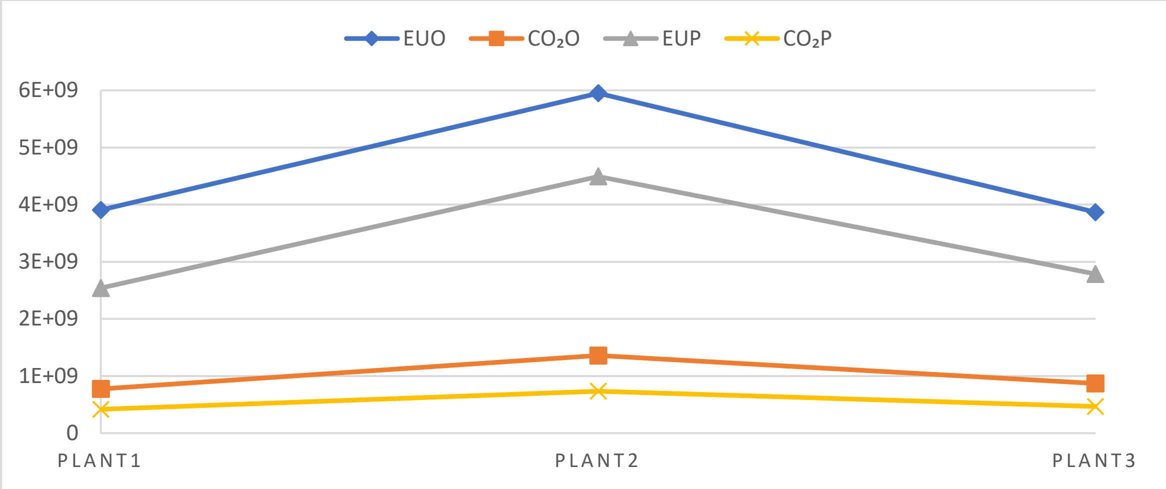


Figure 6.2. Environmental Impact by Plant.

These gains underscore the substantial environmental benefits of even moderate SCM integration, aligning with previous findings in the literature [445, 467].

6.6.2 Environmental Trade-offs and Performance Insights.

Figure 6.3 presents the optimized cement production distribution by plant. Facilities with greater replacement flexibility especially Plant 1 and Plant 2 were prioritized in the model, allowing a balanced allocation that reduces environmental impact without compromising production capacity.

Exceptionally, Plant 2, operational at a moderate substitution level of 35%, displayed strong localized environmental performance. When compared to its baseline under 100% OPC production, Plant 2 achieved a 19.8% reduction in energy consumption and a 33% reduction in CO_2 emissions. This highlights the effectiveness of moderate SCM replacement rate in yielding substantial environmental gains, especially when implemented in plants with favourable operational profiles.

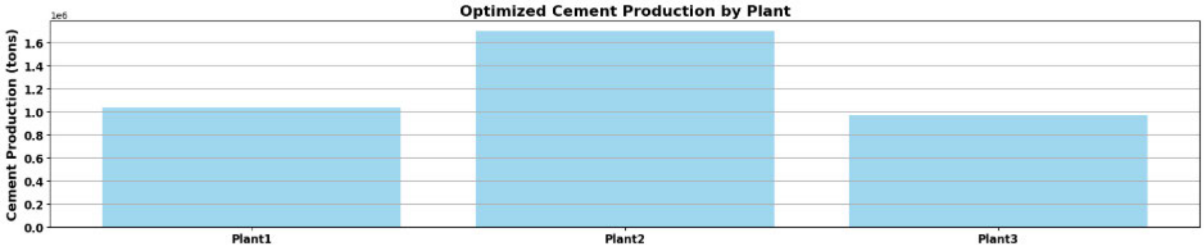


Figure 6.3. Optimized Cement Production by Plant with Fly ash Replacement.

Also, Figure 6.4 illustrates the nonlinear trade-off between substitution level and environmental benefits. Although increasing the amount of fly ash substitution initially account for substantial reductions in both energy use and CO_2 emissions, the gains began to respite beyond the 35–40% substitution level. This trend indicates an optimal substitution window, beyond which environmental enhancements become less definite relative to the required adjustments in material sourcing or process conditions.

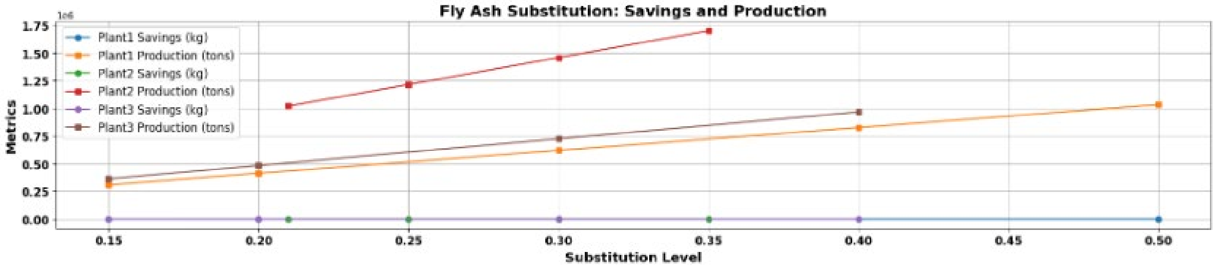


Figure 6.4. Fly Ash Substitution- Savings and Production.

6.6.3 Sensitivity to Fly Ash Availability.

A sensitivity analysis was carried out by varying the availability of fly ash from 50% to 150% of baseline. As represented in Figure 6.5. Plant 1, which allowed up to 50% substitution, showed the highest sensitivity to increased availability. Plant 3 remained mostly static, signifying technical limitations or physical. Optimal emissions reduction occurred when fly ash availability surpassed 100%, demonstrating supply constraints as a potential bottleneck. These insights highlight the need for a robust SCM supply chain to support sustainable cement strategies.

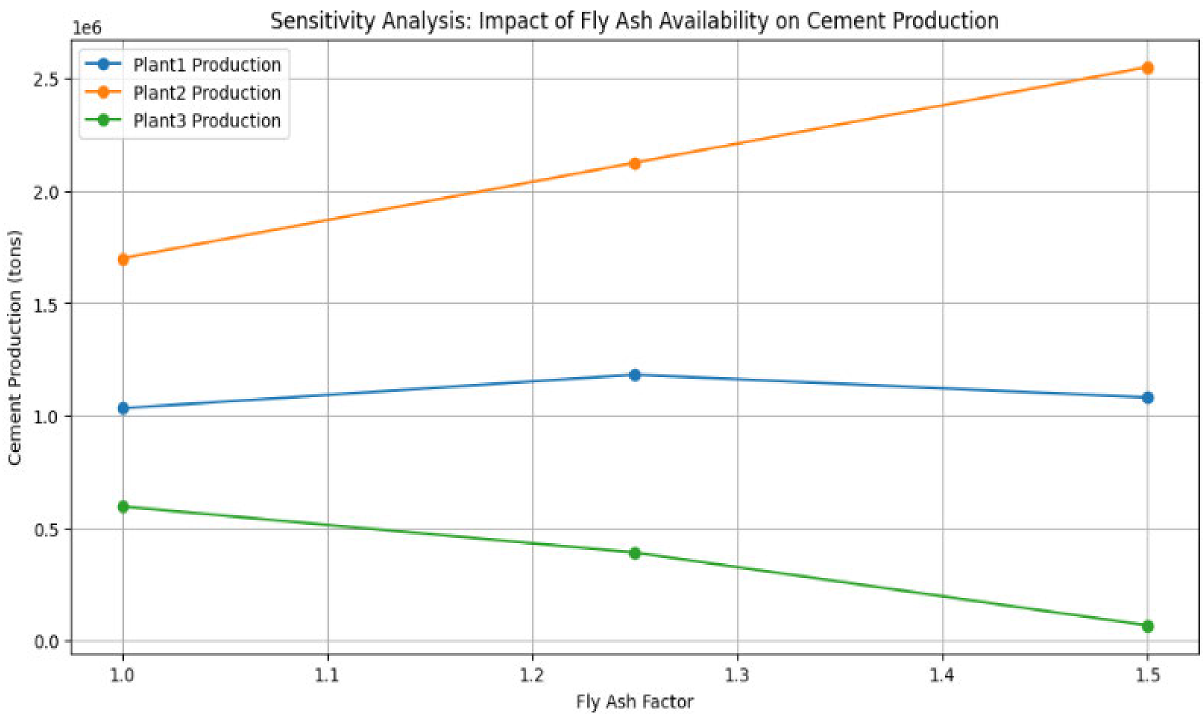


Figure 6.5. Sensitivity Analysis of the Impact of Fly Ash Availability on Cement Production.

6.6.4 Substitution-Energy Dynamics.

Figure 6 displays the inverse relationship between substitution level and energy consumption. For instance, Plant 1's energy use decreased from 3,385 MJ/ton at 15% substitution to 2,459 MJ/ton at 50% substitution. Comparable trends were observed for Plants 2 and 3, validating literature-reported energy savings of ~0.7% per 1% fly ash replacement [441].

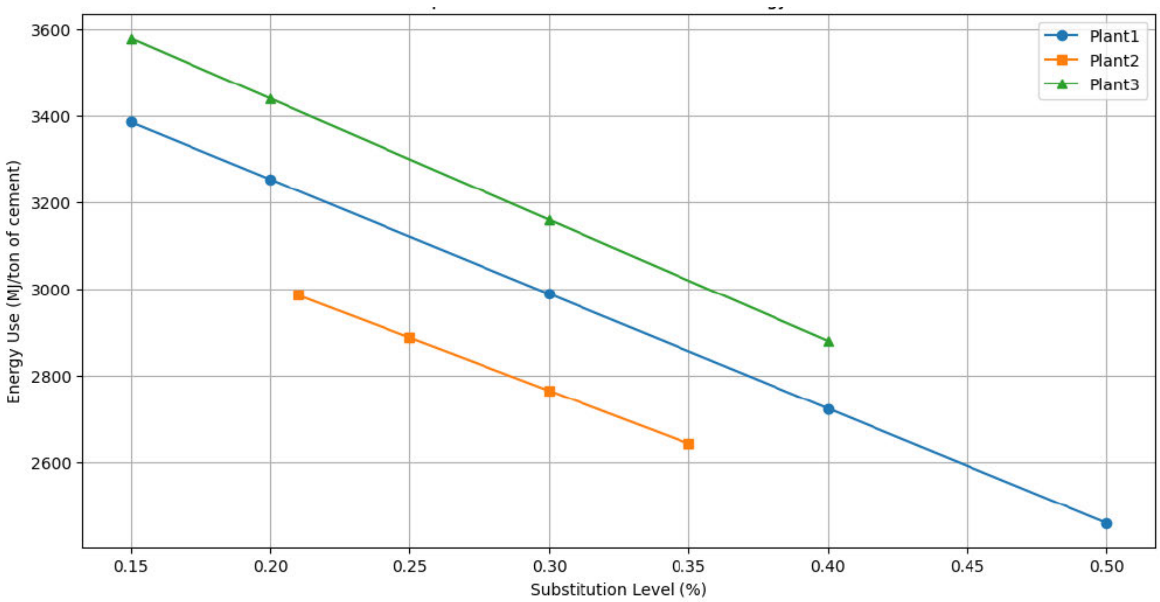


Figure 6.6. Impact of Substitution levels on energy use.

The MILP model successfully identified optimal plant-level production strategies that balance environmental impact and cement output under real-life constraints. The use of adaptive substitution demonstrated to be particularly effective in aligning industrial operations with emission reduction goals, setting the stage for the LCA evaluation that follows.

6.7 Life Cycle Assessment (LCA).

6.7.1 Purpose and Scope.

To assess the wider environmental impacts of the optimization strategy outside energy and CO_2, a LCA was carried out. This approach offers a multi-dimensional view of sustainability performance across environmental, human health and resource domains. LCA is especially suited to capture indirect and upstream impacts (e.g., raw material extraction, energy generation) that are not featured in operational emissions alone (ISO 14040; Finkbeiner et al., 2006). By integrating LCA with MILP, this study guarantees that operational decisions modelled for environmental efficiency (e.g., fly ash substitution) also lead to life-cycle gains, avoiding burden-shifting across impact categories.

6.7.2 Methodological Framework.

The LCA was performed using SimaPro 9.1.1 and the ecoinvent v3.6 database. The assessment followed the ISO 14040/14044 standards and adopted a cradle-to-gate system boundary, covering raw material acquisition, processing, and cement production. The functional unit used was 1 ton of cement, allowing for direct comparison between OPC and blended cement with fly ash substitution.

Environmental impacts were quantified using the ReCiPe 2016 Midpoint (H) method, which evaluates 18 midpoint categories, which include GW, TE, Acidification, Fossil Resource Scarcity, Human Toxicity, Fine Particulate Matter Formation, Freshwater and Marine Ecotoxicity. Optimized cement production outputs from the MILP model (Section 6.5) were incorporated into the inventory flows of the LCA model.

6.7.3 Results Overview.

The LCA results revealed significant environmental benefits associated with the fly ash substitution strategy. Table 6.6 present a comparative LCA for both scenarios:100% OPC and PC (fly ash-blended cement). The optimized substitution scenario produced substantial results. Of the 18 ReCiPe 2016 midpoint impact categories evaluated, 14 categories showed approximately 100% reduction, Fossil Resource Scarcity reduced by 93%, Human Non-Carcinogenic Toxicity decreased by 75%, GW was reduced by 41% and TE decreased by 38%.

Table 6.6. Comparison of Environmental Impact Characterization for 1 ton of OPC and PC.

Impact category	Unit	OPC	PC	% change
Global warming	kg CO_2 eq	995.61	586.3301	-41%
Stratospheric ozone depletion	kg CFC11 eq	0.000173	0.0000643	-100%
Ionizing radiation	kBq Co-60 eq	9.73	3.77	-100%
Ozone formation, Human health	kg NOx eq	2.11	1.44	-100%
Fine particulate matter formation	kg PM2.5 eq	0.79	0.37	-100%
Ozone formation, Terrestrial ecosystems	kg NO_x eq	2.12	1.45	-100%

Terrestrial acidification	kg SO_2 eq	2.43	1.049	-100%
Freshwater eutrophication	kg P eq	0.32	0.157	-100%
Marine eutrophication	kg N eq	0.0195	0.00988	-100%
Terrestrial ecotoxicity	kg 1,4-DCB	772.08	619.18	-38%
Freshwater ecotoxicity	kg 1,4-DCB	13.76	8.18	-99%
Marine ecotoxicity	kg 1,4-DCB	18.81	11.14	-99%
Human carcinogenic toxicity	kg 1,4-DCB	31.22	16.69	-98%
Human non-carcinogenic toxicity	kg 1,4-DCB	474.28	248.03	-75%
Land use	m^2a crop eq	17.20	11.16	-99%
Mineral resource scarcity	kg Cu eq	2.04	1.98	-100%
Fossil resource scarcity	kg oil eq	139.8	73.70	-93%
Water consumption	m^3	1.34	0.88	-100%

These findings confirm that clinker substitution not only lowers operational emissions but also reduces impacts related to air quality, human health and resource extraction. However, the lower improvements in GW and TE required further analysis at the substance level.

6.7.3.1 Global Warming.

GW was quantified as 996 kg CO_2 eq for OPC and 586 kg CO_2 eq for PC. As presented in Figure 6.7, more than 99% of the GW impact in both systems was actual CO_2 emissions. In absolute terms, CO_2 dropped from 996 kg to 586 kg per ton of cement produced. This guarantees the effectiveness of the optimization strategy in reducing emissions from fuel combustion and calcination, while also highlighting that residual emissions from thermal processes continue to control the carbon footprint even in blended systems.

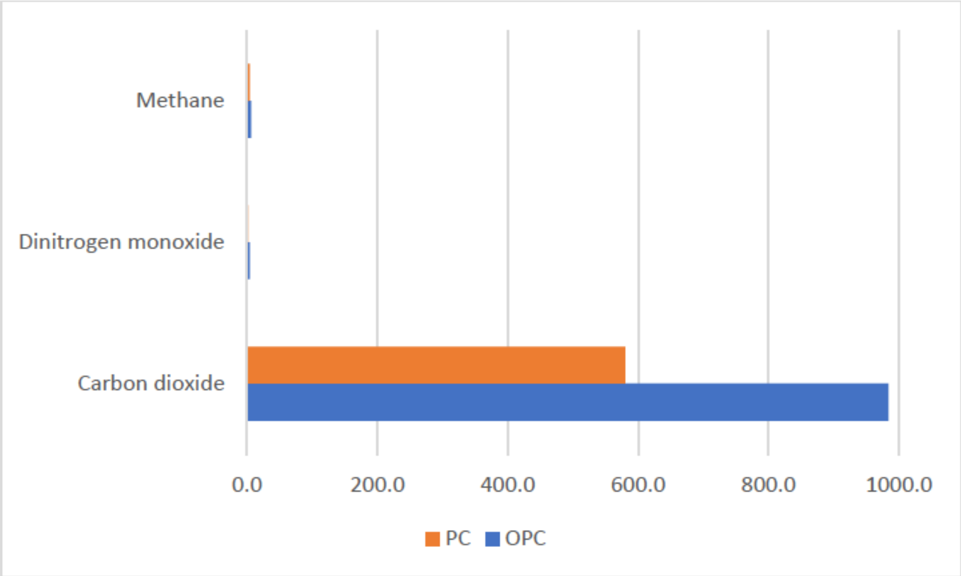


Figure 6.7. Substances Contributing to Global Warming.

6.7.3.2 Terrestrial Ecotoxicity (TE).

TE was estimated as 772 kg 1,4-DCB eq for OPC and 619 kg 1,4-DCB eq for PC. While this indicates a net reduction, a closer look at the contributing substances analysis presented in Table 6.7 presents subtle trade-offs.

Table 6.7. Comparison of Substances Contributing to TE.

Substance	OPC (%)	PC (%)
Antimony	18.42	16.79
Chromium	0.92	0.88
Copper	60.69	57.51
Lead	1.12	1.38
Mercury	8.02	9.54
Nickel	1.79	2.74
Vanadium	1.82	2.76
Zinc	5.61	6.40

Though the overall impact decreased, the fly ash-blended system showed slightly higher proportions of heavy metals such as lead, mercury, nickel, zinc and vanadium. These increases though very minute indicate that partial substitution may lead to trace surges in heavy metal emissions, possibly from handling-related emissions or impurities in fly ash. This underlines the significance of quality control and trace metal monitoring when sourcing and applying industrial waste materials like fly ash.

6.7.4 Interpretation.

The LCA study confirms that the MILP-optimized fly ash substitution strategy yields wide life-cycle environmental benefits, especially across mineral resource use, fossil fuel depletion and air pollution. The outcomes align with prior LCA findings and offer new insights into substance-level emissions trade-offs. The moderate reductions in GW and TE point to consistent CO_2 emissions from combustion processes and trace metal contributions from fly ash. The observed reductions in GW (41%) and TE (38%) are consistent with trends reported in previous LCA studies (within the last 10-15 years) on blended cement systems. [445] presented that replacing 30–40% of clinker with fly ash can achieve up to 30% reduction in CO_2 emissions, with energy intensity and clinker content being the primary determinant of performance. Also, [268] stated important improvements in GW and toxicity potentials with fly ash integration, although reductions in ecotoxicity were found to be very sensitive to the presence of trace number of heavy metals. [480] highlighted that the extent of environmental impact mitigation specifically in toxicity categories is significantly a function of regional upstream material processing and power generation mixes.

Similarly, in recent studies, [481] stated in their study that substituting 30 % fly ash reduces GWP by 29 %, and [201], found a slight reduction in decline in TE with 25–45% of fly ash. Considering the existing literature, the current study establishes comparable reductions across most categories, while presenting a more explicit analysis through substance-specific contributions and multi-plant optimization under realistic operational constraints. This improves the industrial relevance and robustness of the proposed MILP–LCA framework, particularly in informing data-driven SCM substitution strategies subject to environmental regulation and dynamic demand.

Although these findings do not offset the overall environmental gains, they highlight the need for rounded SCM management, including sourcing strategies that minimize toxic metal content. While the fly ash substitution strategy yielded significant improvements across most impact categories, more reduction in TE may involve further treatment or pre-processing of fly ash to eliminate trace heavy metals. But such interventions like chemical stabilization or advanced filtration can increase water use, chemical input or energy consumption, which could unconsciously increase impacts in categories like Water Consumption, Human Toxicity or Fossil Resource Scarcity. This highlights a serious trade-off: achieving higher reductions in one impact area may alter burdens to others.

Furthermore, decarbonization strategies like carbon capture, electrification or fuel switching, may be essential to push further GWP reductions. These nuanced results validate the utility of combining MILP-based operational models with LCA, allowing both high-level optimization and coarse environmental accountability. Future studies should consider multi-objective optimization to balance these trade-offs in a holistic and site-specific manner.

6.8. Discussion.

This study established that an integrated MILP–LCA framework can significantly improve the sustainability of cement production by optimizing plant-level fly ash substitution strategies. The results confirm that even moderate substitution levels (30–40%) can substantially reduce CO_2 emissions 33% and energy use 19.8%, while providing environmental benefits across several impact categories.

The application of MILP permitted practicable modelling of operational constraints, like capacity, substitution flexibility, and demand. Unlike single-plant or static models, this framework assigned production based on each plant's environmental efficiency, with different dynamics thereby aligning with best practices in sustainable operations research [448, 451].

The complementary LCA study revealed system-wide improvements, with 14 out of 18 categories achieving near-complete reductions. The utilization of ReCiPe midpoint indicators allowed a balanced assessment across human health, ecological and resource dimensions. However, the LCA also exposed impact hotspots specifically in GW and TE which showed lower reductions (41% and 38%, respectively). Further analysis of substances contributing to these impact categories attributed these gaps to residual CO_2 emissions and trace release of heavy chemicals potentially from fuel combustion and fly ash handling. These findings resonate with existing concerns in the literature about potential trade-offs in SCM utilization [82, 83, 237, 482].

Significantly, these limitations do not undermine the model's ability or utility but rather spotlight areas for future enhancement. To further reduce GW, plants may need to explore carbon capture technologies, renewable electrification or alternative fuels. For TE, efforts should be made to regulate and monitor heavy metal content in fly ash, possibly selective sourcing or through pre-treatment.

From a policy and industry view, the study supports the inclusion of multi-objective decision tools in decarbonization roadmaps for the cement sector. By offering a replicable framework rooted in both environmental accountability and operational efficiency, this model could be adapted by manufacturers and regulatory bodies in aligning with net-zero targets.

Finally, although this study focused on three plants within a specific operational range, the modelling approach is essentially scalable. Future research could extend this work by incorporating economic costs, geographically, and transport logistics diverse energy profiles to build regional or national-scale optimization tools.

6.9. Conclusion.

Cement production remains one of the most carbon-intensive industrial activities universally, largely due to the process emissions and energy demands associated with clinkerization. In response to increasing environmental pressures and policy mandates, this study introduced a novel and scalable optimization framework that integrates MILP with LCA to guide environmentally aware decision-making in cement manufacturing.

The proposed model displayed how adaptive fly ash substitution, strategically allocated across multiple plants, can proffer important environmental benefits under real-world constraints. Using operational data and scientifically validated environmental coefficients, the MILP model minimized system-specific emissions and energy use while satisfying capacity and demand limits. The LCA component offered an accompanying environmental assessment, showing that optimizations did not result in burden shifting across other impact categories. Key outcomes from this integrated approach include:

A 46% reduction in total CO_2 emissions and a 28% decrease in energy consumption compared to a conventional 100% OPC scenario.

A 100% reduction in 14 out of 18 LCA midpoint impact categories, emphasizing wide-reaching environmental improvements outside carbon emissions alone.

Moderate reductions in GW (41%) and TE (38%), attributed to persistent CO_2 emissions and trace heavy metal releases highlighting the importance of tackling fuel sources and SCM quality alongside clinker substitution.

Practically, this research contributes a transparent, data-driven decision-support tool that can be adapted to other cement plants, regions, or even other material-intensive industries. It presents a way forward for stakeholders seeking to align operational planning with net-zero carbon goals and life-cycle environmental accountability.

Although this study focused on environmental performance and technical feasibility, future work could extend the model to include economic policy scenario modelling, cost optimization, and logistics and transport emissions. Also, expanding the LCA boundary to a cradle-to-grave scope would give insight into use-phase and end-of-life dynamics of fly ash-blended cement.

In conclusion, this work provides both a prototype and a practical roadmap for leveraging industrial waste valorisation and optimization modelling in pursuit of a low-carbon, circular cement industry.

CHAPTER 7

CONCLUSIONS, RECOMMENDATIONS, IMPLICATION, CHALLENGES AND FUTURE PERSPECTIVES.

This chapter presents the major findings obtained in this work based on the following specific objectives: (i) Analyse the environmental impacts of cement production in supply chain management using Life Cycle Assessment (LCA) and mid-point and endpoint LCIA methodologies, (ii) Assess the effectiveness of material substitution strategies in reducing energy consumption and greenhouse gas emissions in cement manufacturing through a systematic review of recent advancements, (iii) Evaluate and compare the environmental impacts of different cement production methods using an integrated Life Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM) approach to identify the most sustainable alternative, (iv) Critically analyse the physical, chemical, and hydraulic properties of Ground Granulated Blast Furnace Slag (GGBFS) and fly ash (FA) as a supplementary cementitious material in sustainable concrete production, evaluating its impact on mechanical properties, durability, and environmental sustainability while identifying optimal replacement levels for enhanced performance, (v) Develop and optimize a Mixed-Integer Linear Programming (MILP) model for adaptive fly ash substitution strategies in cement production, aiming to minimize carbon emissions and energy consumption while ensuring production efficiency and compliance with operational constraint and conduct an impact assessment to know the environmental gains.

7.1. Conclusions

The proposed study presented a novel Mixed-Integer Linear Programming (MILP) model that enables adaptive substitution strategies to effectively reduce environmental impacts in cement production across different plants. This model ensures that neither quality nor cost is compromised while maintaining compliance with operational constraints. Its flexibility allows adaptation to diverse conditions, optimizing production capacity, market demand, and sustainability without losing sight of environmental and economic feasibility. The extent to which these objectives have been achieved, along with the key findings, is summarized below:

I. Using both the mid-point and end-point approaches of the Life Cycle Impact Assessment (LCIA), LCA of cement produced in a typical SA plant was evaluated from cradle-to-gate. The result showed that for every 1 kg of cement produced, 0.993 CO_2 eq was emitted into the atmosphere; 98.8% was actual CO_2 emission, and its resultant effect was global warming, which causes changes in climatic conditions. Also, 1.6 kg of 1,4-Dichlorobenzene (1,4-DCB) eq was emitted into the air and water, which caused high toxicity in these media, and for every 1 kg of cement produced, 0.139 kg of oil eq was produced, and its effect was seen in fossil resources' scarcity. The end-point result showed that 55,404 was the potential number of human lives that could be endangered annually; 133 species had the potential to be endangered annually, and the effect of a potential scarcity of resources caused a total marginal price increase of ZAR 6.2 billion due to these damages indicating the need for urgent mitigation and adaptation strategies to counter these environmental impacts.

II. It is important to investigate several methods of handling the environmental issue, and material replacement has been proposed as the best option among many others. Different strategies that have employed material substitution to reduce energy use and GHG emissions during the past decade was examined. The overview of the cement production processes and various material replacement choices available (including waste or recycled materials and other materials) was well explored. This study found that partial (1–60%) and total material substitution in cement production processes have been reported to lower energy consumption by 5.5% to 40% and greenhouse gas emissions by 1% to 94%. This highlights the importance of material substitution in cement production for reducing energy consumption and emissions of greenhouse gases.

III. Selecting sustainable cement alternatives is vital but entails difficult trade-offs between numerous variables. To determine the most environmentally beneficial method of cement manufacturing, an integration of life cycle assessment and multi-criteria decision-making techniques was employed. The LCA is employed to quantitatively evaluate the environmental effects of ten different methods of cement production across eighteen distinct categories. Meanwhile, the CRITIC weighted TOPSIS and EDAS MCDM approaches are utilized to rank the various alternatives by determining their proximity to the optimal solution. The LCA results showed that CEM III/A slag cement had lower environmental impacts than Portland cement. With a ranking score of 0.9094 and 1.7228 for EDAS and TOPSIS techniques, respectively, both MCDM identified CM10: GGBFS as the most recommended. In addition, midpoint characterization revealed that clinker production was responsible for 55% of the global warming impact. Based on these findings, slag cements are more environmentally friendly than Portland cement. Overall, this research shows that blast furnace slag cements, notably CM10, are ideal alternatives for reducing the environmental consequences of cement production in a variety of areas. This integrated methodology provides a systematic framework for making informed decisions in the production of sustainable cement.

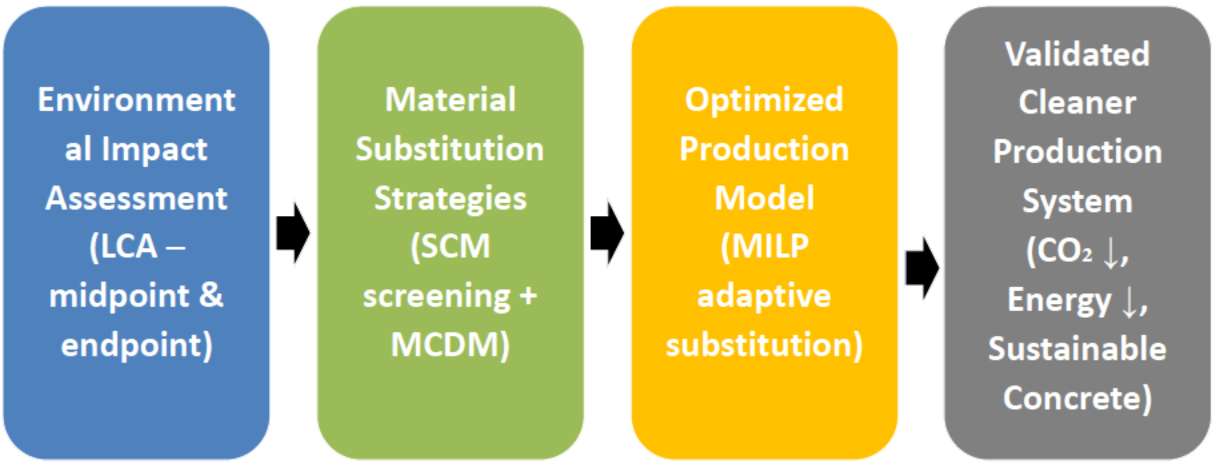
IV. In addressing environmental impact from the cement industry, the valorisation of industrial waste as supplementary cementitious materials SCMs has emerged as a worthy strategy for enabling both circular economy practices and decarbonising cement. Critically evaluation of wide-range spectrum of agro-industrial by-products and industrial which includes ground granulated blast furnace slag, fly ash, silica fume, red mud, biomass ash, metakaolin, amongst many others for their suitability as SCMs was carried out. Using a robust multi-criteria framework, each alternative is assessed across regulatory, environmental, economic, and technical dimensions. The results reveal that while well-established SCMs like GGBFS and fly ash continue to lead in availability and performance, emerging materials such as bagasse ash, geopolymer and calcined clay precursors provide region-specific benefits with lower embodied carbon. Life cycle assessment (LCA) comparisons further validate the environmental savings of these materials, with various SCMs demonstrating 50–90% lower global warming potential than Portland cement. The study highlights the importance of waste consistency, regional supply chains, and performance-based material standards in scaling SCM implementation. By combining material science with sustainability metrics, this work proffers a strategic pathway to reduce the carbon footprint of cement-based materials while valorising industrial waste at scale.

V. The problem of emission reduction using adaptive fly ash substitution strategies, which employ a Mixed-Integer Linear Programming (MILP) model was addressed. The MILP model helped improve the cement production process by optimizing the substitution ratios of $CaCO_3$ with fly ash across different plants. It also considers several constraints, including emission limits, energy consumption, and resource availability. The substitution rates of 30%-40% are the most effective as they reduce CO_2 emissions by 33% and reduce energy usage by up to 19.8%. This method offers a viable solution for reducing greenhouse gas emissions in the cement industry. Optimisation results are combined with Life Cycle Assessment (LCA) to ensure a systematic analysis of environmental impact: about 80% of the various impacts reduced by 100% in the system with partial replacement and global warming potential reduces by 41 and Terrestrial ecotoxicity reduces by 38% respectively. CO_2 as a major contributor to GW dwindled greatly. Though study delineate can slight increase of some heavy chemicals (Lead, Mercury, Nickel, Vanadium and Zinc) emitted into the environment might be experience. This study presents a systematic approach for the cement industry to achieve its environmental goals while meeting business needs.

For decision-makers, policymakers, cement plant owners, and industry leaders seeking to adopt the optimized cement plant model presented in this study, it is essential to address the following key considerations to ensure effective implementation:

1. Defining Strategic Objectives: What is the primary goal of the plant's optimization strategy? Is the focus solely on achieving a sustainable production process, or is the aim to integrate sustainability with increased cement production capacity? A clear articulation of this objective will guide the adaptation of the proposed model.
2. Availability and Quality of Fly Ash or any other SCM: What is the availability and quality of fly ash within the plant's geographical location? The feasibility of integrating fly ash into the production process depends on a consistent and reliable supply of high-quality material.

The optimized cement plant model proposed in this study is designed to balance both sustainability and production efficiency. It integrates an environmentally sustainable cement production process while optimizing output, given an average availability of quality fly ash. This approach ensures that the industry can progress toward reduced environmental impact without compromising production capacity. The proposed novel environmental framework therefore is:



7.2. Implications

The implications of this research are far-reaching for both the South African cement industry and the global construction sector. Firstly, the findings provide a clear roadmap for policymakers and industry stakeholders to formulate regulations and incentives that promote the use of SCMs, renewable energy, and advanced technologies in cement production. The study's LCA results highlight the critical need for reducing clinker content and transitioning to lower-carbon fuels, which can significantly lower greenhouse gas emissions. Additionally, the optimization model demonstrates that a balanced approach to production and sustainability is achievable, offering a replicable framework for other industries facing similar environmental challenges. The research also underscores the importance of quality control and standardization in the use of SCMs, particularly fly ash, to ensure consistent performance and widespread adoption. By addressing the environmental and operational challenges of cement production, this study contributes to the broader global agenda of sustainable development and climate change mitigation.

7.3. Recommendations

7.3.1 Recommendations based on study findings

Several recommendations are proposed to reduce the environmental impact of cement production in South Africa and beyond:

1. Adoption of Supplementary Cementitious Materials (SCMs): The cement industry should prioritize the use of fly ash and/ GGBFS as partial replacements for clinker. Fly ash, in particular, should be utilized at optimal substitution rates (30%–40%) to maximize environmental benefits without compromising concrete performance.

2. Technological Advancements: Investment in advanced processing technologies, waste heat recovery systems, and pollution control equipment (e.g., filters and scrubbers) is essential to enhance energy efficiency and reduce emissions. The adoption of renewable energy sources, such as solar and wind, should also be encouraged.

3. Policy and Regulatory Frameworks: Governments should enforce stricter emissions regulations and provide incentives for the use of renewable energy and SCMs. Taxes on fossil fuel consumption and raw material extraction could further incentivize sustainable practices.

4. Quality Control and Standardization: To address the variability in fly ash quality, stringent quality control measures and standardized testing protocols should be implemented. This will ensure consistent performance and foster greater confidence in the use of SCMs.

5. Research and Development: Further research is needed to explore the potential of other waste materials as SCMs and to optimize their use in cement production. Dynamic modelling approaches should be developed to account for market fluctuations and regulatory changes.

6. Public Awareness and Training: Increasing awareness about the benefits of sustainable cement production and providing training for industry professionals will facilitate the adoption of best practices and innovative technologies.

7.3.2 Recommendations based on adoption of industrial wastes as SCM for sustainable concrete design

To maximize the impact of industrial waste as SCMs in sustainable cement design, the following actions are recommended:

1. Institutionalize MCDM-based SCM selection tools:

   Infrastructure planners and cement producers are encouraged to adopt MCDM model such as the EDAS framework used in this study for considering regional material availability, environmental trade-offs, objective selection of SCM, and long-term performance.

2. Enhance data for MCDM optimization:

   Future studies should improve the quality and granularity of data for key SCM attributes (e.g., reactivity, life cycle emissions, supply chain metrics) to strengthen the input-output robustness of MCDM tools.

3. Standardize SCM evaluation criteria:

   Establish a universal set of weighted criteria which includes environmental, technical, practical and economical for SCM performance evaluation to support transparent and replicable MCDM analysis across geographies.

4. Expand MCDM models with AI and GIS:

   Integrate artificial intelligence (AI) and geographic information systems (GIS) with MCDM techniques to create dynamic, location-specific SCM recommendation platforms for industry practitioners.

5. Blend high-ranking SCMs in composite designs:

   Regulatory bodies should promote the use of hybrid SCM blends based on MCDM rankings to boost performance, sustainability and cost. For example, blending Fly Ash with Calcined Clay may offset early strength issues while maintaining environmental benefits.

6. Policy Support for data-driven SCM adoption**:**

   Regulatory bodies should develop framework that promote the use of scientifically ranked SCMs based on multi-criteria analyses, enabling data-informed transitions in construction practices.

7.4. Challenges of the Study

One of the most significant challenges encountered in this study was the availability of reliable data. The authors devoted over 12 months to obtaining on-site datasets for use in the model; however, these efforts were ultimately unsuccessful. As a result, the study had to rely on secondary data from various scholarly sources. Despite this alternative approach, the data acquired remained insufficient, with notable discrepancies across different datasets. Additionally, certain critical data points were entirely unavailable, thereby imposing restrictions on the scope of the study, particularly in terms of determining accurate replacement factors for the cement production plant.

The lack of accessible and comprehensive datasets poses a major barrier to advancing research in this field. Cement production organizations, industry bodies, and companies should be encouraged to facilitate seamless and transparent access to essential data to support further studies. Furthermore, government agencies should implement policies and strategies that incentivize these organizations to share data more readily. Ensuring the availability of high-quality datasets would enhance the accuracy and applicability of future research, ultimately contributing to more sustainable and efficient cement production practices.

7.5. Future perspective

The future of sustainable cement production lies in the continued exploration and adoption of innovative materials and technologies. While fly ash and other SCM have shown significant potential, there is a need to expand the pool of SCMs by investigating other industrial and municipal waste materials. Research should focus on identifying materials with high emission-reduction potential, low cost, and ease of application. Additionally, the integration of carbon capture and storage (CCS) technologies into cement production processes could further reduce CO_2 emissions. The development of dynamic optimization models that account for real-world constraints, such as supply chain variability and regulatory changes, will enhance the applicability of sustainable strategies in the cement industry. Furthermore, interdisciplinary collaborations between researchers, industry stakeholders, and policymakers will be crucial in driving the transition toward a low-carbon cement industry. By embracing these future perspectives, the cement industry can play a pivotal role in achieving global sustainability goals while maintaining operational efficiency and economic viability.

This comprehensive approach not only addresses the immediate environmental challenges of cement production but also sets the stage for long-term sustainability and resilience in the construction sector.

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APPENDIX

CHAPTER 2
SUPPLEMENTARY FILE OF THE MANUSCRIPT 3

Table 1: Ecoinvent 3.6 database documentation of clinker production: South Africa (ZA)

Reference product	Amount
Clinker	1 kg
Inputs from Technosphere	Amount
Ammonia, liquid	0.000918 kg
Bauxite	0.04 kg
Cement factory	6.2e-12 unit
Diesel, burned in building machine	0.0132 MJ
Diesel, low-sulphur	0.000427 kg
Electricity, medium voltage	0.14 kWh
Hard coal	0.145 kg
Industrial machine, heavy, unspecified	3.76e-05 kg
Iron ore, crude ore, 46% Fe	0.000143 kg
Light fuel oil	0.000367 kg
Lime, hydrated, loose weight	0.00388 kg
Limestone, crushed, for mill	0.9 kg
Lubricating oil	4.71e-05 kg
Magnetite	0.01 kg
Refractory, basic, packed	0.00019 kg

Refractory, fireclay, packed	8.21e-05 kg
Refractory, high aluminum oxide, packed	0.000137 kg
Sand	0.05 kg
Steel, chromium steel 18/8, hot rolled	5.86e-05 kg
Inputs from Technosphere	**Amount**
Tap water	0.336 kg
Urea, as N	1.5e-06 kg
Inputs from environment	**Amount**
Water, cooling, unspecified natural origin	9.57e-06 m3
Water, unspecified natural origin	0.0016 m3
Emissions to air	**Amount**
Ammonia	2.25e-05 kg
Antimony	2.24e-09 kg
Arsenic	1.22e-08 kg
Beryllium	2.97e-09 kg
Cadmium	6.87e-09 kg
Carbon dioxide, fossil	0.838 kg
Carbon dioxide, non-fossil	0.0155 kg
Carbon monoxide, fossil	0.000489 kg
Chromium	2.1e-09 kg
Chromium VI	5.44e-10 kg
Cobalt	3.98e-09 kg
Copper	1.42e-08 kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	9.43e-13 kg

Lead	8.39e-08 kg
Manganese	5.74e-10 kg

Mercury	3.25e-08 kg
Methane, fossil	8.79e-06 kg
NMVOC, non-methane volatile organic compounds	5.59e-05 kg
Nickel	6.71e-09 kg
Nitrogen oxides	0.000977 kg
Particulates, < 2.5 um	2.37e-05 kg
Particulates, > 10 um	6.5e-06 kg
Particulates, > 2.5 um, and < 10um	0.000123 kg
Selenium	1.98e-09 kg
Sulphur dioxide	5.92e-05 kg
Thallium	1.3e-08 kg
Tin	9.05e-09 kg
Vanadium	4.97e-09 kg
Water	0.000294 m3
Zinc	6.34e-08 kg
Emissions to air	**Amount**
Ammonia	2.25e-05 kg
Antimony	2.24e-09 kg
Arsenic	1.22e-08 kg
Beryllium	2.97e-09 kg
Cadmium	6.87e-09 kg
Carbon dioxide, fossil	0.838 kg
Carbon dioxide, non-fossil	0.0155 kg

Carbon monoxide, fossil	0.000489 kg
Chromium	2.1e-09 kg
Chromium VI	5.44e-10 kg
Cobalt	3.98e-09 kg
Copper	1.42e-08 kg
Dioxins, measured as 2,3,7,8- tetrachlorodibenzo-p-dioxin	9.43e-13 kg
Lead	8.39e-08 kg
Manganese	5.74e-10 kg
Mercury	3.25e-08 kg
Methane, fossil	8.79e-06 kg
NMVOC (non-methane volatile organic compounds, unspecified origin)	5.59e-05 kg

Table 2: Ecoinvent 3.6 dataset documentation for Portland cement production: South Africa.

Reference product	Amount
Cement, Portland	1 kg
Inputs from Technosphere	Amount
Cement factory	5.36e-11 unit
Clinker	0.902 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	5.25e-05 kg
Emissions to air	Amount
Heat, waste	0.135 MJ

Table 3: Uncertainty results for mid-point analysis

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Fine particulate matter formation	kg PM2.5 eq	0.000803	0.000737	0.000325	40.5%	0.000355	0.001615	1.03E-05
Fossil resource scarcity	kg oil eq	0.141404	0.12733	0.062775	44.34%	0.05776	0.300724	0.001985
Freshwater ecotoxicity	kg 1,4-DCB	0.016241	0.013214	0.011798	72.6%	0.005574	0.04833	0.000373
Freshwater eutrophication	kg P eq	0.000329	0.000243	0.0003	91.2%	6.02E-05	0.001051	9.48E-06
Global warming	kg CO2 eq	1.00863	0.913186	0.459852	45.6%	0.388636	2.158094	0.014542
Human carcinogenic toxicity	kg 1,4-DCB	0.026046	0.012594	0.06141	235.8%	0.003659	0.12182	0.001942

Human non-carcinogenic toxicity	kg 1,4-DCB	0.494297	0.358147	0.439479	88.9%	0.120207	1.767484	0.013898
Ionizing radiation	kBq Co-60 eq	0.0104	0.005285	0.024081	231.6	0.001014	0.050712	0.000762
Land use	m2a crop eq	0.00797	0.007082	0.003759	47.2%	0.003102	0.01781	0.000119
Marine ecotoxicity	kg 1,4-DCB	0.022008	0.017491	0.016481	74.9%	0.007482	0.067542	0.000521
Marine eutrophication	kg N eq	1.95E-05	1.75E-05	9.64E-06	49.4%	7.25E-06	4.38E-05	3.05E-07
Mineral resource scarcity	kg Cu eq	0.002204	0.002005	0.00093	42.2%	0.000926	0.004503	2.94E-05
Ozone formation, Human health	kg NOx eq	0.002116	0.001942	0.000937	44.3%	0.000851	0.004525	2.96E-05
	kg NOx eq							

Ozone formation, Terrestrial ecosystems		0.002132	0.001959	0.000945	44.3%	0.000857	0.00456	2.99E-05
Stratospheric ozone depletion	kg CFC11 eq	1.97E-07	1.70E-07	1.08E-07	54.9%	6.95E-08	4.73E-07	3.43E-09
Terrestrial acidification	kg SO2 eq	0.00247	0.002266	0.001	40.5%	0.001096	0.005009	3.16E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.050833	0.939033	0.498372	47.4%	0.412359	2.398997	0.01576
Water consumption	m^3	0.001112	0.002269	0.016392	1473.9%	0.03951	0.033396	0.000518

Table 4: Uncertainty results for end-point impacts of analysis

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Fine particulate matter formation	DALY	5.06E-07	4.62E-07	2.06E-07	40.7%	2.40E-07	1.03E-06	6.51E-09
Fossil resource scarcity	USD2013	0.016632	0.014993	0.007489	45.03%	0.007227	0.036052	0.000237
Freshwater ecotoxicity	Species.yr	1.10E-11	9.05E-12	8.41E-12	76.3%	3.61E-12	3.06E-11	2.66E-13
Freshwater eutrophication	Species.yr	2.13E-10	1.54E-10	1.94E-10	90.8%	3.72E-11	7.49E-10	6.12E-12
Global warming, Freshwater ecosystems	Species.yr	7.73E-14	6.91E-14	3.55E-14	45.8%	3.17E-14	1.71E-13	1.12E-15

Global warming, Human health	DALY	9.38E-07	8.38E-07	4.30E-07	45.9%	3.84E-07	2.07E-06	1.36E-08
Global warming, Terrestrial ecosystems	Species.yr	2.83E-09	2.53E-09	1.30E-09	45.9%	1.16E-09	6.26E-09	4.10E-11
Human carcinogenic toxicity	DALY	8.28E-08	4.14E-08	1.81E-07	218.9%	1.30E-08	3.91E-07	5.73E-09
Human non-carcinogenic toxicity	DALY	1.14E-07	8.32E-08	1.16E-07	102.3%	2.67E-08	3.78E-07	3.67E-09
Ionizing radiation	DALY	8.95E-11	4.74E-11	1.46E-10	162.5%	9.41E-12	3.91E-10	4.60E-12
Land use	Species.yr	7.05E-11	6.27E-11	3.24E-11	45.9%	2.84E-11	1.54E-10	1.02E-12
Marine ecotoxicity	Species.yr	2.26E-12	1.85E-12	1.78E-12	78.8%	7.24E-13	6.48E-12	5.64E-14

Marine eutrophication	Species.yr	3.37E-14	2.99E-14	1.67E-14	49.5%	1.23E-14	7.59E-14	5.28E-16
Mineral resource scarcity	USD2013	0.000513	0.000461	0.000222	43.3%	0.000225	0.001092	7.01E-06
Ozone formation, Human health	DALY	1.94E-09	1.75E-09	8.74E-10	44.9%	8.17E-10	4.34E-09	2.76E-11
Ozone formation, Terrestrial ecosystems	Species.yr	2.78E-10	2.50E-10	1.25E-10	44.9%	1.17E-10	6.20E-10	3.95E-12
Stratospheric ozone depletion	DALY	1.05E-10	9.28E-11	5.30E-11	50.7%	3.88E-11	2.45E-10	1.68E-12
Terrestrial acidification	Species.yr	5.25E-10	4.82E-10	2.13E-10	40.6%	2.51E-10	1.08E-09	6.75E-12

Terrestrial ecotoxicity	Species.yr	1.21E-11	1.08E-11	6.48E-12	53.4%	4.70E-12	2.76E-11	2.05E-13
Water consumption, Aquatic ecosystems	Species.yr	1.97E-15	1.94E-15	1.51E-14	766.7%	-2.86E-14	3.51E-14	4.78E-16
Water consumption, Human health	DALY	2.33E-09	3.96E-09	3.29E-08	1414.0%	-6.99E-08	6.41E-08	1.04E-09
Water consumption, Terrestrial ecosystem	Species.yr	2.52E-11	3.72E-11	2.00E-10	791.7%	-4.18E-10	4.17E-10	6.32E-12

Table 5: Uncertainty results for end-point impacts analysis: Damage assessment

Damage category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Ecosystems	Species.yr	3.97E-09	3.54E-09	1.79E-09	45.2%	1.68E-09	8.58E-09	5.67E-11
Human health	DALY	1.64E-06	1.46E-06	7.50E-07	45.6%	7.07E-07	3.64E-06	2.37E-08
Resources	USD2013	0.017145	0.015467	0.007701	44.9%	0.007478	0.037304	0.000244

CHAPTER 4

SUPPLEMENTARY FILE OF THE MANUSCRIPT 2

TOPSIS Method

Table S1. Decision matrix

Weight	0.354153	2.57865E-08	0.004248	0.000687	0.000165961	0.000683	0.000477	2.13617E-05	1.42667E-06	0.308914	0.013194	0.017201	0.008304	0.252707	0.008307	0.002909	0.027585	0.000442
Production n strategy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**
CM 1	0.851597	9.18E-08	0.007206	0.001649	0.000543389	0.001663	0.00139	8.88E-05	8.02E-06	0.418043	0.008929	0.012053	0.014369	0.259824	0.015919	0.003393	0.078807	0.001509
CM2	0.559779	6.84E-08	0.008432	0.001175	0.000423677	0.001188	0.001029	7.45E-05	6.95E-06	0.557746	0.009457	0.012674	0.015094	0.243036	0.02228	0.004154	0.060166	0.001271
CM3	0.532051	6.87E-08	0.006162	0.001107	0.000434097	0.00112	0.001016	7.08E-05	6.91E-06	0.587264	0.011649	0.015579	0.015667	0.297745	0.01634	0.003067	0.058024	0.001284
CM4	0.553763	8.10E-08	0.011542	0.001138	0.000454833	0.001156	0.001095	8.44E-05	9.09E-06	0.884963	0.016266	0.021746	0.021117	0.395618	0.020251	0.004311	0.062663	0.001931
CM5	0.435247	6.30E-08	0.005772	0.000939	0.000391701	0.000952	0.000895	6.52E-05	6.51E-06	0.629395	0.012319	0.01644	0.015829	0.304862	0.016173	0.002948	0.051454	0.001229
CM6	0.677262	7.53E-08	0.009046	0.001403	0.000479292	0.001415	0.00119	7.86E-05	7.02E-06	0.451518	0.006972	0.009413	0.01249	0.197688	0.02183	0.002518	0.067671	0.001229
CM 7	0.837683	8.90E-08	0.011795	0.00169	0.000586671	0.001704	0.001449	0.000103379	8.92E-06	0.525667	0.007419	0.010158	0.01486	0.236651	0.024245	0.003042	0.084882	0.00168
CM8	0.607195	6.88E-08	0.009406	0.001238	0.00044118	0.001248	0.001073	7.55E-05	6.61E-06	0.37455	0.006619	0.00889	0.011232	0.184811	0.01603	0.002238	0.06196	0.001193
CM9	0.5876	6.69E-08	0.00554	0.00128	0.00044550	0.00129	0.00108	7.37E-05	6.03E-06	0.41453	0.00710	0.00955	0.01391	0.19629	0.01747	0.00586	0.06247	0.00095

	34		9		6		2			7	6	1		1	5	2	3	7
CM10	0.100869	2.97E-08	0.002977	0.000246	0.000193252	0.000264	0.000364	4.70E-05	6.99E-06	0.615516	0.021477	0.028369	0.022129	0.488819	0.006651	0.00466	0.020759	0.001476

Table S2 Normalized decision matrix

Production strategy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**
CM 1	0.442586	0.402429667	0.277041	0.418078	0.381583315	0.417294	0.401297	0.362559473	0.344286933	0.234383	0.240319	0.243077	0.28386	0.278337	0.274644	0.284582	0.395378	0.340568
CM2	0.290925	0.29978155	0.324166	0.297925	0.297518216	0.298117	0.297027	0.303944987	0.298133725	0.312709	0.25454	0.255609	0.298177	0.260353	0.384401	0.34845	0.301857	0.286879
CM3	0.276514	0.301143271	0.236898	0.280637	0.304835234	0.281206	0.293471	0.289051424	0.296303771	0.329259	0.313535	0.314185	0.309507	0.31896	0.281911	0.257277	0.291109	0.289738
CM4	0.287798	0.355280105	0.443728	0.288595	0.319396884	0.290192	0.316206	0.344560215	0.390026523	0.496169	0.437798	0.438572	0.417171	0.423808	0.349397	0.361591	0.314384	0.435771
CM5	0.226203	0.276127068	0.221884	0.237989	0.27506396	0.238951	0.258322	0.266130276	0.279301299	0.352881	0.331559	0.331559	0.312692	0.326585	0.279029	0.247266	0.258145	0.277312
CM6	0.351982	0.330124627	0.347769	0.355677	0.336572818	0.355154	0.343597	0.320970084	0.301266899	0.253151	0.187647	0.189838	0.246738	0.211774	0.37664	0.211194	0.339507	0.27739
CM 7	0.435355	0.390032357	0.453448	0.42845	0.411977326	0.427791	0.418504	0.421895172	0.382868825	0.294724	0.199694	0.204868	0.293563	0.253513	0.418308	0.255149	0.425857	0.37922
CM8	0.315567	0.30153195	0.361594	0.313896	0.309809364	0.313366	0.309828	0.307932489	0.283509493	0.209997	0.178141	0.179288	0.221883	0.197979	0.276569	0.187698	0.310856	0.269324
CM9	0.305401	0.29323611	0.213337	0.324439	0.312846931	0.323871	0.312489	0.300806848	0.258905218	0.232417	0.191256	0.192625	0.274791	0.210277	0.301499	0.49173	0.313432	0.216023
CM10	0.052423	0.130413048	0.114435	0.062464	0.135707	0.066149	0.105101	0.191691872	0.299828509	0.345099	0.578058	0.572128	0.437162	0.523649	0.114741	0.390874	0.104149	0.333185

Table S3 Weighted normalized matrix

Production strategy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**
CM 1	0.156743	1.03772E-08	0.001177	0.000287	6.33279E-05	0.000285	0.000192	7.74487E-06	4.91183E-07	0.072404	0.003171	0.004181	0.002357	0.070338	0.002281	0.000828	0.010907	0.00015
CM2	0.103032	7.73031E-09	0.001377	0.000205	4.93764E-05	0.000204	0.000142	6.49277E-06	4.25338E-07	0.0966	0.003358	0.004397	0.002476	0.065793	0.003193	0.001014	0.008327	0.000127
CM3	0.097928	7.76543E-09	0.001006	0.000193	5.05907E-05	0.000192	0.00014	6.17462E-06	4.22727E-07	0.101713	0.004137	0.005404	0.00257	0.080603	0.002342	0.000749	0.00803	0.000128
CM4	0.101924	9.16143E-09	0.001885	0.000198	5.30074E-05	0.000198	0.000151	7.36038E-06	5.56439E-07	0.153274	0.005776	0.007544	0.003464	0.107099	0.002902	0.001052	0.008672	0.000192
CM5	0.080111	7.12035E-09	0.000942	0.000164	4.56498E-05	0.000163	0.000123	5.68498E-06	3.9847E-07	0.10901	0.004375	0.005703	0.002597	0.08253	0.002318	0.000719	0.007121	0.000122
CM6	0.124655	8.51276E-09	0.001477	0.000244	5.58579E-05	0.000243	0.000164	6.85645E-06	4.29808E-07	0.078202	0.002476	0.003265	0.002049	0.053517	0.003129	0.000614	0.009365	0.000122
CM 7	0.154182	1.00576E-08	0.001926	0.000294	6.83721E-05	0.000292	0.0002	9.01238E-06	5.46227E-07	0.091044	0.002635	0.003524	0.002438	0.064065	0.003475	0.000742	0.011747	0.000167
CM8	0.111759	7.77545E-09	0.001536	0.000216	5.14162E-05	0.000214	0.000148	6.57795E-06	4.04474E-07	0.064871	0.00235	0.003084	0.001842	0.050031	0.002297	0.000546	0.008575	0.000119
CM9	0.108159	7.56153E-09	0.000906	0.000223	5.19203E-05	0.000221	0.000149	6.42573E-06	3.69372E-07	0.071797	0.002523	0.003313	0.002282	0.053139	0.002504	0.001431	0.008646	9.54E-05
CM10	0.018566	3.36289E-09	0.000486	4.29E-05	2.2522E-05	4.52E-05	5.02E-05	4.09486E-06	4.27756E-07	0.106606	0.007627	0.009841	0.00363	0.13233	0.000953	0.001137	0.002873	0.000147

Table S4 Ideal best and Ideal worst

V+	0.018566	3.36289E-09	0.000486	4.29E-05	2.2522E-05	4.52E-05	5.02E-05	4.09486E-06	3.6937E-07	0.064871	0.00235	0.003084	0.001842	0.050031	0.000953	0.000546	0.002873	9.54E-05
V-	0.156743	1.03772E-08	0.001926	0.000294	6.83721E-05	0.000292	0.0002	9.01238E-06	5.5644E-07	0.153274	0.007627	0.009841	0.00363	0.13233	0.003475	0.001431	0.011747	0.000192

Table S5 Closeness index calculation

Si+	Si-	Pi	Rank
0.140112	0.102174	0.831403	8
0.091808	0.102885	1.223541	5
0.092889	0.094036	1.106378	7
0.134516	0.060501	0.510269	10
0.082607	0.101808	1.334245	4
0.107205	0.113824	1.17556	6
0.139147	0.092768	0.759459	9
0.093384	0.129232	1.513111	2
0.09012	0.123904	1.498787	3
0.092693	0.146145	1.722799	1

EDAS Method

Table S6. Form decision matrix

Weight	0.354153	2.58E-08	0.004248	0.000687	0.000166	0.000683	0.000477	2.136E-05	1.43E-06	0.308914	0.013194	0.017201	0.008304	0.252707	0.008307	0.002909	0.027585	0.00044
Production strategy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**
CM 1	0.851597	9.18E-08	0.007206	0.001649	0.0005434	0.001663	0.00139	8.88E-05	8.02E-06	0.418043	0.008929	0.012053	0.014369	0.259824	0.015919	0.003393	0.078807	0.00151
CM2	0.559779	6.84E-08	0.008432	0.001175	0.0004237	0.001188	0.001029	7.45E-05	6.95E-06	0.557746	0.009457	0.012674	0.015094	0.243036	0.02228	0.004154	0.060166	0.00127
CM3	0.532051	6.87E-08	0.006162	0.001107	0.0004341	0.00112	0.001016	7.08E-05	6.91E-06	0.587264	0.011649	0.015579	0.015667	0.297745	0.01634	0.003067	0.058024	0.00128
CM4	0.553763	8.10E-08	0.011542	0.001138	0.0004548	0.001156	0.001095	8.44E-05	9.09E-06	0.884963	0.016266	0.021746	0.021117	0.395618	0.020251	0.004311	0.062663	0.00193
CM5	0.435247	6.30E-08	0.005772	0.000939	0.0003917	0.000952	0.000895	6.52E-05	6.51E-06	0.629395	0.012319	0.01644	0.015829	0.304862	0.016173	0.002948	0.051454	0.00123
CM6	0.677262	7.53E-08	0.009046	0.001403	0.0004793	0.001415	0.00119	7.86E-05	7.02E-06	0.451518	0.006972	0.009413	0.01249	0.197688	0.02183	0.002518	0.067671	0.00123
CM 7	0.837683	8.90E-08	0.011795	0.00169	0.0005867	0.001704	0.001449	0.0001034	8.92E-06	0.525667	0.007419	0.010158	0.01486	0.236651	0.024245	0.003042	0.084882	0.00168
CM8	0.607195	6.88E-08	0.009406	0.001238	0.0004412	0.001248	0.001073	7.55E-05	6.61E-06	0.37455	0.006619	0.00889	0.011232	0.184811	0.01603	0.002238	0.06196	0.00119
CM9	0.587634	6.69E-08	0.005549	0.00128	0.0004455	0.00129	0.001082	7.37E-05	6.03E-06	0.414537	0.007106	0.009551	0.01391	0.196291	0.017475	0.005862	0.062473	0.00096
CM10	0.100869	2.97E-08	0.002977	0.000246	0.0001933	0.000264	0.000364	4.70E-05	6.99E-06	0.615516	0.021477	0.028369	0.022129	0.488819	0.006651	0.00466	0.020759	0.00148
Avj	0.574308	7.02E-08	0.007789	0.001187	0.0004394	0.0012	0.001058	7.619E-05	7.31E-06	0.54592	0.010821	0.014487	0.01567	0.280534	0.017719	0.003619	0.060886	0.00138

Table S7. Positive distance from average (PDA)

Weight	0.354153	2.58E-08	0.004248	0.000687	0.000166	0.000683	0.000477	2.136E-05	1.43E-06	0.308914	0.013194	0.017201	0.008304	0.252707	0.008307	0.002909	0.027585	0.00044
Production strategy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**
CM 1	0	0	0.074771	0	0	0	0	0	0	0.234241	0.174882	0.168043	0.083003	0.073826	0.10163	0.062583	0	0
CM2	0.025297	0.026715	0	0.009608	0.0356946	0.010267	0.028003	0.0225412	0.048843	0	0.126057	0.12515	0.036754	0.133668	0	0	0.011819	0.0762
CM3	0.073578	0.022294	0.208838	0.067078	0.0119789	0.06641	0.039639	0.0704376	0.054681	0	0	0	0.000154	0	0.07786	0.152526	0.047005	0.06699
CM4	0.035774	0	0	0.040624	0	0.036577	0	0	0	0	0	0	0	0	0	0	0	0
CM5	0.242137	0.103513	0.258979	0.208853	0.1084725	0.206693	0.154661	0.1441498	0.108925	0	0	0	0	0	0.087287	0.185502	0.154917	0.107
CM6	0	0	0	0	0	0	0	0	0.038847	0.172922	0.355728	0.350258	0.202925	0.295316	0	0.304324	0	0.10675
CM 7	0	0	0	0	0	0	0	0	0	0.037098	0.314366	0.298818	0.05166	0.156428	0	0.159535	0	0
CM8	0	0.021032	0	0	0	0	0	0.0097178	0.095499	0.313911	0.388369	0.386366	0.283219	0.341219	0.095334	0.38172	0	0.13273
CM9	0	0.047966	0.287524	0	0	0	0	0.0326332	0.173996	0.240664	0.343339	0.340719	0.1123	0.300296	0.013787	0	0	0.30437
CM10	0.824364	0.576595	0.617823	0.79235	0.5601513	0.780389	0.656066	0.3835368	0.043436	0	0	0	0	0	0.624677	0	0.65905	0

Table S8. Weighted sum of PDA

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	Spi
CM 1	0	0	0.000318	0	0	0	0	0	0	0.07236	0.002307	0.00289	0.000689	0.018656	0.000844	0.000182	0	0	0.098247
CM2	0.008959	6.89E-10	0	6.6E-06	5.924E-06	7.02E-06	1.34E-05	4.815E-07	6.97E-08	0	0.001663	0.002153	0.000305	0.033779	0	0	0.000326	3.4E-05	0.047252
CM3	0.026058	5.75E-10	0.000887	4.61E-05	1.988E-06	4.54E-05	1.89E-05	1.505E-06	7.8E-08	0	0	0	1.28E-06	0	0.000647	0.000444	0.001297	3E-05	0.029477
CM4	0.01267	0	0	2.79E-05	0	2.5E-05	0	0	0	0	0	0	0	0	0	0	0	0	0.012722
CM5	0.085754	2.67E-09	0.0011	0.000144	1.8E-05	0.000141	7.38E-05	3.079E-06	1.55E-07	0	0	0	0	0	0.000725	0.00054	0.004273	4.7E-05	0.092819
CM6	0	0	0	0	0	0	0	0	5.54E-08	0.053418	0.004694	0.006025	0.001685	0.074628	0	0.000885	0	4.7E-05	0.141382
CM 7	0	0	0	0	0	0	0	0	0	0.01146	0.004148	0.00514	0.000429	0.039531	0	0.000464	0	0	0.061171
CM8	0	5.42E-10	0	0	0	0	0	2.076E-07	1.36E-07	0.096972	0.005124	0.006646	0.002352	0.086228	0.000792	0.001111	0	5.9E-05	0.199283
CM9	0	1.24E-09	0.001221	0	0	0	0	6.971E-07	2.48E-07	0.074344	0.00453	0.005861	0.000933	0.075887	0.000115	0	0	0.00013	0.163026
CM10	0.291951	1.49E-08	0.002624	0.000545	9.296E-05	0.000533	0.000313	8.193E-06	6.2E-08	0	0	0	0	0	0.005189	0	0.01818	0	0.319437

Table S9. Negative distance from Average (NDA).

Weight	0.354153	2.58E-08	0.004248	0.000687	0.000166	0.000683	0.000477	2.136E-05	1.43E-06	0.308914	0.013194	0.017201	0.008304	0.252707	0.008307	0.002909	0.027585	0.00044
Production strategy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**	**C18**
CM 1	0.482822	0.306548	0	0.389819	0.2367742	0.385397	0.313212	0.1659575	0.098403	0	0	0	0	0	0	0	0.294338	0.09669
CM2	0	0	0.08261	0	0	0	0	0	0	0.021663	0	0	0	0	0.257387	0.147799	0	0
CM3	0	0	0	0	0	0	0	0	0	0.075733	0.076498	0.075331	0	0.061349	0	0	0	0
CM4	0	0.153469	0.48191	0	0.0352178	0	0.034758	0.1080735	0.24433	0.621048	0.503146	0.501059	0.34765	0.410232	0.142888	0.191084	0.02919	0.40326
CM5	0	0	0	0	0	0	0	0	0	0.152907	0.13838	0.134797	0.010135	0.086718	0	0	0	0
CM6	0.179265	0.071798	0.161438	0.182377	0.0908878	0.179096	0.124395	0.0322099	0	0	0	0	0	0	0.232001	0	0.111434	0
CM 7	0.458595	0.266298	0.51437	0.424297	0.3352862	0.420247	0.369521	0.3567756	0.221494	0	0	0	0	0	0.368299	0	0.394116	0.22116
CM8	0.057264	0	0.207607	0.043487	0.004143	0.040359	0.013888	0	0	0	0	0	0	0	0	0	0.017639	0
CM9	0.023204	0	0	0.078533	0.0139883	0.075237	0.022596	0	0	0	0	0	0	0	0	0.619763	0.026074	0
CM10	0	0	0	0	0	0	0	0	0	0.127485	0.984716	0.958168	0.412232	0.742455	0	0.287543	0	0.07292

Table S10. Weighted sum of NDA

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	Sni
CM 1	0.170993	7.9E-09	0	0.000268	3.93E-05	0.000263	0.00015	3.545E-06	1.4E-07	0	0	0	0	0	0	0	0.008119	4.3E-05	0.179879
CM2	0	0	0.000351	0	0	0	0	0	0	0.006692	0	0	0	0	0.002138	0.00043	0	0	0.009611
CM3	0	0	0	0	0	0	0	0	0	0.023395	0.001009	0.001296	0	0.015503	0	0	0	0	0.041203
CM4	0	3.96E-09	0.002047	0	5.845E-06	0	1.66E-05	2.309E-06	3.49E-07	0.191851	0.006639	0.008619	0.002887	0.103668	0.001187	0.000556	0.000805	0.00018	0.318461
CM5	0	0	0	0	0	0	0	0	0	0.047235	0.001826	0.002319	8.42E-05	0.021914	0	0	0	0	0.073378
CM6	0.063487	1.85E-09	0.000686	0.000125	1.508E-05	0.000122	5.94E-05	6.881E-07	0	0	0	0	0	0	0.001927	0	0.003074	0	0.069497
CM 7	0.162413	6.87E-09	0.002185	0.000292	5.564E-05	0.000287	0.000176	7.621E-06	3.16E-07	0	0	0	0	0	0.003059	0	0.010872	9.8E-05	0.179445
CM8	0.02028	0	0.000882	2.99E-05	6.876E-07	2.76E-05	6.63E-06	0	0	0	0	0	0	0	0	0	0.000487	0	0.021713
CM9	0.008218	0	0	5.4E-05	2.322E-06	5.14E-05	1.08E-05	0	0	0	0	0	0	0	0	0.001803	0.000719	0	0.010859
CM10	0	0	0	0	0	0	0	0	0	0.039382	0.012992	0.016481	0.003423	0.187624	0	0.000837	0	3.2E-05	0.260771

Table S11. Ranking index calculations

	Spi	Sni	Nspi	Nsni	Asi	Rank
CM 1	0.098247	0.179879	0.307565	0.564838	0.4362014	3
CM2	0.047252	0.009611	0.147923	0.030179	0.0890512	10
CM3	0.029477	0.04120	0.092278	0.129383	0.1108303	9

		3				
CM4	0.012722	0.318461	0.039828	1	0.5199139	2
CM5	0.092819	0.073378	0.290571	0.230414	0.2604926	8
CM6	0.141382	0.069497	0.442599	0.218228	0.3304136	6
CM 7	0.061171	0.179445	0.191498	0.563476	0.3774872	4
CM8	0.199283	0.021713	0.623858	0.068182	0.34602	5
CM9	0.163026	0.010859	0.510354	0.034098	0.2722257	7
CM10	0.319437	0.260771	1	0.818846	0.9094232	1

CHAPTER 5
SUPPLEMENTARY FILE OF THE MANUSCRIPT 4

Scoring Framework for Table 3 - SCM Suitability Matrix

The Supplementary Cementitious Materials (SCM) Suitability Scoring Matrix (Table 3) uses a 1–10 scale to evaluate industrial by-products, agricultural residues, and engineered pozzolan against seven criteria. This scoring was based on quantitative and qualitative data from peer-reviewed literature and international standards. Below is the detailed scoring framework for each criterion.

1. Pozzolanic or Latent Hydraulic Activity

This score reflects the degree to which the material exhibits pozzolanic reactivity (reaction with calcium hydroxide to form C-S-H) or latent hydraulic behavior (cementitious behavior under alkaline activation).

Score	Description	Example Materials	References
1–3	Negligible or no pozzolanic/hydraulic activity	Eggshells, Aspiration Dust	Juenger & Siddique (2015), Mehta & Siddique (2022)
4–6	Moderate or conditional reactivity (requires activation or fine grinding)	Red Mud, Bottom Ash	Siddique (2010), Onn et al. (2021)
7–10	High and well-documented reactivity in cementitious systems	Fly Ash, GGBFS, Silica Fume, Metakaolin	ASTM C618, Scrivener et al. (2018), Mehta & Siddique (2022)

2. Oxide Composition (SiO_2, Al_2O_3, CaO)

Assesses the richness in key reactive oxides necessary for hydration and pozzolanic activity.

Score	SiO_2 + Al_2O_3 + Fe_2O_3 / CaO Profile	Example Materials	References
1–3	Poor in reactive oxides; fails ASTM thresholds	Eggshells, MDW	ASTM C618, Juenger & Siddique (2015)
4–6	Moderate oxide content; may require blending	Red Mud, Bottom Ash	Siddique (2010), Chen et al. (2021)

Score	$SiO_2 + Al_2O_3 + Fe_2O_3$ / CaO Profile	Example Materials	References
7–10	Rich in SiO_2/Al_2O_3 or balanced CaO; optimal for reaction	Fly Ash, Silica Fume, MK, GGBFS	ASTM C618, Scrivener et al. (2018)

3. Fineness (Particle Size Distribution / Surface Area)

Evaluated based on reactivity potential linked to particle size and Blaine/BET surface area.

Score	Fineness Profile	Example Materials	References
1–3	Coarse (>75 µm); low surface area	Ceramic Dust, Boiler Slag	Mehta & Siddique (2022)
4–6	Moderate fineness (10–75 µm)	RHA, Bagasse Ash	Onn et al. (2021), Siddique (2010)
7–10	Ultrafine (<10 µm); high reactivity	Silica Fume, MK	Scrivener et al. (2018), ASTM C1240

4. Compatibility with Cement Chemistry

Reflects how well the material integrates with OPC hydration processes and avoids detrimental reactions like ASR.

Score	Description	Example Materials	References
1–3	High incompatibility, risk of ASR or chloride attack	Waste Glass Powder (untreated)	Mehta & Siddique (2022)
4–6	Conditional compatibility; needs pre-treatment	Red Mud, Biomass Ash	Juenger & Siddique (2015)
7–10	Fully compatible and enhances cement performance	Fly Ash, GGBFS, SF	ASTM standards, Scrivener et al. (2018)

5. Availability and Consistency

Evaluates how widespread and reliable the material is across regions.

Score	Description	Example Materials	References
1–3	Niche/unstable supply or variable composition	Napier Grass Ash, Copper Slags	Onn et al. (2021)
4–6	Moderately available or variable supply chain	Bagasse Ash, Biomass Ash	Mehta & Siddique (2022)

Score	Description	Example Materials	References
7–10	Globally available and consistent	Fly Ash, GGBFS, RHA	Habert et al. (2020), Chen et al. (2021)

6. Environmental Benefit (CO_2 Reduction, Circularity)

Based on LCA studies, CO_2 savings, and waste diversion potential.

Score	Impact	Example Materials	References
1–3	Minor or uncertain savings	Eggshells, Ceramic Dust	Chen et al. (2021)
4–6	Moderate benefit (e.g., 20–40% CO_2 savings)	Calcined Clay, POFA	Scrivener et al. (2018), Onn et al. (2021)
7–10	Major LCA advantage (e.g., >50% CO_2 savings)	Fly Ash, GGBFS, Geopolymers	Habert et al. (2020), Mehta & Siddique (2022)

7. Standards Compliance

Whether the SCM meets or aligns with global standards (ASTM, EN, etc.) for use in cement.

Score	Status	Example Materials	References
1–3	No standard; low confidence	Aspiration Dust, Eggshells, Oil-Based Mud.	ASTM, Juenger & Siddique (2015)
4–6	Under evaluation or regionally accepted	Marble Dust Waste (MDW), Copper Slags, Steel Slag	Chen et al. (2021)
7–10	Fully standardized (ASTM C618, EN 197-1, etc.)	Fly Ash, GGBFS, MK	ASTM, EN standards

This structured scoring ensures transparency and reproducibility and was used to generate the suitability scores shown in Table 3.

Entropy method for evaluating criteria weights

The entropy method objectively calculates criteria weights based on intrinsic variability of the data supplied. The following steps are used in implementing entropy method:

Step 1: Normalize the decision matrix

Given a decision-making matrix $X = [x_{ij}]_{m\times n}$., normalize the elements for each j as follows

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, i = 1,2, \dots, m; \; j = 1,2, \dots, n \qquad \text{A1}$$

Where, x_{ij} is the performance of alternative i concerning criterion j, and p_{ij} is the normalized value of x_{ij}

Step 2: Calculate the Entropy of Each criterion. The entropy E_j for each criterion j is computed as:

$$E_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij}), \; j = 1,2, \dots, n \qquad \text{A2}$$

Where $k = \frac{1}{\ln(m)}$, a constant ensuring $0 \le E_j \le 1$. If $p_{ij} = 0$, set $p_{ij}\ln(p_{ij}) = 0$

Step 3: Calculate the degree of diversification. The degree of diversification for each criterion is given by:

$$d_j = 1 - E_{j,} \quad j = 1,2, \dots, n \qquad \text{A3}$$

A larger d_j value indicates greater discrimination power of the criterion.

Step 4: Determine the weights of the Criteria. The final weight w_j of each criterion j calculate by normalizing d_j:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \quad j = 1,2, \dots, n \qquad \text{A4}$$

Where $w_j \ge 0$ and $\sum_{j=1}^{n} w_j = 1$.

CHAPTER 6

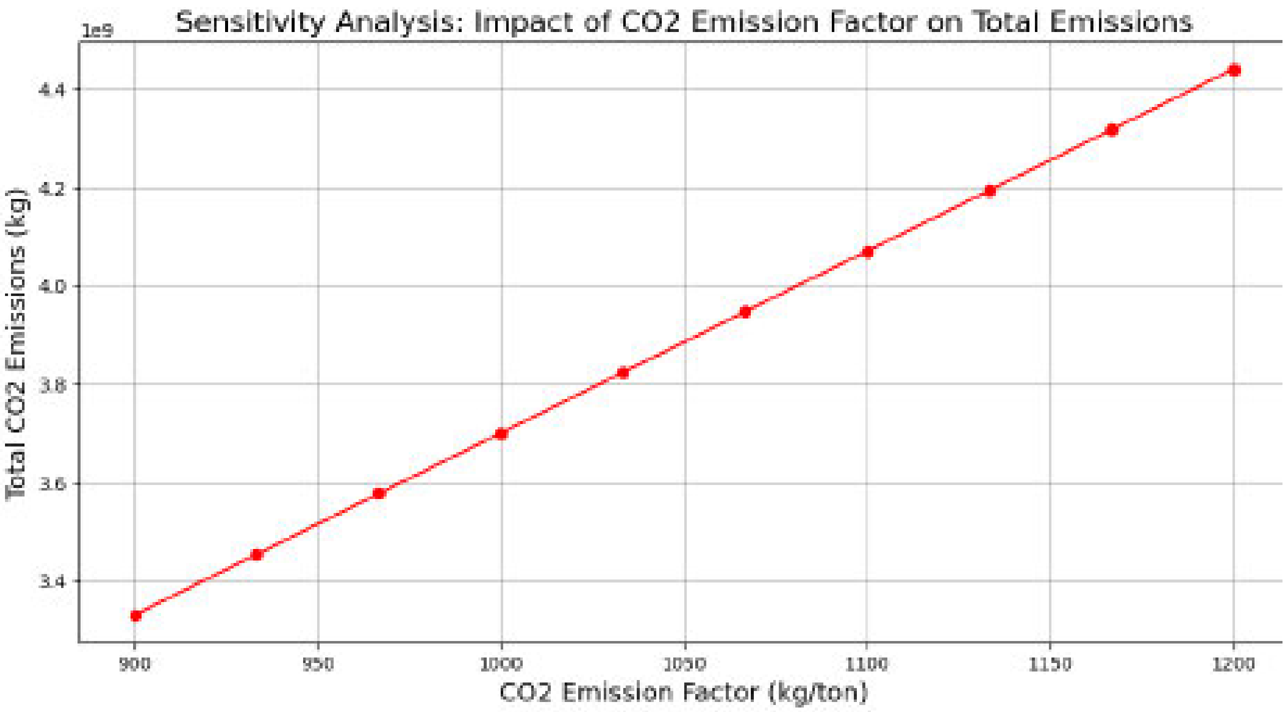
SUPPLEMENTARY FILE OF THE MANUSCRIPT 5

Codes without replacement

```
[1]: import pyomo.environ as pyo
     from pyomo.opt import SolverFactory
     import pandas as pd
     import matplotlib.pyplot as plt
     import numpy as np

     # Step 1: Initialize the MILP Model
     model = pyo.ConcreteModel()

     # Step 2: Define sets and parameters
     plants = ['Plant1', 'Plant2', 'Plant3']

     # Emission and energy use factors for 100% OPC
     emission_factors_opc = {'Plant1': 750, 'Plant2': 800, 'Plant3': 900}  # CO2␣
      ↪emissions (kg/ton)
     energy_use_opc = {'Plant1': 3783, 'Plant2': 3500, 'Plant3': 4000}       #␣
      ↪Energy use (MJ/ton)

     # Production capacities and demand
     capacity = {'Plant1': 1032967, 'Plant2': 1700000, 'Plant3': 1000000}
     total_demand = 3700000  # Total cement demand in tons

     # Step 3: Define the decision variables
     model.x = pyo.Var(plants, domain=pyo.NonNegativeReals)

     # Objective function: Minimize environmental impact
     def objective_rule(model):
         return sum(model.x[p] * emission_factors_opc[p] + model.x[p] *␣
      ↪energy_use_opc[p] for p in plants)

     model.obj = pyo.Objective(rule=objective_rule, sense=pyo.minimize)

     # Constraints
     # Total production constraint
     model.total_production = pyo.Constraint(expr=sum(model.x[p] for p in plants) ==␣
      ↪total_demand)
```

```python
# Capacity constraints for each plant
model.capacity_constraints = pyo.ConstraintList()
for p in plants:
    model.capacity_constraints.add(model.x[p] <= capacity[p])

# Solve the MILP using Gurobi
solver = pyo.SolverFactory('gurobi')
solver.solve(model, tee=True)

# Extract results
results = pd.DataFrame({
    'Plant': plants,
    'Cement Production (tons)': [pyo.value(model.x[p]) for p in plants],
    'Energy Use (MJ)': [pyo.value(model.x[p]) * energy_use_opc[p] for p in plants],
    'CO2 Emissions (kg)': [pyo.value(model.x[p]) * emission_factors_opc[p] for p in plants]
})

print("\nOptimized Cement Production:")
print(results)

# Sensitivity Analysis: Varying Emission Factors
emission_sensitivity = np.linspace(900, 1200, 10)  # Vary emissions from 900 to 1200 kg/ton
emission_impact = []

for e in emission_sensitivity:
    temp_emission_factors = {p: e for p in plants}
    temp_model = pyo.ConcreteModel()
    temp_model.x = pyo.Var(plants, domain=pyo.NonNegativeReals)

    def temp_objective_rule(temp_model):
        return sum(temp_model.x[p] * temp_emission_factors[p] + temp_model.x[p] * energy_use_opc[p] for p in plants)

    temp_model.obj = pyo.Objective(rule=temp_objective_rule, sense=pyo.minimize)
    temp_model.total_production = pyo.Constraint(expr=sum(temp_model.x[p] for p in plants) == total_demand)
    temp_model.capacity_constraints = pyo.ConstraintList()
    for p in plants:
        temp_model.capacity_constraints.add(temp_model.x[p] <= capacity[p])

    solver.solve(temp_model)

    total_emissions = sum(pyo.value(temp_model.x[p]) * temp_emission_factors[p] for p in plants)
```

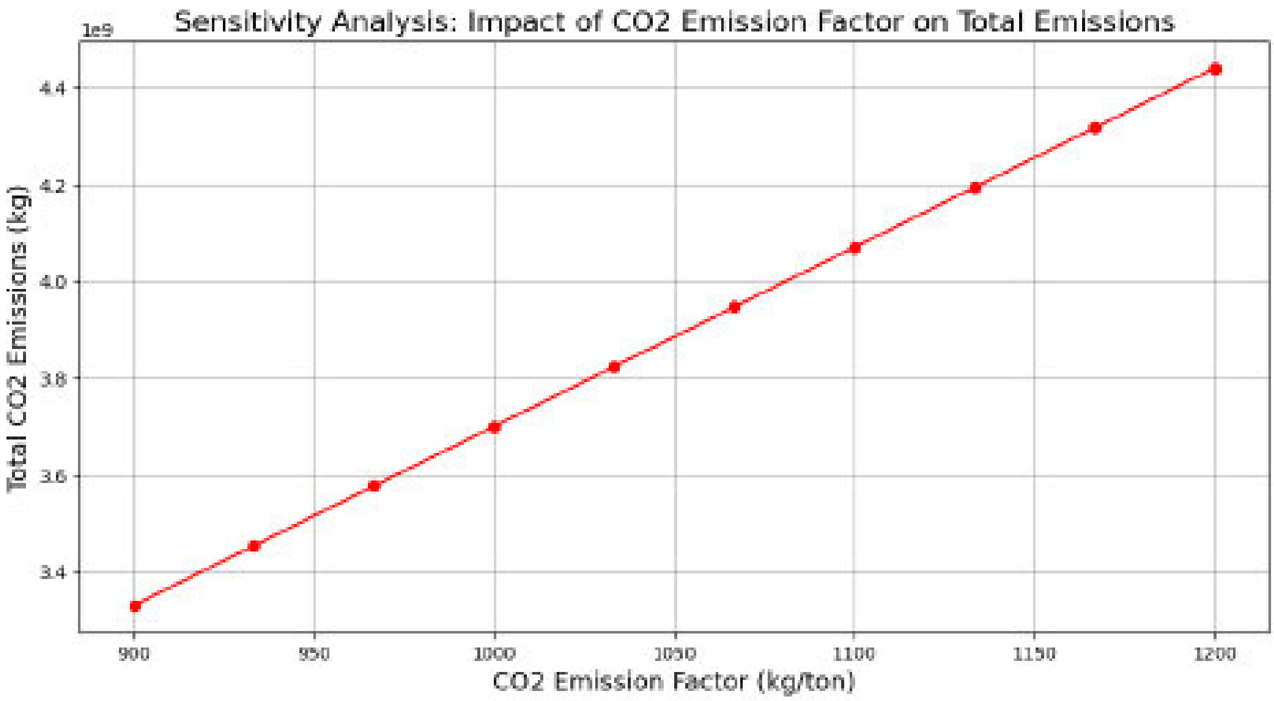
```
[SSE2|AVX|AVX2]
Thread count: 2 physical cores, 4 logical processors, using up to 4 threads

Optimize a model with 4 rows, 3 columns and 6 nonzeros
Model fingerprint: 0x59a0cea7
Coefficient statistics:
  Matrix range     [1e+00, 1e+00]
  Objective range  [4e+03, 5e+03]
  Bounds range     [0e+00, 0e+00]
  RHS range        [1e+06, 4e+06]
Presolve removed 4 rows and 3 columns
Presolve time: 0.00s
Presolve: All rows and columns removed
Iteration    Objective       Primal Inf.    Dual Inf.      Time
       0    1.6730901e+10   0.000000e+00   0.000000e+00      0s

Solved in 0 iterations and 0.00 seconds (0.00 work units)
Optimal objective  1.673090111e+10

Optimized Cement Production:
    Plant  Cement Production (tons)  Energy Use (MJ)  CO2 Emissions (kg)
0  Plant1                 1032967.0     3.907714e+09        7.747252e+08
1  Plant2                 1700000.0     5.950000e+09        1.360000e+09
2  Plant3                  967033.0     3.868132e+09        8.703297e+08
```

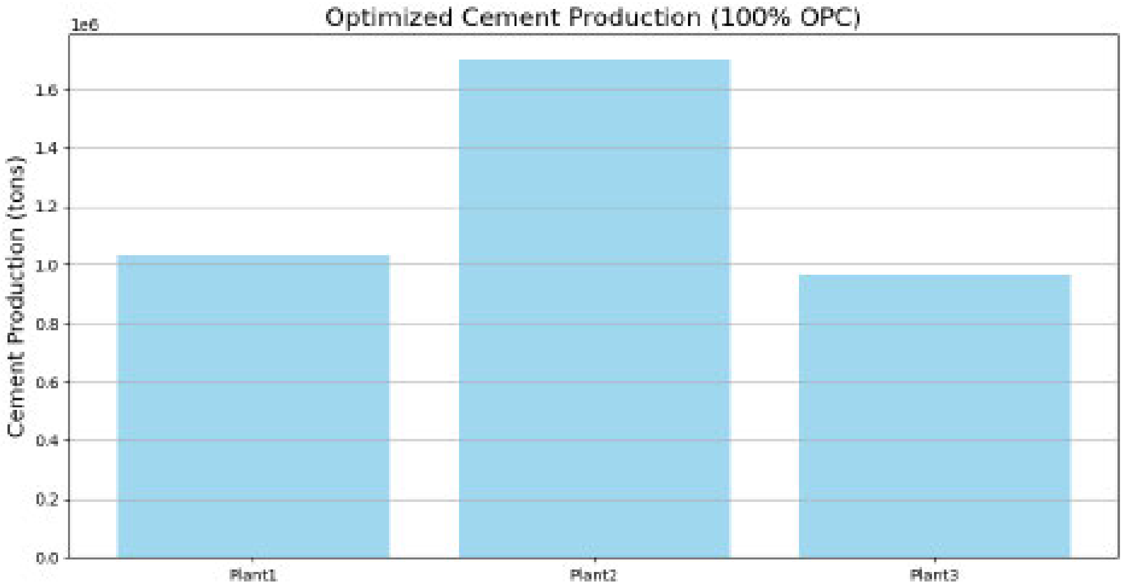


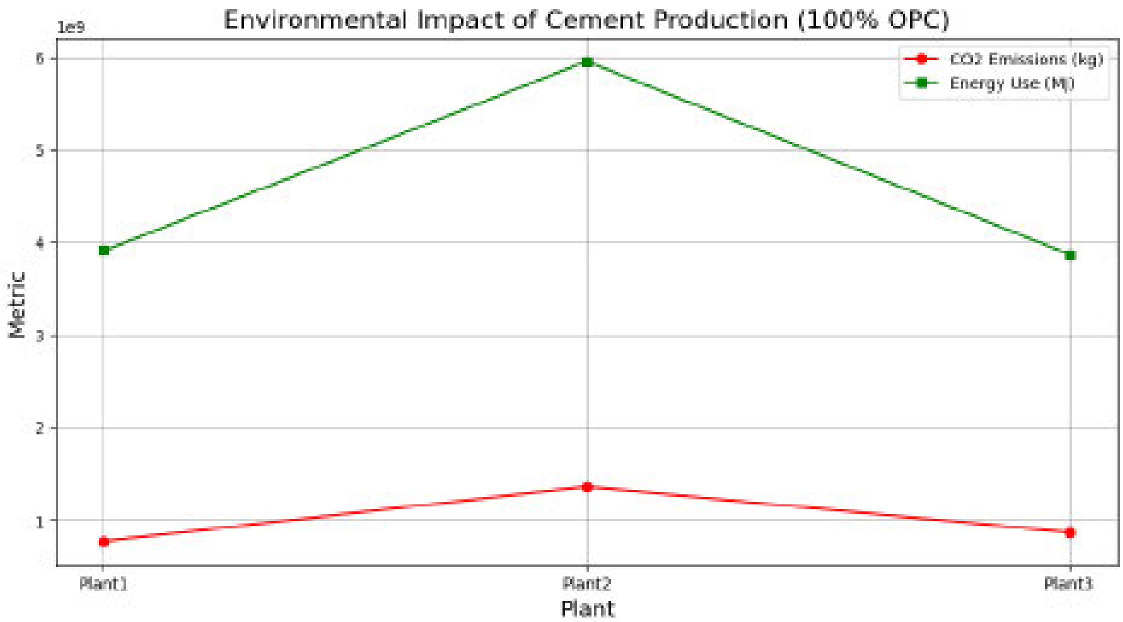
```python
    emission_impact.append(total_emissions)

# Plot Sensitivity Analysis
plt.figure(figsize=(12, 6))
plt.plot(emission_sensitivity, emission_impact, marker='o', linestyle='-',␣
 ↪color='red')
plt.xlabel('CO2 Emission Factor (kg/ton)', fontsize=14)
plt.ylabel('Total CO2 Emissions (kg)', fontsize=14)
plt.title('Sensitivity Analysis: Impact of CO2 Emission Factor on Total␣
 ↪Emissions', fontsize=16)
plt.grid()
plt.savefig('Sensitivity_Analysis_CO2_Emissions.png', dpi=300)
plt.show()

# Plot Optimized Production Data
plt.figure(figsize=(12, 6))
plt.bar(results['Plant'], results['Cement Production (tons)'], color='skyblue',␣
 ↪alpha=0.8)
plt.title('Optimized Cement Production (100% OPC)', fontsize=16)
plt.ylabel('Cement Production (tons)', fontsize=14)
plt.grid(axis='y')
plt.savefig('Optimized_Cement_Production_OPC.png', dpi=300)
plt.show()

plt.figure(figsize=(12, 6))
plt.plot(results['Plant'], results['CO2 Emissions (kg)'], label='CO2 Emissions␣
 ↪(kg)', marker='o', color='red')
plt.plot(results['Plant'], results['Energy Use (MJ)'], label='Energy Use (MJ)',␣
 ↪marker='s', color='green')
plt.title('Environmental Impact of Cement Production (100% OPC)', fontsize=16)
plt.xlabel('Plant', fontsize=14)
plt.ylabel('Metric', fontsize=14)
plt.legend()
plt.grid()
plt.savefig('Environmental_Impact_Cement_OPC.png', dpi=300)
plt.show()
```

```
Set parameter Username
Academic license - for non-commercial use only - expires 2025-10-01
Read LP format model from file
C:\Users\TOSHIBA\AppData\Local\Temp\tmpy_owg5bn.pyomo.lp
Reading time = 0.01 seconds
x1: 4 rows, 3 columns, 6 nonzeros
Gurobi Optimizer version 11.0.3 build v11.0.3rc0 (win64 - Windows 11.0
(22000.2))

CPU model: Intel(R) Core(TM) i7-5500U CPU @ 2.40GHz, instruction set
```

```
[SSE2|AVX|AVX2]
Thread count: 2 physical cores, 4 logical processors, using up to 4 threads

Optimize a model with 4 rows, 3 columns and 6 nonzeros
Model fingerprint: 0x59a0cea7
Coefficient statistics:
  Matrix range     [1e+00, 1e+00]
  Objective range  [4e+03, 5e+03]
  Bounds range     [0e+00, 0e+00]
  RHS range        [1e+06, 4e+06]
Presolve removed 4 rows and 3 columns
Presolve time: 0.00s
Presolve: All rows and columns removed
Iteration    Objective       Primal Inf.    Dual Inf.      Time
       0    1.6730901e+10   0.000000e+00   0.000000e+00      0s

Solved in 0 iterations and 0.00 seconds (0.00 work units)
Optimal objective  1.673090111e+10

Optimized Cement Production:
    Plant  Cement Production (tons)  Energy Use (MJ)  CO2 Emissions (kg)
0  Plant1                 1032967.0     3.907714e+09        7.747252e+08
1  Plant2                 1700000.0     5.950000e+09        1.360000e+09
2  Plant3                  967033.0     3.868132e+09        8.703297e+08
```




Optimized Cement Production (100% OPC)
1e6
Cement Production (tons)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Plant1
Plant2
Plant3


Environmental Impact of Cement Production (100% OPC)
1e9
CO2 Emissions (kg)
Energy Use (MJ)
Metric
1
2
3
4
5
6
Plant1
Plant2
Plant3
Plant

```
[ ]:
```

Codes with replacement

```
[1]: import pyomo.environ as pyo
from pyomo.opt import SolverFactory
import pandas as pd
import matplotlib.pyplot as plt

# Step 1: Initialize the MILP Model using Pyomo
model = pyo.ConcreteModel()

# Step 2: Define sets and parameters
plants = ['Plant1', 'Plant2', 'Plant3']
substitution_levels = {
    'Plant1': [0.15, 0.20, 0.30, 0.40, 0.50],  # 15%-50%  [0.15, 0.20, 0.30, 0.
 ↪40, 0.50]
    'Plant2': [0.21, 0.25, 0.30, 0.35],        # 21%-35%  [0.21, 0.25, 0.30, 0.
 ↪35]
    'Plant3': [0.15, 0.20, 0.30, 0.40]         # 15%-40% [0.15, 0.20, 0.30, 0.
 ↪40]
}

# Data for emissions, energy use, etc.
emission_factors = {'Plant1': 750 - (46/100 * 750), 'Plant2': 800 - (46/100 *␣
 ↪800), 'Plant3': 900 - (46/100 * 900)}  # CO2 emissions in kg/ton of cement
energy_use = {'Plant1': 3783-1324.05, 'Plant2': 3500-857.5, 'Plant3':␣
 ↪4000-1120}   # Energy use in MJ/ton of cement

# Fly ash substitution savings (e.g., per ton of substitution)
# 1% replacement of CaCO3 with fly ash represents a 0.7% reduction in energy␣
 ↪consumption
fly_ash_savings = {
    0.15: 397.215, 0.20: 529.62, 0.30: 794.43, 0.40: 1059.24, 0.50: 1324.05,
    0.21: 514.5, 0.25: 612, 0.35: 857.5  # Ensure all levels are covered
}


# Production capacities and demand
capacity = {'Plant1': 1032967, 'Plant2': 1700000, 'Plant3': 1000000}
total_demand = 3700000  # Total cement demand in tons
```

```python
# Step 3: Define the decision variables
model.x = pyo.Var(plants, domain=pyo.NonNegativeReals)

# Objective function: Minimize environmental impact
def objective_rule(model):
    return sum(model.x[p] * (emission_factors[p] -␣
 ↪fly_ash_savings[max(substitution_levels[p])]) +
               model.x[p] * energy_use[p] for p in plants)

model.obj = pyo.Objective(rule=objective_rule, sense=pyo.minimize)

# Constraints
# Total production constraint
model.total_production = pyo.Constraint(expr=sum(model.x[p] for p in plants) ==␣
 ↪total_demand)

# Capacity constraints for each plant
model.capacity_constraints = pyo.ConstraintList()
for p in plants:
    model.capacity_constraints.add(model.x[p] <= capacity[p])

# Solve the MILP using Gurobi
solver = pyo.SolverFactory('gurobi')
solver.solve(model, tee=True)

# Extract results
results = pd.DataFrame({
    'Plant': plants,
    'Cement Production (tons)': [pyo.value(model.x[p]) for p in plants],
    'Energy Use (MJ)': [pyo.value(model.x[p]) * energy_use[p] for p in plants],
    'CO2 Emissions (kg)': [pyo.value(model.x[p]) * emission_factors[p] for p in␣
 ↪plants]
})

print("\nOptimized Cement Production:")
print(results)

# Add Fly Ash Substitution Analysis
substitution_analysis = []
for p in plants:
    for level in substitution_levels[p]:
        savings = fly_ash_savings[level]
        production = pyo.value(model.x[p]) * (level /␣
 ↪max(substitution_levels[p]))
        substitution_analysis.append({'Plant': p, 'Substitution Level': level,␣
 ↪'Fly Ash Savings (kg)': savings,
```

```
                                              'Cement Production (tons)': production})

df_substitution = pd.DataFrame(substitution_analysis)

# Scientific Plots
plt.figure(figsize=(18, 12))

# Cement Production Bar Plot
plt.subplot(3, 1, 1)
plt.bar(results['Plant'], results['Cement Production (tons)'], color='skyblue',␣
 ↪alpha=0.8)
plt.title('Optimized Cement Production by Plant', fontsize=16,␣
 ↪fontweight='bold')
plt.ylabel('Cement Production (tons)', fontsize=14, fontweight='bold')
plt.xticks(fontsize=12, fontweight='bold')
plt.yticks(fontsize=12, fontweight='bold')
plt.grid(axis='y')

# CO2 Emissions and Energy Use Line Plot
plt.subplot(3, 1, 2)
plt.plot(results['Plant'], results['CO2 Emissions (kg)'], label='CO2 Emissions␣
 ↪(kg)', marker='o', color='red')
plt.plot(results['Plant'], results['Energy Use (MJ)'], label='Energy Use (MJ)',␣
 ↪marker='s', color='green')
plt.title('Environmental Impact by Plant', fontsize=16, fontweight='bold')
plt.xlabel('Plant', fontsize=14, fontweight='bold')
plt.ylabel('Metric', fontsize=14, fontweight='bold')
plt.xticks(fontsize=12, fontweight='bold')
plt.yticks(fontsize=12, fontweight='bold')
plt.legend(fontsize=12, frameon=True)
plt.grid()

# Fly Ash Substitution vs. Savings and Production
plt.subplot(3, 1, 3)
for p in plants:
    plant_data = df_substitution[df_substitution['Plant'] == p]
    plt.plot(plant_data['Substitution Level'], plant_data['Fly Ash Savings␣
 ↪(kg)'],
             label=f'{p} Savings (kg)', marker='o')
    plt.plot(plant_data['Substitution Level'], plant_data['Cement Production␣
 ↪(tons)'],
             label=f'{p} Production (tons)', marker='s')
plt.title('Fly Ash Substitution: Savings and Production', fontsize=16,␣
 ↪fontweight='bold')
plt.xlabel('Substitution Level', fontsize=14, fontweight='bold')
plt.ylabel('Metrics', fontsize=14, fontweight='bold')
```

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plt.xticks(fontsize=12, fontweight='bold')
plt.yticks(fontsize=12, fontweight='bold')
plt.legend(fontsize=12, frameon=True)
plt.grid()

plt.tight_layout()
plt.savefig('Optimized Cement Production by Plant', dpi=300)
plt.savefig('Environmental Impact by Plant', dpi=300)
plt.savefig('Fly Ash Substitution', dpi=300)
plt.show()
```

```
Set parameter Username
Academic license - for non-commercial use only - expires 2025-10-01
Read LP format model from file
C:\Users\TOSHIBA\AppData\Local\Temp\tmpwwfg4t3m.pyomo.lp
Reading time = 0.01 seconds
x1: 4 rows, 3 columns, 6 nonzeros
Gurobi Optimizer version 11.0.3 build v11.0.3rc0 (win64 - Windows 11.0
(22000.2))

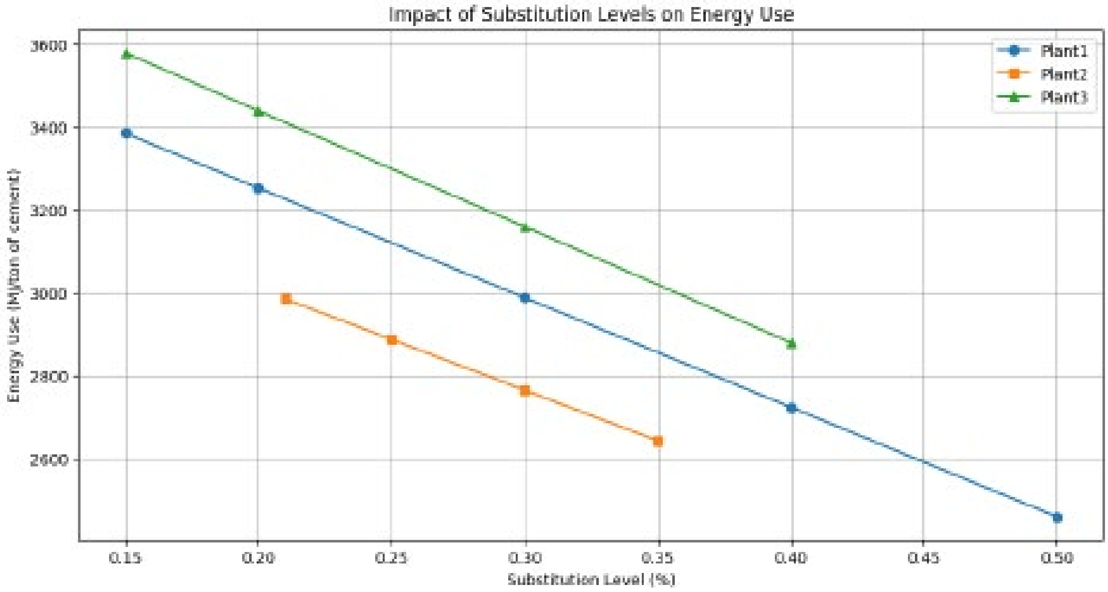
CPU model: Intel(R) Core(TM) i7-5500U CPU @ 2.40GHz, instruction set
[SSE2|AVX|AVX2]
Thread count: 2 physical cores, 4 logical processors, using up to 4 threads

Optimize a model with 4 rows, 3 columns and 6 nonzeros
Model fingerprint: 0x443517f7
Coefficient statistics:
  Matrix range     [1e+00, 1e+00]
  Objective range  [2e+03, 2e+03]
  Bounds range     [0e+00, 0e+00]
  RHS range        [1e+06, 4e+06]
Presolve removed 4 rows and 3 columns
Presolve time: 0.00s
Presolve: All rows and columns removed
Iteration    Objective       Primal Inf.    Dual Inf.      Time
       0    7.5902789e+09   0.000000e+00   0.000000e+00      0s

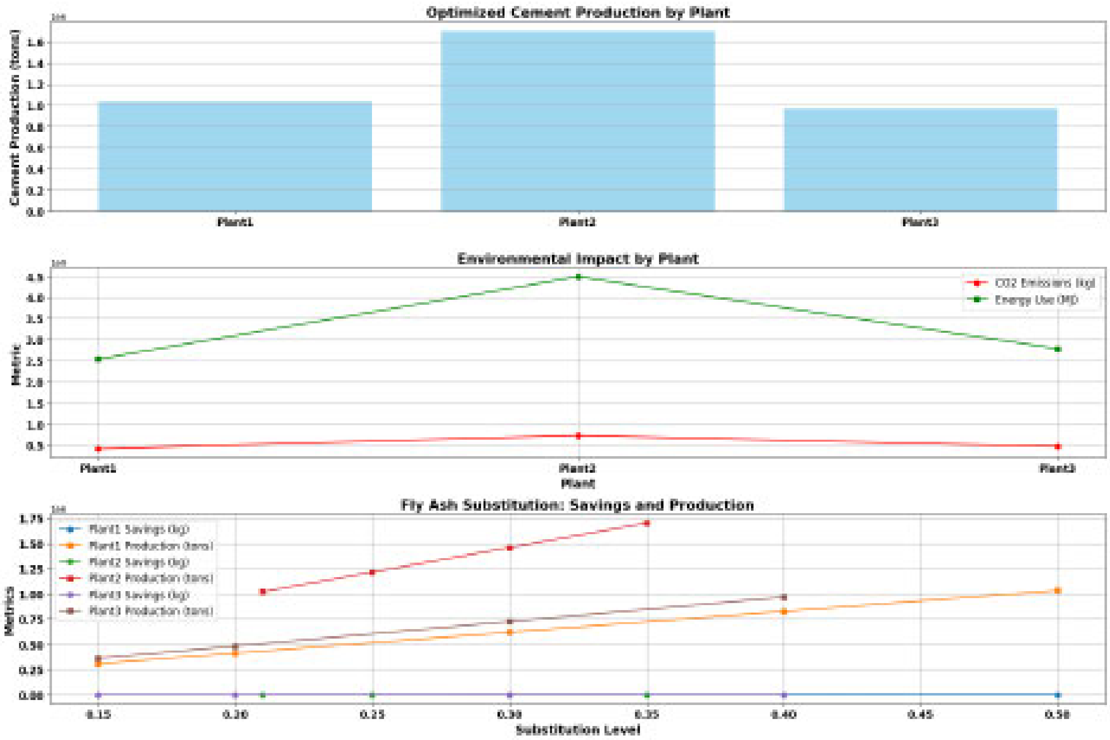
Solved in 0 iterations and 0.00 seconds (0.00 work units)
Optimal objective  7.590278926e+09

Optimized Cement Production:
    Plant  Cement Production (tons)  Energy Use (MJ)  CO2 Emissions (kg)
0  Plant1                 1032967.0     2.540014e+09         418351635.0
1  Plant2                 1700000.0     4.492250e+09         734400000.0
2  Plant3                  967033.0     2.785055e+09         469978038.0
```

```
plt.show()
```



Impact of Substitution Levels on Energy Use
Plant1
Plant2
Plant3
Energy Use (MJ/ton of cement)
Substitution Level (%)
3600
3400
3200
3000
2800
2600
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50



[2]:
```
# Sample Data for Substitution Levels and Energy Use
substitution_levels = [0.15, 0.20, 0.30, 0.40, 0.50]
energy_use_plant1 = [3783-397.215, 3783-529.62, 3783- 794.43, 3783-1059.24, 3783-1324.05]  # Energy use in MJ/ton
energy_use_plant2 = [3500-514.5, 3500-612.5, 3500-735, 3500-857.5]        # Energy use for Plant2 (21%-35%)
energy_use_plant3 = [4000-420.0, 4000-560, 4000-840, 4000-1120]        # Energy use for Plant3 (15%-40%)

# Plot energy use vs substitution levels
plt.figure(figsize=(12, 6))
plt.plot(substitution_levels, energy_use_plant1, label='Plant1', marker='o')
plt.plot([0.21, 0.25, 0.30, 0.35], energy_use_plant2, label='Plant2', marker='s')
plt.plot([0.15, 0.20, 0.30, 0.40], energy_use_plant3, label='Plant3', marker='^')

plt.title('Impact of Substitution Levels on Energy Use')
plt.xlabel('Substitution Level (%)')
plt.ylabel('Energy Use (MJ/ton of cement)')
plt.legend()
plt.grid()
plt.savefig('Impact of Substitution Levels on Energy Use',dpi=300)
```