sustainability

MDPI

Article

Comparative Analysis of Cement Production Methods Using a Life Cycle Assessment and a Multicriteria Decision-Making Approach

Busola Dorcas Akintayo [1,*], Olubayo Moses Babatunde [2] and Oludolapo Akanni Olanrewaju [1]

[1] Department of Industrial Engineering, Durban University of Technology, Durban 4001, South Africa; oludolapoo@dut.ac.za

[2] Department of Electrical Electronics Engineering, University of Lagos, Akoka 101017, Nigeria; olubayobabatunde@gmail.com

* Correspondence: olagunjubusola52@gmail.com

Abstract: Manufacturing cement has a major impact on climate change, resource depletion, and pollution. Selecting sustainable cement alternatives is vital but entails difficult trade-offs between numerous variables. The objective of this study is to determine the most environmentally beneficial method of cement manufacturing by employing an integrated life cycle assessment multi-criteria decision-making technique. 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. 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. Furthermore, an integrated LCA-MCDM approach offers a thorough sustainability evaluation that incorporates many aspects. 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.

Keywords: cement production; slag; emissions; life cycle assessment; multi-criteria decision making; technique for order of preference by similarity to ideal solution; evaluation based on distance from average solution

Citation: Akintayo, B.D.; Babatunde, O.M.; Olanrewaju, O.A. Comparative Analysis of Cement Production Methods Using a Life Cycle Assessment and a Multicriteria Decision-Making Approach. *Sustainability* **2024**, *16*, 484. https://doi.org/10.3390/su16020484

Academic Editors: Pierfrancesco De Paola, Alessandro Malerba, Mariangela Musolino and Domenico Enrico Massimo

Received: 7 December 2023
Revised: 24 December 2023
Accepted: 29 December 2023
Published: 5 January 2024

1. Introduction

The construction industry is essential to global development; however, its contributions to pollution, resource depletion, and greenhouse gas emissions make it a major negative influence on the environment [1]. This is due to globalization and industrialization [2]. The building industry must urgently transition to sustainable practices as urbanization picks up speed [3]. First, the building industry consumes a significant number of natural resources, including minerals, water, and wood [4]. Deforestation, habitat destruction, and soil degradation are caused by the unsustainable extraction and use of natural resources [5]. Accepting sustainable substitutes, including repurposed materials and resources obtained ethically, can lessen these negative impacts while fostering ecosystem health and biodiversity [6]. Secondly, a significant portion of carbon emissions is caused by the construction sector [7]. 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 [8,9]. The sector's carbon footprint can be significantly decreased by using renewable energy sources, energy-efficient technologies, and eco-friendly materials [10]. Using sustainable building methods increases a facility's energy efficiency and lowers operating costs over time for both owners and inhabitants [11]. Employing green building standards guarantees that buildings are planned and built with an emphasis on environmental performance, water efficiency, and energy conservation [12]. Promoting a sustainable environment in the building industry is essential to reducing environmental deterioration [13]. 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 [14].

The sustainable environment is greatly impacted by cement manufacture, which also contributes to a number of environmental problems [15]. 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 [16]. Cement manufacture is a significant source of greenhouse gas emissions since this process is responsible for a significant amount of the industry's emissions [17]. In addition, the extraction of raw materials like clay and limestone from the ground can result in habitat degradation, soil erosion, and biodiversity loss [18]. The process of extraction damages ecosystems and depletes natural resources, which affects the equilibrium of the environment as a whole [19]. Adding to energy use and air pollution is the transportation of both raw materials and completed cement products [20]. 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 [21], in order to address these issues and move toward a more sustainable future. Research is being conducted to investigate new production technologies including carbon capture and utilization (CCU) in an effort to reduce CO_2 emissions from cement plants [22].

Cement production has a significant environmental impact, mostly because of its resource-intensive nature and high carbon emissions [23]. 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 [24]. 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 [25]. 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 [20]. The calcination of raw materials and other high-temperature clinker production processes are the main sources of energy requirement [26]. The industry uses a lot of energy for the transportation, blending, and grinding of both raw materials and completed cement [20]. 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 [27].

The manufacturing of cement is responsible for around 7% of CO_2 emissions worldwide [28]. When limestone is heated to a high temperature and converted into clinker, CO_2 is released during the process. Cement manufacture emits between 0.73 and 0.99 tonnes of CO_2 per tonne of cement [8]. 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 friend method of cement production, hence the need for the study. The following section reviews the various techniques in terms of technologies, models, and policies among others that scholars have investigated to mitigate the emissions emanating from the production of cement. The Section 3 presents the integration of LCA and MCDM, and the Section 4 explain the findings of this study.

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 [29]. Global anthropogenic CO_2 emissions from cement production are estimated to be between 5 and 7%, based on research published [30]. 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 [31]. Furthermore, scholars are exploring CCU technology as a means of reducing carbon dioxide emissions associated with the production of cement [22]. Evaluating the viability of using CCU to absorb and use CO_2 emissions from cement factories was researched [32]. 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 [33]. Magnesium oxide cement is suitable for specific applications; nevertheless, its higher prices prevent the widespread replacement of steel-reinforced concrete on a large scale [33]. Calcium aluminate cements offer regulated solidification but require improvements in performance [34]. The durability of sustainable foam concretes using additional cement varies [35]. 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. [36] 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 [37]. The use of blast furnace slag (18–30%) and other alternative elements (18–30%) to reduce environmental effects is highlighted in [38]. Juenger and Siddique [39] highlight 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 fume are investigated in studies conducted by [40]. Dixon et al. [41] acknowledge the good benefits of the environment but also mention 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 [42]. Research demonstrates the advantages of greater blast furnace slag percentages in concrete for the environment and better performance [43]. 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%) [44]. Gartner and Sui [45] 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 forgoing, there are several reasons why it is crucial to integrate MCDM tools and the LCA approaches in cement manufacturing studies [46]. 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 [47]. 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 [48]. A flexible framework that can adjust to shifting circumstances and preferences over time is frequently offered by the MCDM approach [49]. MCDM considers a number of elements, including social, economic, and environmental aspects [50]. 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 multiple variables, guiding decision makers through the challenges of striking a balance between conflicting goals in the production of building materials [51].

With regard 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 determine the mix parameters that have the greatest impact on the quality of sustainable concrete [52]. Gökcekuş et al. [53] evaluated these MCDM approaches, 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, Marina and Janardhanan [54] 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. [55] 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.

3. Methodology

This 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 [56]. 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 [57]. The adoption of an inclusive method guarantees a comprehensive analysis of all aspects pertaining to environmental effects, 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 [58]. 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.

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. This study offers a comprehensive assessment of sustainability by combining MCDM's structured comparison using EDAS and TOPSIS weighted with CRITIC with LCA's rigorous environmental impact data. The integrated strategy identifies the cement manufacturing method that is most favorable in terms of environmental objectives (Figure 1).

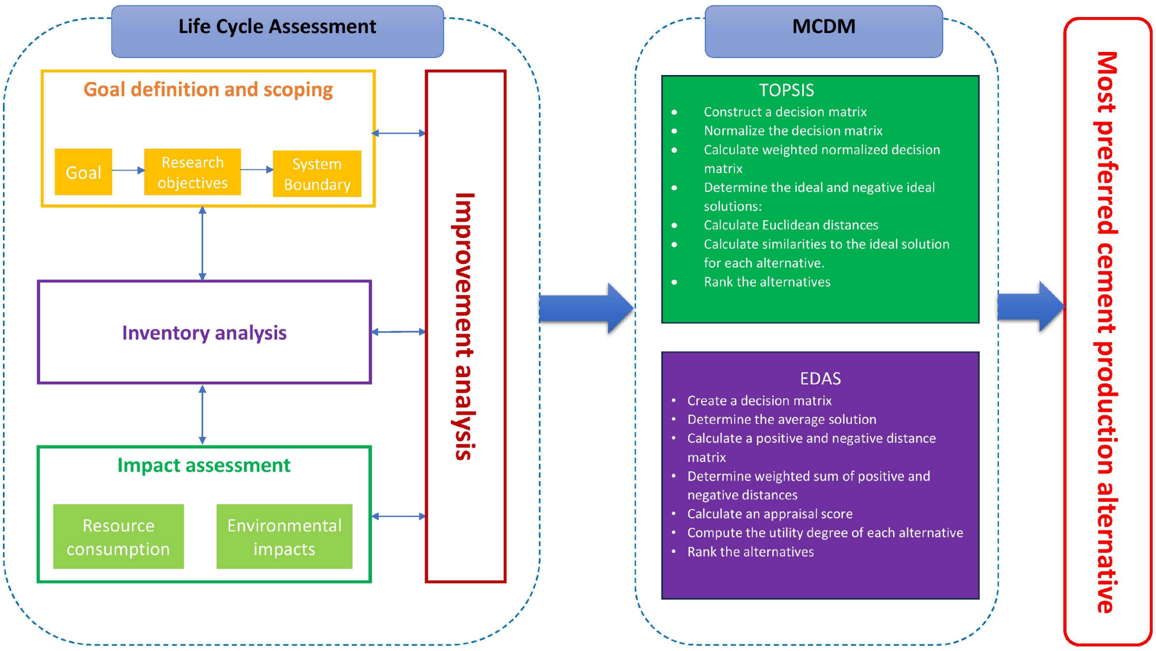

Figure 1. Proposed methodology for selecting the most preferred cement production method.

3.2. LCA Assessment

LCA functions on the core idea of aggregating inputs and outputs related to the environmental, economic, and social characteristics of products, goods, or services throughout their lifespan [59]. 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 [59]. 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 analyzing a product from beginning to end, from the extraction of raw materials to 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 [60,61].

3.3. Goal and Scope Definition

The goal of this LCA study is to analyze and compare the environmental impacts associated with various methods of cement manufacturing method. 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 1 kg 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.

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 traveled, 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 come 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.

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 effects related to the life cycle inventory information that was acquired in earlier stages. It comprises examining 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, adding to a thorough comprehension of the intrinsic sustainability characteristics associated with this industrial procedure.

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 lessons that guide choices and future thinking regarding environmentally friendly cement manufacturing.

3.7. Multi-Criteria 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 [62]. 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 (1)) is constructed utilizing the chosen criteria.

$$X_{ij} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{12} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{1}$$

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 [58]. The steps involved in the implementation process are as follows:

1. 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.

$$R_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X^2{}_{ij}}} \quad (2)$$

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.

$$V_{ij} = R_{ij} \times W_j \quad (3)$$

3. Determine the Positive-Ideal and Negative-Ideal Solutions: For each criterion, identify the maximum and minimum values across all alternatives.

$$A_j{}^{+} = max\left(V_{ij}\right),\ A_j{}^{-} = min\left(V_{ij}\right), \quad (4)$$

4. Distance Calculation: Calculate the Euclidean distance $\left(D^{+}\right)$ from each alternative to the ideal positive solution and $\left(D^{-}\right)$ to the negative ideal solution.

$$D_i{}^{+} = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - A_j{}^{+}\right)^2},\ D_i{}^{-} = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - A_j{}^{-}\right)^2}, \quad (5)$$

5. Calculate the Relative Closeness to the Ideal Solution: Determine the relative closeness of each alternative to the ideal solution.

$$C_i = \frac{D_i{}^{-}}{D_i{}^{+} + D_i{}^{-}} \quad (6)$$

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 favored answer.

3.9. Evaluation Based on Distance from Average Solution (EDAS)

EDAS is an MCDM method that ranks alternatives across criteria based on their distances from the average solution [63]. 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 low 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 are replaced by an overall average. Changing the relative importance of criteria can also have a significant impact on rankings. In general, EDAS offers an 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 favorable and unfavorable variables.

Step 1: Determine each criterion's average solution.

$$\mathrm{AV} = [AV_J]_{1\times m} \quad (7)$$

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

If j-th criterion is beneficial,

$$\text{PDA}_{ij} = \frac{\max(0, \ (X_{ij} - AV_j))}{AV_j} \tag{8}$$

If j-th criterion is non-beneficial,

$$\text{PDA}_{ij} = \frac{max(0, \ (AV_j - X_{ij}))}{AV_j} \tag{9}$$

If j-th criterion is beneficial,

$$\text{NDA}_{ij} = \frac{\max(0, \ (AV_j - X_{ij}))}{AV_j} \tag{10}$$

If j-th criterion is non-beneficial,

$$\text{NDA}_{ij} = \frac{\max(0, \ (X_{ij} - AV_j))}{AV_j} \tag{11}$$

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*

$$SP_i = \sum_{j=1}^{m} w_j PDA_{ij} \tag{12}$$

$$SN_i = \sum_{j=1}^{m} w_j NDA_{ij} \tag{13}$$

where w_j stands criterion j weight.

Step 4: Normalize the alternatives' *SP* and *SN* values.

$$\text{NSP}_i = \frac{\text{SP}_i}{max_i(\text{SP}_i)} \tag{14}$$

$$\text{NSN}_i = \frac{\text{SN}_i}{max_i(\text{SN}_i)} \tag{15}$$

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

$$AS_i = \frac{(\text{NSP}_i + \text{NSN}_i)}{2} \tag{16}$$

4. Results 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.

4.1. Results

4.1.1. LCA Results

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 the negative effects in terms of global warming potential, carcinogenic toxicity, and fossil resource scarcity. Reductions in certain impacts were observed with the increase in limestone content in CEM II/A-L. The utilization of fly ash cement CEM IV/A and pozzolana-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 favorable 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.

4.1.2. 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 significantly high weight of 35.4% (Figure 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.

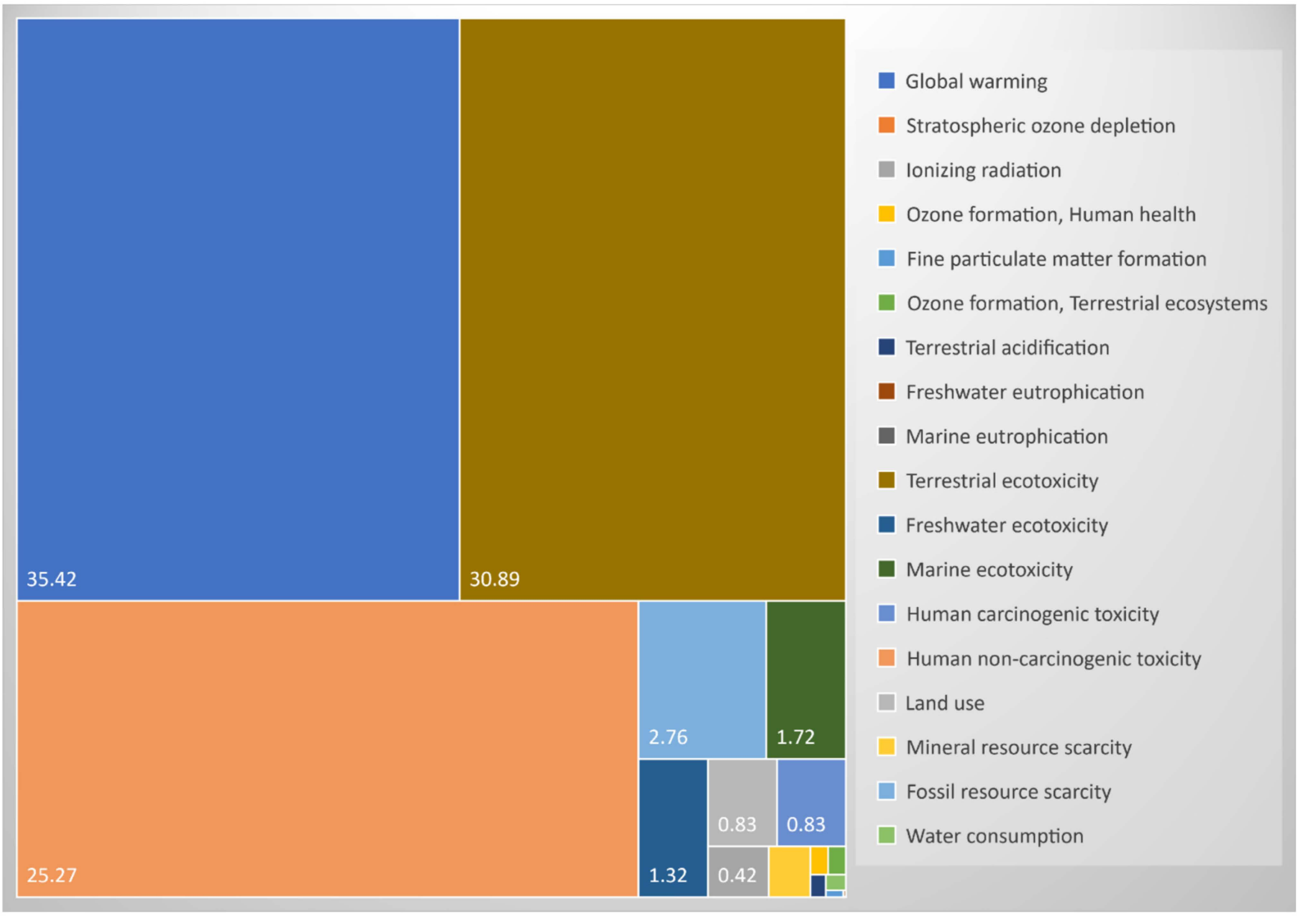

Figure 2. Weight contribution of each environmental impact criteria.

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 pyroprocessing 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.

4.1.3. MCDM Results

Table 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 Table S1, show 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 are 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.

Table 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 NO_x 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 NO_x 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 SO_2 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	m^3	0.00151	0.00127	0.00128	0.00193	0.00123	0.00123	0.00168	0.00119	0.00096	0.00148

Subsequently, the raw performance data for each approach were subjected to normalization, resulting in a scale ranging from 0 to 1 (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 a normalized decision matrix by multiplying the normalized matrix by the weights to obtain the values in 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 Table S5. This coefficient reflects the proximity every cement production technique has to the best and worst solution. The highest rating of 1.7228 for CM10 indicates that it is the closest to ideal (Table 2). The coefficient of 0.510 for CM4 indicates that it is the furthest away from the optimum solution.

Table 2. Results of the MCDM analyses.

Cement Production Alternative	EDAS		TOPSIS	
	Appraisal Score (Asi)	Rank	Relative Closeness (Ci)	Rank
CM1	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
CM7	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 favored by TOPSIS. This supports CM10's position as the best option. The least favored 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 3), although it is placed tenth according to the TOPSIS ranking. According to the rankings provided by EDAS, CM3 is ranked ninth, whereas, according to TOPSIS, it is ranked seventh. 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.

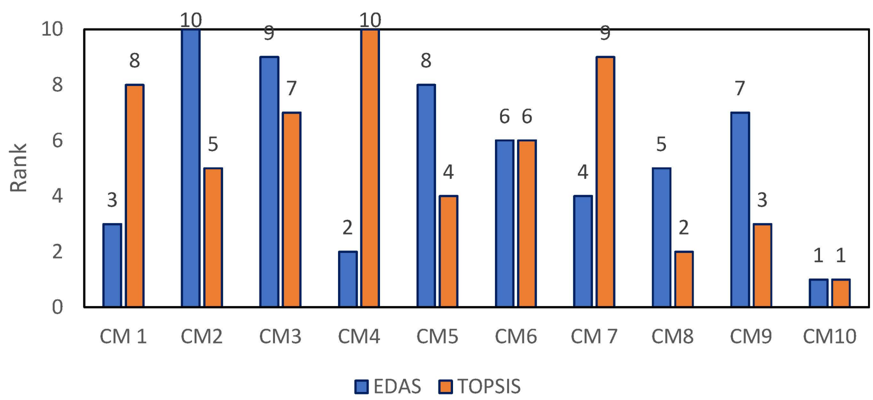

Figure 3. Comparison between EDAS and TOPSIS.

4.1.4. Midpoint Characterization Results

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). 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.

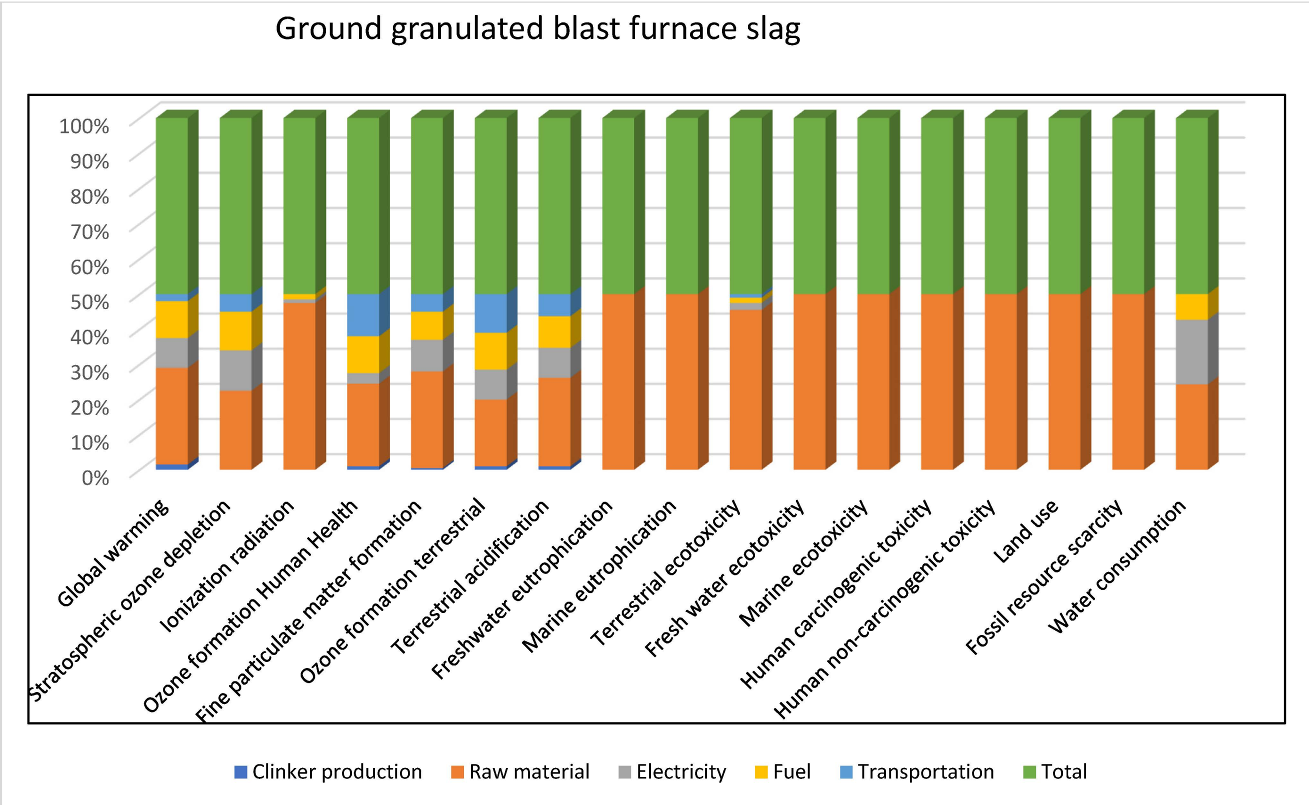

Figure 4. Midpoint Characterization of GGBFS.

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 a comparatively lower 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.

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 a number of environmental consequences for fly ash cement (CEM IV/A) and pozzolana-fly ash cement (CEM IV/B). Nevertheless, GGBFS has emerged as the most favorable option because to 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 for cement manufacturing. Based on the TOPSIS technique, it can be observed that CM10 stands out as the highest-ranking 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) instills 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 GGBF—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 for 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.

Interconnection with Sustainable Development Goals

The findings of this 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, this 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. This 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.

5. Conclusions

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 methods 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 reductions in various environmental impacts, such as global warming potential and toxicity. According to the MCDM ranking, GGBF emerges as the most favorable 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 they 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 in 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 including government and industry stakeholders. Additional cement substitutes like silica fumes or magnesium oxides could be assessed by more LCA research. Endpoint modeling has the potential to offer valuable insights focused on damage-oriented assessment.

This study is based on quantitative data obtained from the LCA; however, future studies 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, and financial constraints as well as environmental favorability. 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. Policymakers should implement rigorous quality control mechanisms to assure the consistency and reliability of GGBFS, to retain the intended performance characteristics of the concrete.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16020484/s1, Table S1. Decision matrix; Table S2. Normarlised decision matrix; Table S3. Weighted normalized matrix; Table S4. Ideal best and Ideal worst; Table S5. Closeness index calculation; Table S6. Form decision matrix; Table S7. Positive distance from average (PDA); Table S8. Weighted sum of PDA; Table S9. Negative distance from Average (NDA); Table S10. Weighted sum of NDA; Table S11. Ranking index calculations.

Author Contributions: Conceptualization, B.D.A. and O.M.B.; methodology, B.D.A. and O.M.B.; software, B.D.A.; validation, B.D.A., O.M.B. and O.A.O.; formal analysis, B.D.A. and O.M.B.; investigation, B.D.A.; resources, O.A.O.; data curation, B.D.A.; writing—original draft preparation, B.D.A.; writing—review and editing, B.D.A. and O.M.B.; visualization, O.A.O.; supervision, O.A.O.; project administration, B.D.A.; funding acquisition, O.A.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sev, A. How can the construction industry contribute to sustainable development? A conceptual framework. *Sustain. Dev.* **2009**, *17*, 161–173. [CrossRef]
2. Ayodele, A.; Ayoninuoluwa, O.; Binuyo, B.; Olanrewaju, G.O.R. Impact of globalisation on the industrial growth in Nigeria (1981–2014): Implication to psychologist and economist. *Eur. J. Bus. Econ. Account.* **2017**, *5*, 52–60.
3. Shahidehpour, M.; Li, Z.; Ganji, M. Smart cities for a sustainable urbanization: Illuminating the need for establishing smart urban infrastructures. *IEEE Electrif. Mag.* **2018**, *6*, 16–33. [CrossRef]
4. Bribián, I.Z.; Capilla, A.V.; Usón, A.A. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Build. Environ.* **2011**, *46*, 1133–1140. [CrossRef]
5. Bodo, T.; Gimah, B.G.; Seomoni, K.J. Deforestation and habitat loss: Human causes, consequences and possible solutions. *J. Geogr. Res.* **2021**, *4*, 22–30. [CrossRef]
6. Vezzoli, C.; Manzini, E. *Design for Environmental Sustainability*; Springer: Berlin/Heidelberg, Germany, 2008.
7. Yildirim, A.E.; Yildirim, M.O. Revisiting the determinants of carbon emissions for Turkey: The role of construction sector. *Environ. Sci. Pollut. Res.* **2021**, *28*, 42325–42338. [CrossRef]
8. Hasanbeigi, A.; Price, L.; Lin, E. Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6220–6238. [CrossRef]
9. Sanal, I. Significance of concrete production in terms of carbondioxide emissions: Social and environmental impacts. *Politek. Derg.* **2018**, *21*, 369–378.

10. Tetteh, E.K.; Amankwa, M.O.; Yeboah, C. Emerging carbon abatement technologies to mitigate energy-carbon footprint-a review. *Clean. Mater.* **2021**, *2*, 100020. [CrossRef]
11. Akadiri, P.O.; Chinyio, E.A.; Olomolaiye, P.O. Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. *Buildings* **2012**, *2*, 126–152. [CrossRef]
12. Zhang, Y.; Wang, J.; Hu, F.; Wang, Y. Comparison of evaluation standards for green building in China, Britain, United States. *Renew. Sustain. Energy Rev.* **2017**, *68*, 262–271. [CrossRef]
13. Omer, A.M. Energy, environment and sustainable development. *Renew. Sustain. Energy Rev.* **2008**, *12*, 2265–2300. [CrossRef]
14. Bungau, C.C.; Bungau, T.; Prada, I.F.; Prada, M.F. Green Buildings as a Necessity for Sustainable Environment Development: Dilemmas and Challenges. *Sustainability* **2022**, *14*, 13121. [CrossRef]
15. Habert, G.; Miller, S.A.; John, V.M.; Provis, J.L.; Favier, A.; Horvath, A. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat. Rev. Earth Environ.* **2020**, *1*, 559–573. [CrossRef]
16. Bosoaga, A.; Masek, O.; Oakey, J.E. CO_2 capture technologies for cement industry. *Energy Procedia* **2009**, *1*, 133–140. [CrossRef]
17. Kajaste, R.; Hurme, M. Cement industry greenhouse gas emissions–management options and abatement cost. *J. Clean. Prod.* **2016**, *112*, 4041–4052. [CrossRef]
18. Mohamad, N.; Muthusamy, K.; Embong, R.; Kusbiantoro, A.; Hashim, M.H. Environmental impact of cement production and Solutions: A review. *Mater. Today Proc.* **2022**, *48*, 741–746. [CrossRef]
19. Nassani, A.A.; Aldakhil, A.M.; Zaman, K. Ecological footprints jeopardy for mineral resource extraction: Efficient use of energy, financial development and insurance services to conserve natural resources. *Resour. Policy* **2021**, *74*, 102271. [CrossRef]
20. Madlool, N.A.; Saidur, R.; Hossain, M.S.; Rahim, N.A. A critical review on energy use and savings in the cement industries. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2042–2060. [CrossRef]
21. Panesar, D.K.; Zhang, R. Performance comparison of cement replacing materials in concrete: Limestone fillers and supplementary cementing materials—A review. *Constr. Build. Mater.* **2020**, *251*, 118866. [CrossRef]
22. da Cruz, T.T.; Balestieri, J.A.P.; de Toledo Silva, J.M.; Vilanova, M.R.N.; Oliveira, O.J.; Ávila, I. Life cycle assessment of carbon capture and storage/utilization: From current state to future research directions and opportunities. *Int. J. Greenh. Gas Control* **2021**, *108*, 103309. [CrossRef]
23. Tun, T.Z.; Bonnet, S.; Gheewala, S.H. Life cycle assessment of Portland cement production in Myanmar. *Int. J. Life Cycle Assess.* **2020**, *25*, 2106–2121. [CrossRef]
24. Vizcaino-Andrés, L.M.; Sánchez-Berriel, S.; Damas-Carrera, S.; Pérez-Hernández, A.; Scrivener, K.L.; Martirena-Hernández, J.F. Industrial trial to produce a low clinker, low carbon cement. *Mater. Constr.* **2015**, *65*, e045.
25. Cao, Z.; Myers, R.J.; Lupton, R.C.; Duan, H.; Sacchi, R.; Zhou, N.; Miller, T.R.; Cullen, J.M.; Ge, Q. The sponge effect and carbon emission mitigation potentials of the global cement cycle. *Nat. Commun.* **2020**, *11*, 3777. [CrossRef] [PubMed]
26. Wu, W.-N.; Liu, X.-Y.; Hu, Z.; Zhang, R.; Lu, X.-Y. Improving the sustainability of cement clinker calcination process by assessing the heat loss through kiln shell and its influencing factors: A case study in China. *J. Clean. Prod.* **2019**, *224*, 132–141. [CrossRef]
27. Biernacki, J.J.; Bullard, J.W.; Sant, G.; Banthia, N.; Brown, K.; Glasser, F.P.; Jones, S.; Ley, T.; Livingston, R.; Nicoleau, L.; et al. Cements in the 21st century: Challenges, perspectives, and opportunities. *J. Am. Ceram. Soc.* **2017**, *100*, 2746–2773. [CrossRef] [PubMed]
28. Benhelal, E.; Zahedi, G.; Shamsaei, E.; Bahadori, A. Global strategies and potentials to curb CO_2 emissions in cement industry. *J. Clean. Prod.* **2013**, *51*, 142–161. [CrossRef]
29. Krishnan, S.; Emmanuel, A.; Shah, V.; Parashar, A. Industrial production of limestone calcined clay cement: Experience and insights. *Green Mater.* **2018**, *7*, 15–27. [CrossRef]
30. Andrew, R.M. Global CO_2 emissions from cement production, 1928–2018. *Earth Syst. Sci. Data* **2019**, *11*, 1675–1710. [CrossRef]
31. Juenger, M.C.G.; Snellings, R.; Bernal, S.A. Supplementary cementitious materials: New sources, characterization, and performance insights. *Cem. Concr. Res.* **2019**, *122*, 257–273. [CrossRef]
32. Amran, M.; Makul, N.; Fediuk, R.; Lee, Y.H.; Vatin, N.I.; Lee, Y.Y.; Mohammed, K. Global carbon recoverability experiences from the cement industry. *Case Stud. Constr. Mater.* **2022**, *17*, e01439. [CrossRef]
33. Walling, S.A.; Provis, J.L. Magnesia-based cements: A journey of 150 years, and cements for the future? *Chem. Rev.* **2016**, *116*, 4170–4204. [CrossRef] [PubMed]
34. Zhou, G.; Su, R.K.L. A review on durability of foam concrete. *Buildings* **2023**, *13*, 1880. [CrossRef]
35. Sereewatthanawut, I.; Prasittisopin, L. Effects of accelerating and retarding agents on nucleation and crystal growth of calcium aluminate cement. *Open Ceram.* **2022**, *11*, 100290. [CrossRef]
36. Environment, U.N.; Scrivener, K.L.; John, V.M.; Gartner, E.M. Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cem. Concr. Res.* **2018**, *114*, 2–26.
37. Diaz-Loya, I.; Juenger, M.; Seraj, S.; Minkara, R. Extending supplementary cementitious material resources: Reclaimed and remediated fly ash and natural pozzolans. *Cem. Concr. Compos.* **2019**, *101*, 44–51. [CrossRef]
38. Radwan, M.K.H.; Onn, C.C.; Mo, K.H.; Yap, S.P.; Chin, R.J.; Lai, S.H. Sustainable ternary cement blends with high-volume ground granulated blast furnace slag—Fly ash. *Environ. Dev. Sustain.* **2021**, *24*, 4751–4785. [CrossRef]
39. Juenger, M.C.G.; Siddique, R. Recent advances in understanding the role of supplementary cementitious materials in concrete. *Cem. Concr. Res.* **2015**, *78*, 71–80. [CrossRef]

40. Vijayan, D.S.; Devarajan, P.; Sivasuriyan, A. A review on eminent application and performance of nano based silica and silica fume in the cement concrete. *Sustain. Energy Technol. Assess.* **2023**, *56*, 103105. [CrossRef]
41. Dixon, N.; Fowmes, G.; Frost, M. Global challenges, geosynthetic solutions and counting carbon. *Geosynth. Int.* **2017**, *24*, 451–464. [CrossRef]
42. Bayraktar, O.Y. The possibility of fly ash and blast furnace slag disposal by using these environmental wastes as substitutes in portland cement. *Environ. Monit. Assess.* **2019**, *191*, 560. [CrossRef] [PubMed]
43. Gholampour, A.; Ozbakkaloglu, T. Performance of sustainable concretes containing very high volume Class-F fly ash and ground granulated blast furnace slag. *J. Clean. Prod.* **2017**, *162*, 1407–1417. [CrossRef]
44. Olagunju, B.D.; Olanrewaju, O.A. Comparative Analysis of Different Fly Ash Percentage of Pozzolanic Cement. In Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management, Detroit, MI, USA, 10–14 August 2020.
45. Gartner, E.; Sui, T. Alternative cement clinkers. *Cem. Concr. Res.* **2018**, *114*, 27–39. [CrossRef]
46. Yoris-Nobile, A.I.; Slebi-Acevedo, C.J.; Lizasoain-Arteaga, E.; Indacoechea-Vega, I.; Blanco-Fernandez, E.; Castro-Fresno, D.; Alonso-Estebanez, A.; Alonso-Cañon, S.; Real-Gutierrez, C.; Boukhelf, F.; et al. Artificial reefs built by 3D printing: Systematisation in the design, material selection and fabrication. *Constr. Build. Mater.* **2023**, *362*, 129766. [CrossRef]
47. Ige, O.E.; Olanrewaju, O.A.; Duffy, K.J.; Obiora, C. A review of the effectiveness of Life Cycle Assessment for gauging environmental impacts from cement production. *J. Clean. Prod.* **2021**, *324*, 129213. [CrossRef]
48. AUTODESK. *Energy Settings | Revit Products 2020 | Autodesk Knowledge Network. Energy Settings*; AUTODESK: San Francisco, CA, USA, 2020.
49. Bonissone, P.P.; Subbu, R.; Lizzi, J. Multicriteria decision making (MCDM): A framework for research and applications. *IEEE Comput. Intell. Mag.* **2009**, *4*, 48–61. [CrossRef]
50. Castro-Nuño, M.; Arévalo-Quijada, M.T. Assessing urban road safety through multidimensional indexes: Application of multicriteria decision making analysis to rank the Spanish provinces. *Transp. Policy* **2018**, *68*, 118–129. [CrossRef]
51. Yang, J.; Ogunkah, I.C.B. A multi-criteria decision support system for the selection of low-cost green building materials and components. *J. Build. Constr. Plan. Res.* **2013**, *1*, 89. [CrossRef]
52. Ahmed, M.; Mallick, J.; AlQadhi, S.; Kahla, N.B. Development of concrete mixture design process using MCDM approach for sustainable concrete quality management. *Sustainability* **2020**, *12*, 8110. [CrossRef]
53. Gökcekucs, H.; Ghaboun, N.; Ozsahin, D.U.; Uzun, B. Evaluation of Cement Manufacturing Methods Using Multi Criteria Decision Analysis (MCDA). In Proceedings of the 2021 14th International Conference on Developments in eSystems Engineering (DeSE), Sharjah, United Arab Emirates, 7–10 December 2021; pp. 39–43.
54. Marinelli, M.; Janardhanan, M. Green cement production in India: Prioritization and alleviation of barriers using the best—worst method. *Environ. Sci. Pollut. Res.* **2022**, *29*, 63988–64003. [CrossRef]
55. Bathrinath, S.; Nagesh, S.M.; Dinesh, V.; Ganesh, M.S.R.; Koppiahraj, K.; Bhalaji, R.K.A. Analysing the Primary Influential Factors in Cement Manufacturing Industry Using DEMATEL Methodology. In *Materials, Design and Manufacturing for Sustainable Environment: Select Proceedings of ICMDMSE 2022*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 489–498.
56. Akintayo, B.D.; Ige, O.E.; Babatunde, O.M.; Olanrewaju, O.A. Evaluation and Prioritization of Power-Generating Systems Using a Life Cycle Assessment and a Multicriteria Decision-Making Approach. *Energies* **2023**, *16*, 6722. [CrossRef]
57. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. *Life Cycle Assessment*; Springer: Berlin/Heidelberg, Germany, 2018.
58. Babatunde, S.; Ighravwe, D. A fuzzy multi-criteria approach for hosting-right selection: A case study of sport event. *Int. J. Data Netw. Sci.* **2019**, *3*, 1–12. [CrossRef]
59. Jacquemin, L.; Pontalier, P.-Y.; Sablayrolles, C. Life cycle assessment (LCA) applied to the process industry: A review. *Int. J. Life Cycle Assess.* **2012**, *17*, 1028–1041. [CrossRef]
60. Moretti, C.; Hamelin, L.; Jakobsen, L.G.; Junginger, M.H.; Steingrimsdottir, M.M.; Høibye, L.; Shen, L. Cradle-to-grave life cycle assessment of single-use cups made from PLA, PP and PET. *Resour. Conserv. Recycl.* **2021**, *169*, 105508. [CrossRef]
61. Olagunju, B.D.; Olanrewaju, O.A.; Irusta-Mata, R. A Comparative Life Cycle Assessment Study of Conventional and Best Available Techniques Incorporated Cement Production Processes using midpoint approach. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Monterrey, Mexico, 3–5 November 2021.
62. Singh, A.; Malik, S.K. Major MCDM Techniques and their application—A Review. *IOSR J. Eng.* **2014**, *4*, 15–25. [CrossRef]
63. Chakraborty, S.; Chatterjee, P.; Das, P.P. Evaluation Based on Distance from Average Solution (Edas) Method. In *Multi-Criteria Decision-Making Methods in Manufacturing Environments*; Apple Academic Press: Palm Bay, FL, USA, 2024; pp. 183–189.