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Assessing the Environmental Impact of Cement Production in Zambia: An Integration of Life Cycle Assessment and SimaPro Software

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Abstract: This study rigorously assesses the environmental impact of Zambia's cement industry, utilizing the methodology of Life Cycle Assessment (LCA) and the application of SimaPro software. The focus is primarily laid on the stages of raw material extraction and transportation, pivotal in the cement production process. The analysis, grounded in the use of the eco-invent database, renowned for its reliability, encompasses a comprehensive evaluation of resource depletion, energy usage, and greenhouse gas (GHG) emissions, with a particular emphasis on the latter. Findings reveal that raw material extraction and transportation collectively contribute to 80% of the environmental footprint associated with the production of 1000 tonnes of cement as a functional unit. Specifically, raw material extraction is responsible for 44%, transportation 36%, and coal consumption for limestone decomposition 19% of the total impact. The assessment critically examines environmental impact categories such as climate change, freshwater eutrophication, terrestrial acidification, fossil depletion, and human toxicity. These categories are selected due to their direct relevance to the overarching goal of the study. A noteworthy aspect of the analysis is the cement industry's dependency on hydroelectricity. The role of renewable energy sources, particularly hydroelectricity, in mitigating ecological impacts is underscored. The systematic approach of SimaPro, enhanced through the incorporation of industry-specific and region-specific data, adds a layer of reliability to the study. This research, conforming to industry standards and evaluated by experts, delves deeply into aspects such as energy consumption, GHG emissions, water utilization, and land use. To augment the robustness of the findings, a sensitivity analysis is also conducted. The study underlines that the processes of raw material extraction and transportation are key contributors to the environmental footprint of the cement industry in Zambia. Recommendations are made for ethical sourcing, exploration of alternative transportation methods, and optimization of logistics. The study acknowledges the vital interplay between corporations, governments, and academic institutions in shaping tailored sustainability policies. Proposals for the adoption of alternative fuels and the optimization of transportation logistics are put forward, highlighting that ethical raw material extraction is imperative for transitioning towards a more sustainable cement industry.

Keywords: Zambia cement industry; Life Cycle Assessment (LCA); SimaPro analysis; Greenhouse Gas (GHG) emissions; Sustainable production practices; Renewable energy in industry

1 Introduction

The increasing global population, along with the escalating process of urbanization, presents an unprecedented peril to finite resources and the natural environment [1]. Modern architectural designs are increasingly prioritizing the integration of passive and low-energy usage strategies in buildings [1]. Buildings are a significant factor in this issue, responsible for around 40% of global energy consumption. Developed countries contribute up to 36%, highlighting the urgent requirement for sustainable construction practices [2]. An extensive body of academic research has systematically evaluated the carbon emissions linked to the life cycles of buildings [3–9]. The United States Energy Information Administration predicts a significant increase of 42.7% in worldwide carbon emissions by 2035, in comparison to the levels recorded in 2007. This projection underscores the severe consequences of GHG emissions [10].

Given the increasing concerns about climate change resulting from human actions, international efforts such as the United Nations Framework Convention on Climate Change (UNFCCC) [11] have highlighted the importance of adopting ecologically sustainable construction methods. The progressive "green building" movement seeks to incorporate environmentally friendly materials and techniques [12, 13]. With the increasing emphasis on sustainable construction methods worldwide, it is crucial to recognize the specific impacts at a local level, especially in rapidly developing nations like Zambia. The cement industry in Zambia, driven by increasing demand, plays a crucial role in addressing challenges related to urbanization and infrastructural development.

The development of energy-efficient technologies is essential in order to decrease carbon emissions from buildings [14]. Cement, as the fundamental component of the global construction industry, contributes to economic growth but also poses environmental concerns, namely related to resource consumption and carbon emissions. The cement industry accounts for approximately 4-8% of total carbon dioxide emissions [15]. In 2014, the cement sector in Zambia released a total of 299 thousand metric tons of carbon dioxide (CO_2), which is consistent with the trend of increasing emissions observed from 1965 to 2014. This pattern aligns with the inverted U-shaped correlation observed in other countries, which suggests a country's quick process of industrialization and urbanization [16, 17]. It is crucial to acknowledge and tackle the ecological consequences of the cement sector in order to promote sustainable development in Zambia and align with worldwide initiatives to combat climate change.

Global cement production has steadily risen, reaching 4.13 metric tons in 2016 and an expected 4.68 metric tons per year by 2050 [18, 19]. In 2018, Zambia's yearly production was 2.7 million metric tons, according to statistics. Building materials must be produced, which requires raw resources and energy. Resources for essential raw materials include soil, rocks, sand, wood, minerals, chemicals, etc. Electricity, coal, oil and gas, biomass, and other forms of energy are used. The amount of GHG released and the damage done to the environment are directly proportional to the amount of energy used throughout the building process [14]. The cement sector is a prominent source of GHG emissions, specifically carbon dioxide emissions. While burning fossil fuels and other emissions from industrial processes, the cement industry regularly releases gases into the atmosphere. There are three basic steps involved when making cement: raw material preparation, cement grinding, and clinker burning. During these stages of production, carbon dioxide emissions fall into two categories: direct emissions, which account for 90% of the emissions, and indirect emissions, which come from using electricity and the decomposition of $CaCO_3$ [20]. Depending on the raw ingredients and the procedure utilized, Portland cement production requires somewhere between 3 and 6 MJ/kg of clinker [21]. The kiln is the most energy-intensive step in the fossil fuel-based (hard coal) cement manufacturing process. Cement factories use varying amounts of electricity because it depends on the size and purpose of the facility [22, 23].

Cement production requires significant energy, which results in significant CO_2 emissions. The third-largest industrial energy consumer on the globe today is the cement industry [18]. The task of reducing CO_2 emissions from cement manufacturing remains significant since cement output is predicted to increase. Concrete actions are being discussed and put into practice: cement production, concrete production, and finally the efficient use of cement-based materials in buildings and infrastructure. All these are essential if we are to achieve the goal of curbing global warming to 2°C and achieving net zero GHG emissions by 2050, as asserted in the Paris Agreement [11].

This paper assesses the environmental impact of a cement plant in Zambia, explicitly examining GHG emissions related to the extraction of material, transportation, energy use, and production of cement. The study will also highlight the specific environmental impacts of cement production, emphasizing the need for targeted interventions in affected impact categories. Building industry stakeholders can contribute to global efforts to mitigate climate change and environmental degradation by implementing the recommended policy measures and working towards more sustainable and low-carbon building practices.

2 Literature Review

The construction industry, a key global economic growth generator, is increasingly scrutinized for its environmental impact. Cement manufacturing stands out among the essential components of construction due to its significant contribution to resource consumption and carbon emissions. This literature study examines the available knowledge on the environmental impact of cement production, concentrating on global dimensions and narrowing down on Zambia's specific situation. The incorporation of LCA and SimaPro software in this study elevates it to the status of a complete inquiry into the sustainability of Zambia's building industry. According to Li et al. [24], the cement industry is widely acknowledged as a significant source of CO_2. Grant [25] stated that the manufacturing of cement accounts for 4-8% of total global CO_2 emissions. This frightening statistic emphasizes the industry's urgent need for sustainable procedures. Several studies have used LCA to calculate the carbon footprint of cement, providing insights into the environmental consequences of its manufacturing [25].

2.1 LCA Method in Evaluating Environmental Impact

The LCA methodology is frequently used to quantify the environmental effects of products and activities. Guinee et al. [26] studies offer a thorough foundation for conducting LCA. LCA is a critical method for completely evaluating a product's environmental consequences throughout its life [27]. For an exhaustive evaluation of the environmental impacts of cement production, LCA is essential. Pomponi et al. [28] underline the importance of LCA in understanding the environmental repercussions of cement production at various phases. This highlights the importance of LCA in assessing the specific difficulties connected with the environmental effects of a cement plant in Zambia, taking into account geographical variances, energy sources, and manufacturing methods. This all-encompassing strategy supports the industry's transition to a low-carbon future. Schneider [11] emphasizes how the cement sector has made progress in cutting carbon emissions and how LCA has been crucial in helping to plan this shift. More emphasis is placed on the role that LCA plays in evaluating eco-efficient cements as viable solutions for a low-CO_2 cement-based materials business by Environment [29]. Moreover, LCA's application extends beyond production techniques. Smit et al. [30] discuss carbon capture and utilization for mitigating climate change, showcasing the broader scope of LCA in evaluating strategies aimed at reducing the environmental impact of cement production. But in the context of concrete, Salihbegovic et al. [31] highlight the significance of accurate data and well-defined boundaries within the system. This claim is consistent with that made by Stafford et al. [32], who link differences in LCA results to variances in local circumstances, energy sources, and production methods.

SimaPro, a well-known LCA software, is known for its powerful capabilities in studying environmental consequences. SimaPro has been extensively used by researchers in a variety of studies, including those by Goedkoop et al. [33], demonstrating its efficacy in analyzing resource usage, energy use, and emissions. SimaPro integration in LCA studies provides a systematic and standardized approach that improves the reliability and comparability of outcomes.

2.2 Zambian Cement Production Trends in Emissions

Zambia, like many other developing countries, has seen a boom in cement consumption as a result of growing industrialization and urbanization. In 2014, the cement sector in Zambia emitted 299 thousand metric tons of CO_2, suggesting a growing environmental concern. According to Knoema (https://knoema.com/atlas/Zambia/topics/Environment/CO2-Emissions-from-Fossil-fuel/CO2-emissions-from-cement-production?mode=amp), an increasing trend in emissions from 1965 to 2014, which corresponds to patterns observed in other developing countries. In Zambia, the cement industry's sustainability challenges extend beyond emissions.

While existing literature gives useful insights into the worldwide environmental impact of cement manufacturing and shows Zambia's developing concerns, there is a significant study deficit in this area. suggesting a growing environmental concern. An observation of the rising trend in emissions from 1965 to 2014 (https://knoema.com/atlas/Zambia/topics/Environment/CO2-Emissions-from-Fossil-fuel/CO2-emissions-from-cement-production?mode=amp), aligning with integrating LCA techniques and SimaPro software to completely examine the sustainability of the Zambian building industry. This study seeks to fill this void by adopting a comprehensive methodology that takes into account the unique characteristics of the Zambian setting, thereby providing practical insights for the development of sustainable practices in the cement industry.

The purpose of this research is to evaluate the viability and efficacy of various techniques in the Zambian environment, drawing on scholarly publications on emission reduction strategies in cement manufacturing, such as inventive formulations and alternative energy sources. The work corresponds with worldwide efforts to shift to a low-carbon future by scrutinizing ecologically friendly cements and the possibility of reducing carbon emissions in cement-based materials.

2.3 Sustainable Practices and Innovations in the Cement Industry

This study will focus on assessing the viability and efficacy of such strategies in the Zambian context, drawing on scholarly works on emission reduction strategies in cement manufacturing, such as creative formulations and alternative energy sources for the decomposition of raw materials and transportation. These studies' insights direct the investigation of environmentally friendly cements and the possibility of reducing carbon emissions in cement-based materials.

The influence of the cement sector on worldwide carbon budgets and climate change highlights the pressing necessity for sustainable practices to reduce its significant carbon emissions [34]. The literature examines several important aspects of the sector, including its effects on the environment, the factors that affect carbon emissions, initiatives for sustainability using alternative fuels and materials [29], and the crucial role that legislative interventions play [35]. According to Quéré et al.'s [36] plans to cut emissions, this is still crucial in the cement industry.

The factors that affect carbon emissions in cement manufacturing are analyzed in detail by Liu et al. [37]. These factors include raw materials, energy sources, and production technology. Schneider [11] also examines the use of alternative fuels and technological developments as essential elements of the industry's shift to a low-carbon future.

In order to reduce environmental effects, the enhancement of energy efficiency should be applied, as suggested by Ige and Inambao [38]. Several measures for reducing emissions of GHG from the cement industry are also used in other sectors. These include enhancing the energy efficiency of cement plants, substituting fossil fuels with renewable energy sources for the plant in question, sawdust being used as an alternative for hard coal, and the use of technologies that capture and store carbon to sequester released CO_2.

2.4 Regional Variations in the Environmental Implications of Cement Production

The environmental impact of cement manufacturing is influenced by regional differences; therefore, a thorough assessment of this industry's environmental footprint requires a nuanced approach [39]. McAvoy et al.'s [40] investigation explores regional differences in the industry, comparative studies between different geographic locations, and novel approaches that combine system dynamics and LCA. All contribute to a thorough analysis of how cement production affects the environment. Regional differences in energy supplies, production technologies, and regulatory frameworks have a substantial impact on the environmental impact of cement manufacturing. Studies by Stafford et al. [41] emphasize how critical it is to take these regional differences into account when evaluating the industry's environmental impact. Thwe et al. [42] conducted an environmental impact assessment specifically for Naypyitaw, Myanmar. This evaluation helped to address specific environmental concerns in the area and allowed for a more thorough understanding of the potential for sustainable development [42]. Furthermore, an investigation conducted in Southern Europe by Stafford et al. [43] added to our knowledge of the environmental implications of cement production in a given region.

Diverse methodologies are used in studies examining the environmental effects of cement production using LCA techniques. These variations result from a number of variables, including methodological decisions, system boundaries, and regional conditions. The way functional units are chosen, how co-products are allocated, and how data quality is taken into account all have a big influence on the LCA results in different studies. It is imperative to comprehend these methodological differences because they have an impact on how environmental impacts are interpreted and how mitigation strategies are subsequently implemented.

It is critical to comprehend how regional variations affect the environmental effects of cement production. The literature emphasizes the significance of taking into account regional variations in energy supplies, production technologies, and regulatory frameworks. In order to evaluate the environmental impact of a particular cement plant in Zambia, this study will apply this contextual understanding, taking into account regional nuances.

The justification for this study is supported by the review of the literature. It highlights how evaluating the environmental effects of cement production requires using LCA methodologies, investigating sustainable practices, and taking regional contexts into account. This study, which uses LCA and contextual analysis to examine the precise environmental effects of a cement plant's operations in Zambia, directly relates to these insights. There are unique obstacles when implementing LCA methodologies in the cement industry. The availability and accuracy of data for different stages of cement production, such as raw material extraction, transportation, and energy consumption during manufacturing processes, is one significant challenge. The robustness of LCA results is impacted by regional differences in energy sources and production methods, which further exacerbate the difficulties in gathering and interpreting data. Furthermore, methodological difficulties arise in defining system boundaries and creating precise life cycle inventories, particularly when taking recycling procedures and end-of-life scenarios into consideration, which is why a cradle-to-gate was considered for the research.

Methodological differences between studies are a result of the lack of established procedures for carrying out LCA in the cement sector. The development of standardized LCA techniques tailored to the cement industry is necessary to enable more precise and comparable evaluations among various plants and geographical areas. The necessity of standardizing LCA methodologies to enable more trustworthy interpretations and well-informed decision-making within the sector is highlighted by comparative analyses of various studies.

To sum up, the combination of multiple studies examining carbon emissions, sustainable practices, geographical differences, and creative approaches offers a complex picture of the environmental effects of cement production [34, 44, 45]. A crucial tool for thoroughly assessing the industry's entire environmental footprint is LCA [46, 47]. Integration of alternative fuels, careful raw material procurement, and the establishment of strong regulatory frameworks are essential elements in guiding the cement sector towards sustainability. Ongoing research and cooperative efforts by industry stakeholders, legislators, and researchers are critical to the trajectory towards sustainable practices.

3 Research Scope and Methodology

3.1 Research Scope and Data Sources

Chilanga Cement, a Zambian corporation, operates as a subsidiary of the Chinese company Hua Xin (Hainan). Chilanga is mainly a cement company, specializing in the manufacturing of cement and cement clinker. The researched cement site is shown in Figure 1 and Figure 2.

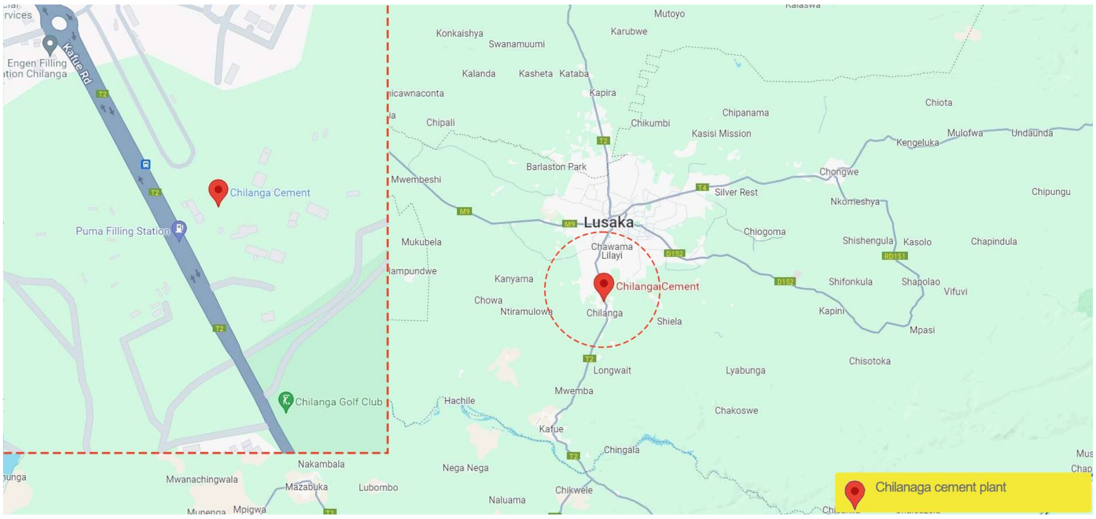

Figure 1. Google map of Chilanga cement, formally known as Lafarge in Lusaka

Figure 2. Drone shot picture of Chilanga cement plant

The environmental impact assessment of Chilanga Cement in Zambia is based on a solid foundation thanks to its reliance on secondary data from the Ecoinvent database. It is necessary to address the data's applicability and relevance to the Zambian context, though. Based on a number of factors, the Ecoinvent database is applicable to the cement industry in Zambia. The database offers a thorough compilation of LCI data for a range of industries globally, but due to variations in energy sources, technological processes, and regional variations, its applicability to the details of cement manufacturing in Zambia may be limited. Due to the lack of specific plant-level data, assumptions are made regarding the applicability of Ecoinvent data to Chilanga Cement's operations in Zambia. These presumptions require that Chilanga Cement's operational procedures and the generalized data found in the Ecoinvent database line up. Variations in energy consumption, transportation techniques, raw material sourcing, and regulatory frameworks are some of the assumptions that were made that could cause differences between the dataset and the real procedures at the Zambian facility.

This research intends to evaluate the environmental effects of a cement factory. When thinking about the limits of the system, the standard LCA method employs a "cradle-to-gate" perspective. The cradle-to-gate methodology is used in most research on cement's environmental impact. This research took a "cradle-to-gate" perspective, as illustrated in Figure 3. Cradle-to-gate refers to the stages of production as well as the procurement of raw materials and internal transportation within the factory. The system boundary in this study was set at the consumption of raw materials, the use of fuels, the use of electricity, transportation, the manufacturing of Portland cement, the finished good, and process emissions. The packing unit, waste treatment, consumption of cement, and final disposal of cement as trash were all omitted from the boundary due to methodological problems and the unavailability of data. The entire production process is divided into five phases, namely, the use of raw materials, the use of fuels, the use of power, the use of transportation, and the production of clinker to streamline the process.

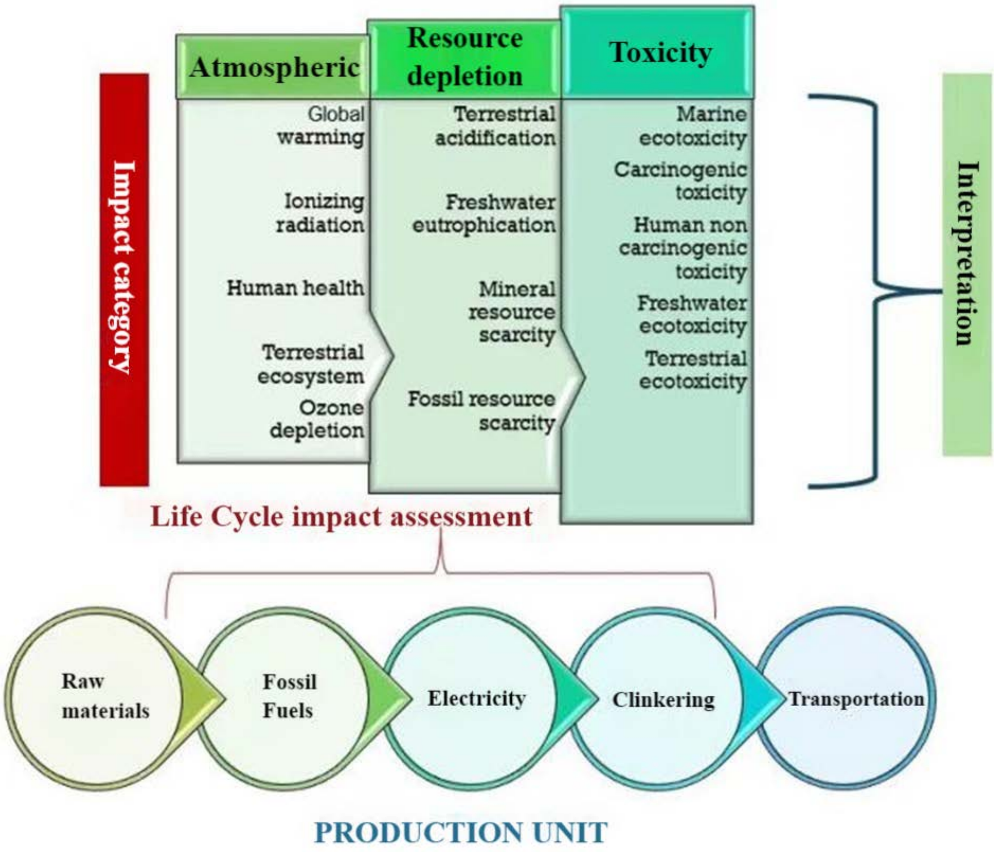

Figure 3. LCA phases in cement production

The LCA technique considers how products, services, and processes affect the environment. A life cycle inventory (LCI) is created by quantifying and compiling all data related to inputs, outputs, energy usage, and waste generation in order to create a functional unit of the product inside the researched system boundary. The data analysis program SimaPro 9.0.0.1 was utilized, and the emission data was computed using the US Environmental Protection Agency's emission parameters.

3.2 Methodology

Although not specifically Zambian-centric, the study assumes that the data from Ecoinvent presents a reasonable approximation of the environmental impacts of cement production in the Zambian context, given the limitations of available plant-level data. It is important to recognize that discrepancies or deviations between Chilanga Cement's specific practices and the database information could potentially affect the accuracy of the assessment. The research cross-validates the Ecoinvent data with any local data or industry-specific insights to reduce any potential discrepancies. Internal validation in SimaPro assessed completeness and coherence, while external validation included cross-referencing with external sources. Sensitivity analyses and scenario-based evaluations were also utilized to comprehend how data variability might affect the overall conclusions, including Monte Carlo simulations, which were conducted to ensure model robustness and quantify uncertainties. Monitoring data quality indicators within SimaPro addressed flagged inconsistencies, collectively enhancing the credibility and reliability of the LCA results.

3.2.1 LCI analysis

The analysis of LCI (ISO 14041) is the process of acquiring all input, including the output data of the inventory, which is consistent with the product under consideration and covers several environmental domains [48]. This study will concentrate on the cradle-to-gate inventory. In contrast, adding the product's disposal or recycling is part of a cradle-to-grave inventory's enlarged scope. This is because all inputs needed during the whole manufacturing process can be found in the cement industry's "cradle-to-gate" inventory. Tools and software are available to help gather inventory data that is compatible with the background system.

The choice of a 1000-ton functional unit in this study aligns with industry standards for reporting cement production, facilitating direct comparisons with industry norms and enhancing comparability with benchmarks. This functional unit allows for a consistent evaluation across impact categories (climate change, freshwater eutrophication, terrestrial acidification, fossil depletion, and human toxicity). It facilitates a comprehensive assessment of the extended impacts of the specified processes, enabling the study to quantify and compare the environmental damage caused by each category. The ultimate goal is to recommend mitigation measures based on the standardized impact assessment, providing a basis for effective environmental management and decision-making. This approach comprehensively evaluates Chilanga Cement's environmental impact, covering the entire production process, including raw material extraction, energy use, transportation, and clinker production. The selected functional unit, equivalent to the daily output of a rotary mill, ensures scalability and statistical significance, providing a meaningful dataset for industry guidance, policy formulation, and decision-making. Furthermore The examination at this production scale allows for robust comparisons and benchmarking against global cement plants, offering valuable insights into Chilanga Cement's environmental performance relative to industry standards. Additionally, the scalability of results makes it adaptable to various production volumes, facilitating scenario analysis and future projections. Overall, the 1000-ton functional unit enhances the study's relevance, applicability, and contribution to a broader understanding of environmental impacts within the cement industry.

However, the data shown below pertains to the production output of a single rotary mill inside a Zambian cement facility. The figures in the table also represent the content of the cement produced; 40 tons of cement are produced by 1 rotary mill in an hour (Table 1). Table 2 presents the inventory input/output statistics for the functional unit.

Table 1. Quantities of material added to the rotary mill per hour

Clinker (t)	L/stone (t)	Gypsum (t)	Total Cement Output
35	4	1	40 ton/h

Table 2. Data from cement production input and output

Input	Amount	Unit
Raw Material		
Clinker	875	t
Limestone	100	t
Gypsum	25	t
Other Additives		
Water (m^3)	10	m^3
Energy/Fuels		
Electricity (KWh)	216.5	Kw
Bituminous coal/Hard coal	175.7	t
Alternative Energy/Fuels		
Sawdust	180.78	t
Cement	1000	t
Emission		
$\mathrm{CO_2}$	0.930	t
PM/Dust	0.0008199	t
NO_x	0.00060682	t
$\mathrm{SO_2}$	0.00027899	t
By-Product		
Fly Ashes	110.2	t
Cement kiln dust	0.55	t

3.2.2 Processes studied in each cement production stage

SimaPro software streamlines the life cycle of inventory construction by integrating various parameters. However, specific steps like packing, waste treatment, consumption, and final disposal were excluded due to data limitations during the establishment of the system boundary. The software utilized databases such as Ecoinvent and emission parameters from the US EPA, entering parameters for energy consumption, raw materials, transportation, emissions, and outputs based on default values and information from the chosen databases. Assumptions related to co-product distribution and energy efficiency were considered, with the option to simplify by combining data from related technologies. Data quality was ensured through validation checks, cross-referencing with industry standards and literature, and site-specific data validation was considered.SimaPro allowed for sensitivity testing and scenario-based analysis, exploring the impact of altering parameters on final results. The software generated LCI results, including environmental impacts and interpretation, which involved understanding consequences within the research framework and aligning them with specific aims and objectives.

The Portland cement manufacturing process involves four distinct stages: Crushing and grinding of raw materials Careful blending of materials in appropriate proportions Subjecting the prepared mixture to high temperatures in a kiln Finely grinding the resulting clinker with approximately 5 percent gypsum Wet, dry, and semi-dry processing are three production techniques, each with specific procedures for preparing raw materials for the kiln. Wet processing grinds materials while wet; dry processing crushes materials into dry powder; and semi-dry processing involves drying and crushing materials into powder before wetting and adding to the kiln. All the above mentioned stages are encompassed within the processes studied as shown in Table 3.

Table 3. Processes studied in production stage of Portland cement in Zambia

Production Unit	Process Considered
Raw materials	Limestone, clinker, gypsum, including the inputs and outputs
Fossil fuels	Sawdust, and coal, including inputs and outputs
Electricity	Mill and other machinery electricity, as regulated by Zambia's Ministry of Production and Distribution
Transportation	The process of bringing gypsum, coal, and sawdust from the extraction site to the plant's gate
Clinker production	Emissions of PM, NO_x, CO_2, and SO_2 from the clinker kiln

3.2.3 Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment procedure integrates the inputs and outputs that were quantified in an inventory analysis to determine how much of an impact they may have on the environment. Different LCIA approaches are available, and some are integrated into the software.

Using the ReCiPe 2016 method, all impact categories were looked at in detail. These included fossil depletion, eutrophication, toxicity, acidification, and climate change. The study looked at environmental effects on a local, regional, and global level. Recipe 2016 was chosen to evaluate Zambia's cement industry because it covers a wide range of impact categories, is up-to-date, is consistent around the world, and strikes a good balance between anthropocentric and ecocentric views. This makes it a suitable and widely accepted method for the region. This methodology aligns with the study's objective of thoroughly evaluating the environmental effects of cement production, offering a nuanced understanding of its consequences. Recipe 2016's adaptability to different geographic locations makes it suitable for assessing impacts in Zambia, considering both local and global effects. Widely recognized and applied globally, the methodology adds credibility to the study, ensuring comparability with industry standards. Its selection demonstrates a commitment to a modern and updated framework, incorporating the latest scientific findings and methodologies.

The selected impact categories for assessing Chilanga Cement's environmental effects align comprehensively with the study's objectives, covering various aspects of environmental impact. They address local concerns, including resource depletion, ecosystem impacts, and air and water quality, aligning with the Zambian ecological context.

Freshwater eutrophication is analyzed explicitly in response to ongoing campaigns to protect the country's water bodies. The impact category of terrestrial acidification selection results from concerns related to the nation's significant dependence on agriculture as a critical economic driver. The focus on the impact category of human toxicity is driven by the necessity to evaluate the working environments in cement production processes and highlight potential impacts on exposed individuals. Lastly, the explicit analysis of the resource depletion category is prompted by various industries in the country relying heavily on both renewable and nonrenewable resources. This comprehensive approach aims to contribute to environmental conservation efforts and encourage sustainable practices to benefit ecosystems and human well-being.

Emphasizing scientific and regulatory importance enhances the study's credibility, ensuring adherence to accepted practices. These impact categories are directly affected by cement production's life cycle, encompassing raw material extraction, energy use, emissions, and waste production. Stakeholder relevance was considered, prioritizing impact categories aligned with local concerns, such as resource depletion, particulate matter, sulfur dioxide, nitrogen oxides, and climate change (CO_2 emissions). This approach supports local efforts to reduce carbon footprints and addresses regional concerns about industrial air pollution and resource conservation.

4 Results and Discussion

In this results section, we meticulously examine the environmental ramifications associated with Zambia's cement production. Employing the LCA methodology, we integrated SimaPro software with methods such as ReCiPe 2016. Additionally, we harnessed the comprehensive Ecoinvent database to inform our analysis. Our focus extends to diverse impact categories, including freshwater eutrophication, terrestrial acidification, climate change, fossil depletion, and human toxicity. By scrutinizing these categories, we aim to spotlight pivotal cement manufacturing processes that significantly contribute to environmental burdens. This comprehensive assessment identifies critical areas requiring attention and suggests potential mitigating measures. Our analysis sheds light on crucial findings, offering detailed insights into the nuanced environmental implications of Zambia's cement industry.

4.1 Results

4.1.1 Analysis of group contributions per impact category

The "Analysis group contributions per impact category" section comprehensively examines the environmental consequences associated with each group or category, including a wide range of impact categories. This study evaluates and compares the individual contributions of these groups to several environmental difficulties or potential challenges, including eutrophication, fossil depletion, human toxicity, and climate change. The identification of groups with the highest environmental effects within certain categories are achieved by analyzing each group's contributions in relation to the impact categories. Based on this understanding, it is possible to categorize sustainability initiatives into key focus areas and allocate resources towards individuals with the greatest global impact potential. This research investigates the impact of the production step categories SimaPro9.0.0.48, as seen in Figure 4. Table 4 provides information about the environmental effects of cement.

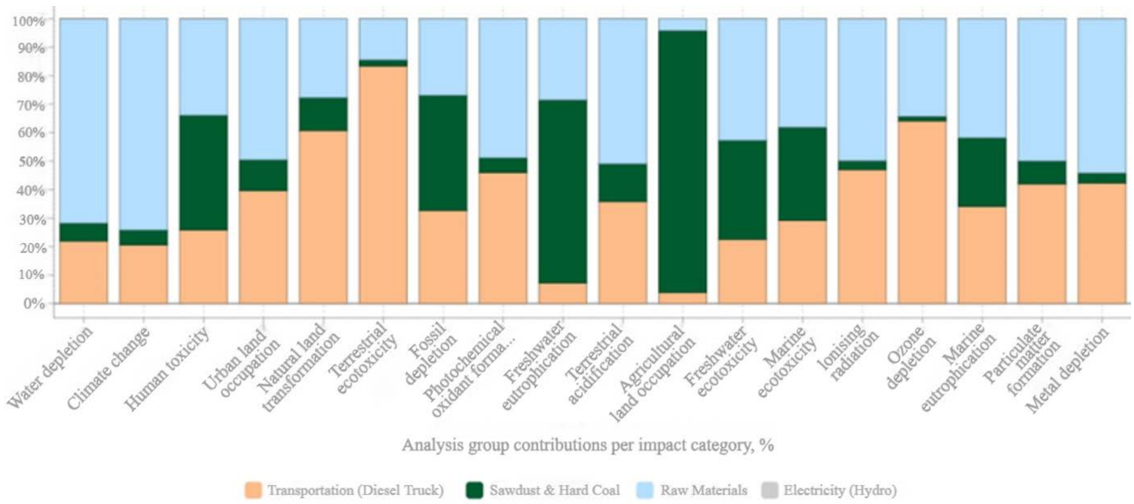

Figure 4. Group contribution per impact category SimaPro 9.0.0.48

Figure 4 analyzes the group contribution per impact category in SimaPro 9.0.0.48.

According to the graph and table above, we investigate assessing environmental repercussions within the atmospheric impact category for the four distinct processes. Climate Change, Human Toxicology, and Fossil Depletion were the different types of impacts that were looked at. It is clear that these three have the biggest effects, as measured by CO_2 equivalent, 1,4-DB equivalent, and oil equivalent, respectively.

The results from our study point to climate change as one of the most severely impacted categories. Specifically, the production process involving the decomposition of raw material, limestone, to form clinker stands out with a striking 75% contribution to this category, resulting in a substantial 1333.932 kg CO_2 equivalent emissions. This emphasizes the significance of raw material usage in affecting climate change.

Fossil Depletion is another impactful category, primarily influenced by three processes: transport, hard coal, and raw material, contributing 32%, 41%, and 27% to this impact category, respectively. Collectively, these processes account for 149.969 kg of oil equivalent emissions. The utilization of fossil fuels for transportation, the burning of coal during limestone processing, and the acquisition of these fuels all directly contribute to the depletion of fossil resources.

Lastly, the category of human toxicity is significantly affected by three processes: transport, hard coal, and raw material, with respective contributions of 26%, 39%, and 35%, totaling up to 154.847 kg of 1,4-DB equivalent. This impact arises from various stages, including transportation and the burning of coal during clinker preparation processes.

Table 4. Impact assessment table of 1000t cement production

No.	Impact Category	Unit	Product	Value
1	Water depletion	m^3	1000 t cement	1.257
2	Climate change	kg CO_2 eq	1000 t cement	1333.932
3	Human toxicity	kg1, 4-DB eq	1000 t cement	154.847
4	Urban land occupation	m^2yr	1000 t cement	24.979
5	Natural land transformation	m^2	1000 t cement	0.113
6	Terrestrial ecotoxicity	kg 1,4 -DB eq	1000 t cement	0.082
7	Fossil depletion	kg oil eq	1000 t cement	149.969
8	Photochemical oxidant formation	kg NMVOC	1000 t cement	1.831
9	Freshwater eutrophication	kg P eq	1000 t cement	0.157
10	Terrestrial acidification	kg SO_2 eq	1000 t cement	1.608
11	Agricultural land occupation	m^2yr	1000 t cement	57.851
12	Freshwater ecotoxicity	kg1, 4-DB eq	1000 t cement	4.632
13	Marine ecotoxicity	kg1, 4-DB eq	1000 t cement	4.690
14	Ionizing radiation	kBq U eq	1000 t cement	20.814
15	Ozone depletion	kg CFC_{-11} eq	1000 t cement	0.00004
16	Marine eutrophication	kg N eq	1000 t cement	0.101
17	Particulate matter formation	kg PM_{10} eq	1000 t cement	0.749
18	Metal depletion	kg Fe eq	1000 t cement	12.850

These results show how important it is to think about the environment in these specific processes. They also show how important sustainable practices are and where improvements could be made to lessen the bad effects in these key impact categories.

Table 4 displays the absolute values for the environmental impact category with the most significant impacts, which include climate change, human toxicity, and fossil depletion. For freshwater eutrophication and terrestrial acidification, they have been included due to ongoing various campaigns to protect water bodies in the country, despite the impact being less significant. In Zambia, ZESCO, the primary electricity utility company, generates 85% of its electricity through hydro, which results in little to no impact on almost all impact categories. However, for transportation, the transport of raw materials such as gypsum and fuels like coal and sawdust to the plant and other necessities such as human labor and the use of coal in the burning of limestone and gypsum to make clinker has the most significant effect on almost all impact categories. Note that the cement plant is on the same premises as the limestone mine. Hence, the conveyance of limestone for clinker preparation has no impact as electricity-powered conveyor belts are utilized.

4.1.2 Climate change

The impact of GHG emissions, particularly regarding climate change, is an essential topic of discussion. Table 5 illustrates how much these products or processes contribute to climate change based on their carbon emissions. The data indicate that transportation of raw materials and clinker production are significant factors. This occurs when limestone is broken down into calcium oxide (CaO) and CO_2 at extremely high temperatures. The CO_2 is then released into the atmosphere, contributing to climate change (global warming). Table 5 shows the environmental effects of different products and activities in their respective units and the damage assessment values for the impact category climate change.

4.1.3 Freshwater eutrophication and terrestrial acidification

For the freshwater eutrophication impact category, extraction of raw materials and use of diesel trucks for transportation are the major contributors. Eutrophication, which can result in an overabundance of algae and other aquatic plants, is over-nourishing water bodies with nutrients, particularly phosphorus. This overgrowth can upset the ecological balance, decrease water oxygen levels, and endanger aquatic life. In the case of this study, limestone is the primary raw material among sand and gypsum.

As for terrestrial acidification, sulfur dioxide emissions may be produced while extracting raw materials used in the production of cement, such as limestone, gypsum, and clay. These pollutants may contribute to the formation of acid rain when they combine with water vapor in the air to create sulfuric acid and nitric acid. Sulfur and nitrogen compounds are discharged into the atmosphere when fossil fuels are used to power the transportation of raw materials and fuels. These substances may contribute to acid deposition, further acidifying the soil and vegetation. Table 6 shows the environmental effects of different products and activities in their respective units and the damage assessment values for terrestrial acidification and freshwater eutrophication.

Table 5. Portland cement production effects on climate change

No.	Category	Unit	Product	Value
1	Climate change	kg CO_2 eq	Sawdust & Hard Coal	35.216
2	Climate change	kg CO_2 eq	Transportation (Diesel Truck)	137.228
3	Climate change	kg CO_2 eq	Electricity - Hydro	0.003
4	Climate change	kg CO_2 eq	Raw material	494.239
5	Climate change	kg CO_2 eq	Sawdust, wet, measured as dry mass	4.521
6	Climate change	kg CO_2 eq	Transport	137.228
7	Climate change	kg CO_2 eq	Electricity from hydroelectric power plant	0.003
8	Climate change	kg CO_2 eq	Tap water	0.002
9	Climate change	kg CO_2 eq	Limestone, crushed, for mill	0.163
10	Climate change	kg CO_2 eq	Sand	1.404
11	Climate change	kg CO_2 eq	Gypsum mineral	0.149
12	Climate change	kg CO_2 eq	Hard coal	30.695
13	Climate change	kg CO_2 eq	Clinker	492.522

Table 6. Damage assessment of fresh water eutrophication and terrestrial acidification impact categories

No.	Category	Unit	Product	Value
1	Freshwater eutrophication	kg P eq	Sawdust & Hard Coal	0.101
2	Freshwater eutrophication	kg P eq	Transportation (Diesel Truck)	0.011
3	Freshwater eutrophication	kg P eq	Electricity Hydro	0.000000007
4	Freshwater eutrophication	kg P eq	Raw material	0.045
5	Terrestrial acidification	kg SO_2 eq	Sawdust & Hard Coal	0.213
6	Terrestrial acidification	kg SO_2 eq	Transportation (Diesel Truck)	0.576
7	Terrestrial acidification	kg SO_2 eq	Electricity-Hydro	0.0000009
8	Terrestrial acidification	kg SO_2 eq	Raw material	0.819

4.1.4 Fossil depletion

Coal is one of the primary fuels used during cement production, mainly during the decomposition of limestone in the kiln. Because limestone has to be heated at high temperatures, large quantities of coal are needed for this process, which directly leads to fossil depletion. To this effect, the long-term viability of the cement industry is thus put at risk. The trucks utilized in the conveying of raw materials and finished goods also depend on fossil fuels, which is an important factor leading to the depletion of fossil fuels. The higher the cement demand, the more fossil fuels will be needed. Environmental degradation and habitat destruction are also effects of fossil depletion. Table 7 shows the environmental impact of products and activities in their respective units and the damage assessment values involved for Fossil depletion.

Table 7. Damage assessment of fossil depletion impact category

No.	Category	Unit	Product	Value
1	Fossil depletion	kg oil eq	sawdust, wet, measured as dry mass	1.332
2	Fossil depletion	kg oil eq	transport	49.027
3	Fossil depletion	kg oil eq	electricity, AC, production mix	0.00006
4	Fossil depletion	kg oil eq	tap water	0.0006
5	Fossil depletion	kg oil eq	limestone, crushed, for mill	0.049
6	Fossil depletion	kg oil eq	sand	0.458
7	Fossil depletion	kg oil eq	gypsum, mineral	0.050
8	Fossil depletion	kg oil eq	hard coal	59.236
9	Fossil depletion	kg oil eq	clinker	39.817

4.1.5 Human toxicity

Carcinogenic substance exposure can pose risks when transporting raw materials for cement production. Vehicle emissions and potential mishaps or spills are the leading causes of these risks. Inhaling carcinogenic pollutants like benzene from DCB reactions, polycyclic aromatic hydrocarbons, and particulate matter from diesel exhaust emissions from moving trucks or ships can harm human health. Accidental releases of harmful substances during transportation can also pollute the environment and harm people's health.

There may be activities involved in extracting fossil fuels, like hard coal, that could expose workers to carcinogens. For instance, mining operations can produce dust and release hazardous chemicals into the air, such as crystalline silica, which is known to cause human cancer. Workers in mining or quarrying operations risk breathing in these cancer-causing particles. Dust and particulate matter emissions may result from grinding and crushing. Fine particles and potentially dangerous substances like silica, heavy metals, and minute amounts of asbestos may be present in these emissions. Long-term exposure to these airborne particles may have long-term carcinogenic effects and increase the risk of respiratory issues.

Workers involved in cement production, such as plant operators, maintenance staff, and those who work in kilns or grinding mills, especially during clinker production, may be exposed to carcinogenic substances on the job. This exposure, which may increase the risk of developing cancers related to the workplace, can happen through handling chemicals, inhaling dust, or coming into contact with other hazardous materials. Table 8 shows the environmental impact of products and activities in their respective units and the damage assessment values for the impact category Human toxicity.

Table 8. Assessment of human toxicity impact category

No.	Category	Unit	Product	Value
1	Human toxicity	$kg1,4-DB$ eq	sawdust, wet, measured as dry mass	1.335
2	Human toxicity	$kg\,1,4-DB$ eq	transport	39.974
3	Human toxicity	$kg\,1,4-DB$ eq	electricity	0.00002
4	Human toxicity	$kg\,1,4-DB$ eq	tap water	0.001
5	Human toxicity	$kg\,1,4-DB$ eq	limestone, crushed, for mill	0.022
6	Human toxicity	$kg\,1,4-DB$ eq	sand	0.345
7	Human toxicity	$kg\,1,4-DB$ eq	gypsum, mineral	0.036
8	Human toxicity	$kg\,1,4-DB$ eq	hard coal	61.081
9	Human toxicity	$kg\,1,4-DB$ eq	clinker	52.052

4.2 Discussion

Utilizing the LCA methodology and SimaPro software is a deliberate and robust choice, grounded in their proven resilience for evaluating the environmental impacts of industrial operations. SimaPro's recognition as a powerful LCA tool, coupled with its extensive database integration capabilities, facilitates a meticulous examination of the complete life cycle of cement production. The application of LCA in this study aligns seamlessly with the need for a comprehensive evaluation encompassing raw material extraction through the entire cement production process. This method enables a thorough quantification of inputs, outputs, and emissions, fostering a profound understanding of the environmental footprint associated with each stage of cement production.

SimaPro, by incorporating secondary data from reputable sources such as the EcoInvent database, renowned for its extensive and verified LCA datasets, enhances the study's legitimacy and applicability, particularly within the unique context of Zambia. The software's role extends to modeling the complete LCI, covering the acquisition of raw materials, energy use, transportation, and clinker production. The study adheres to standard operating procedures, ensuring data consistency and reliability by applying emission parameters set by the United States Environmental Protection Agency.

The results of this study, while consistent with certain academic studies, present disparities, emphasizing the importance of raw material extraction and transportation as significant contributors to environmental burdens. These findings are particularly pertinent in the context of the Zambian cement industry. For example, similar to the results of this study, Shaked et al. [46] emphasized the importance of raw material extraction and transportation as significant contributors to environmental burdens. Furthermore, Jones and colleagues confirmed our study's substantial contribution to climate change by emphasizing the critical role of carbon emissions from limestone decomposition in the clinker production stage [46].

Nevertheless, disparities occur when differing approaches and local environments are considered. Comparing our results to those of studies like Chen et al. [2] which looked at related impact categories like terrestrial acidification and freshwater eutrophication, reveals that raw material extraction has a similar impact on these environmental impacts. Context-specific assessments are crucial because subtle variations emerge when considering regional factors like energy sourcing, transportation infrastructure, and mining practices [47].

Marinković [48], in line with some of our policy recommendations, suggested that effectively incorporating alternative fuels and materials in the cement industry is crucial for strategically planning and advocating diverse methods to diminish environmental impacts, decrease energy and material resource consumption, and lower the economic costs associated with this sector.

SimaPro software and LCA provide a detailed overview of the environmental impacts of cement production in Zambia. This examination delves deeply into the sector's workings, spotlighting raw material extraction (36%) and transportation (44%) as the primary drivers of the industry's environmental impact. It's important to note that the detailed knowledge gained about things like transportation and extracting raw materials, which are often covered in similar studies, varies due to differences in methodology, regions, and industry-specific methods.

Recognizing the study's limitations is crucial for proper contextualization and acknowledging variables such as data availability, methodology specificity, and potential biases in sample selection. These limitations serve as opportunities for refining future study techniques.

The study's implications extend broadly, offering theoretical and industry-specific insights. Recommendations for sustainable logistics, diverse transportation options, and ethical raw material procurement emerge as strategies to alleviate the sector's environmental impact. Not confined to Zambia, these interventions could serve as a model for developing economies reliant on cement production. The study's significance transcends mere analysis; it propels industrial practices toward sustainability. By identifying disproportionate effects in specific cement production steps, the study lays the groundwork for focused interventions, steering the sector toward ecologically responsible practices. It underscores the pivotal role of individuals in developing knowledge and guiding policy creation.

Future research should evaluate the economic viability and practical implementation of the suggested techniques. Additionally, investigating the intricate social and economic implications of incorporating sustainable practices in the cement sector is imperative. A comprehensive analysis of these aspects is essential for formulating robust plans for sustainable cement manufacturing.

In conclusion, this study lays the fundamental groundwork for comprehending the intricate environmental dynamics within Zambian cement manufacturing. Its interdisciplinary contributions significantly advance our understanding of sustainability in industrial processes, extending beyond local contexts. By emphasizing the imperative of sustainable practices, the suggested solutions chart a clear path for steering the cement industry towards responsible environmental stewardship. Notably, the study's findings have broader implications, contributing to a global understanding of sustainability in industrial processes and addressing pressing environmental concerns on a larger scale.

5 Policy Implications and Recommendations

5.1 Transportation

Using alternative modes of transportation, such as railways, may not be a viable option in Zambia's current state as a developing nation. All existing trains continue to rely on coal as a fuel, which poses significant environmental risks. Hence, alternative measures ought to be suggested. The objective is to strategize and enhance transport routes to minimize the distance covered, mitigate fuel consumption, and move towards electric vehicles.

At the moment, electrifying the rail might not be possible because the current hydropower dams need to provide more power for the growing population of Zambia. However, vehicle electrification can be a more realistic approach, as Zambia houses some of the significant minerals used to manufacture electric vehicle batteries. Recently, a Chinese company, Guangzhou Yondway New Energy Technology Company Limited, plans to establish a factory to manufacture electric vehicle batteries. The government should encourage such initiatives by giving tax holidays for a reasonable period to such investors to encourage more investors to come on board.

Furthermore, it evaluates the implementation costs against possible savings by performing a cost-benefit analysis. As Zambia still tries to build and develop its economy, some remedies might need to be simplified for the government to handle; therefore, the private sector has to play an equal role. Using route planning software can optimize truck routes, lowering long-term operating costs and fuel consumption despite the initial investment. To make the investment worthwhile. With the development of a new ministry by the Zambian government, the Ministry of Green Technology, the government should consider investing more in this ministry; route optimization software proves to be a possible undertaking as less investment is needed by improving existing software and integrating Zambia's GPS. Projections should show decreased vehicle wear and tear, increased fuel efficiency, and improved delivery efficiency by performing a thorough economic feasibility analysis that weighs the costs of continuing to use conventional fossil fuels against switching to biodiesel or electrification and thinking about fuel availability, infrastructure investment, and possible incentives or subsidies. To support the change, consider the potential long-term savings in maintenance and fuel expenses and the environmental advantages. By taking this action, GHG emissions and the need for fossil fuels could be significantly decreased. They are working with energy providers to increase the number of renewable energy sources in Zambia so that electrification becomes viable.

5.2 Raw Material

Formulate policies and guidelines on the responsible procurement of primary resources. Collaborating with suppliers who prioritize environmentally sustainable and socially responsible extraction methods is advisable, thereby mitigating ecological disturbances and limiting the employment of hazardous chemicals. Thorough assessments of the environmental effects of extracting raw materials for cement manufacture are essential. The discussed approach will aid in identifying prospective hazards and implementing suitable measures to mitigate environmental harm. Develop and apply strategies to restore ecological balance and reclaim land in areas where extraction activities have been completed and the natural resources have been exhausted. This measure can alleviate the enduring environmental consequences of extraction operations.

5.3 Clinker Production in the Kiln

Cement plants should consider alternative fuels instead of traditional fossil fuels like coal, such as biomass, waste-derived fuels, or renewable energy sources. The implementation of this law has the potential to improve energy efficiency, safeguard the environment, and lower GHG emissions. To lessen the release of air pollutants during the production of clinker, it is advised to create regulations requiring the installation and maintenance of sophisticated emissions control technologies in cement plants, such as electrostatic precipitators, bag filters, and selective catalytic reduction systems. It is commended to encourage the adoption of carbon capture and storage technologies in cement manufacturing facilities to help in the capture and storage of carbon dioxide emissions from clinker production. It is recommended to establish and implement rigorous environmental regulations and standards about the production of clinker, which include limitations on emissions, water consumption, and mandates for waste management.

It's worth noting that in Zambia, the majority stake in the largest cement plants is privately owned. To control the sector's environmental effects, the national government must implement strong regulations. The government should also provide incentives to promote pollution mitigation technologies. For the former, it is essential to put in place improved protocols for environmental impact monitoring and evaluation. Among other things, this entails fortifying the country's emerging environmental impact assessment system to record expected effects precisely and ensure the implementation of suitable mitigation measures [49].

5.4 Enhancing Capacity Building and Environmental Governance

Investing in monitoring technologies by Set aside money to buy state-of-the-art emissions and environmental impact monitoring apparatus. With this investment, the industry's environmental compliance will be more transparent, and accurate data collection will be guaranteed. Training programs for officials that will help To improve the knowledge of government representatives and business regulators regarding environmental compliance, enforcement, and monitoring, training programs should be established. Working with educational establishments or global organizations to create customized programs that center on environmental impact assessments and strategies for mitigation. Creation of a Sturdy Legal Framework that Works with Stakeholders to Create New Environmental Laws or Amend Current Ones, Making Sure They Follow International Best Practices Clear guidelines for environmental impact assessments, emission standards, waste management procedures, and post-extraction land reclamation plans should all be part of this framework.

6 Conclusion

Ultimately, the use of the LCA technique and SimaPro software has led to noteworthy discoveries concerning the ecological consequences of cement production in Zambia. The study identified transportation and raw material extraction as the primary contributors to the environmental impact, with 44% and 36% of the overall effects, respectively. The consumption of coal also led to a 19% impact. The delivery of raw materials resulted in significant emissions, emphasizing the importance of sustainable transportation strategies such as improving logistics and encouraging the use of alternate transportation methods. Remarkably, the environmental factors under assessment were minimally affected by electricity, predominantly derived from renewable hydropower sources. This highlights the benefits of utilizing renewable energy sources in mitigating the release of GHG.

Furthermore, the utilization of alternative fuels, like as sawdust, in the manufacturing of clinker serves as a clear commitment to reducing dependence on fossil fuels and minimizing environmental consequences. In order to enhance the sustainability of Zambia's cement business, it would be beneficial to direct future research towards exploring supplementary alternative fuels and performing a thorough examination of supply chain logistics, taking into account the regional context. Moreover, prospective investigations could analyze the disparities in environmental consequences among different geographical areas, specifically in places with heterogeneous energy resources and fluctuating degrees of industrial advancement. This can provide significant insights for tailoring sustainable approaches to specific geographical and socio-economic conditions. By focusing on the most ecologically impactful sectors and implementing renewable energy sources and alternative fuels, the cement industry in Zambia has the capacity to pave the way for long-term profitability, sustainable growth, and a reduction in detrimental environmental and public health consequences.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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