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Sustainability Assessment of Cement Types via Integrated Life Cycle Assessment and Multi-Criteria Decision-Making Methods

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Abstract

Cement production significantly contributes to global warming, resource depletion, environmental degradation, and environmental pollution. Identifying sustainable alternatives is critical but requires balancing multiple, often conflicting, factors. The objective of this study is to determine the most preferred cement alternative produced in South Africa using an integrated life cycle assessment (LCA) and multi-criteria decision-making (MCDM) framework. The LCA quantified the environmental impacts of seven different cement-type alternatives across 18 midpoint impact categories. The LCA results showed that slag cement-based CEM III/A achieved a 50% reduction in global warming potential (GWP) compared to traditional CEM I (0.57 vs. 0.99 kg CO_2 eq. This study also used the entropy-weighted, COPRAS and ARAS methodologies to evaluate and rank cement types based on their environmental impacts and weighted sustainability criteria and the results showed that fly ash-based CEM II/B-V demonstrated the highest overall sustainability, with utility scores of 100.00 (COPRAS) and 0.7257 (ARAS) in MCDM ranking. These results highlight that fly ash-based cement offers substantial environmental benefits over traditional CEM I, particularly in reducing greenhouse gas emissions and resource consumption. The integrated LCA–MCDM method enables robust prioritization by linking quantitative environmental impacts with objective ranking criteria. Although this analysis focuses on South African cement formulations, the methodology and findings are applicable to other regions with similar production profiles and SCM availability. The framework offers a practical tool for policymakers and industry to support environmentally responsible decision-making in cement production.

Keywords: cement production; multi-criteria decision making; complex proportional assessment; additive ratio assessment; life cycle assessment; entropy

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1. Introduction

The cement industry is a keystone of global infrastructure development and economic growth, providing essential materials for construction projects from buildings to transportation networks [1–3]. Its significance extends beyond construction, as it drives national economies and supports urbanization. However, Cement production involves resource-intensive stages, including raw material extraction, clinker production, grinding, and packaging [4,5]. Each stage consumes substantial materials and energy, emitting carbon dioxide (CO_2) emissions. The sector accounts for 5–8% of global anthropogenic CO_2 emissions [6,7]. On average, cement production releases between 0.6 and 0.81 kg CO_2-equivalent per ton of cement, primarily from fossil fuel combustion and limestone calcination, worsening climate

change and posing risks to ecosystems and human health [8–12]. In 2023, the global cement industry produced over 4 billion metric tons due to population growth and infrastructure expansion, with China producing over 2100 million metric tons above other countries [13–17].

Cement production is projected to grow by 12–23% by 2050 and this growth could increase cement-related CO_2 emissions by 4% compared to 2018 levels, further damaging global climate goals despite sustainability efforts [18]. It emits greenhouse gas (GHG) emissions, including CO_2, sulfur dioxide (SO_2), nitrous oxide (N_2O), and methane (CH_4). These pollutants contribute to global warming and environmental impact, demanding urgent action to mitigate their impact on global warming [19]. The extent of these emissions depends on fuel sources, raw materials, production technologies and the high demand for cement, particularly in construction projects such as roads, bridges and buildings [20–22]. In recent years, environmental protection has gained attention and has become a crucial matter for public policy development in social and political settings [23,24]. The environmental impact of the cement industry is combined with high raw material consumption, energy use, and waste generation, making it a crucial consideration for sustainability initiatives.

Therefore, identifying the most sustainable option for cement production's environmental impact is vital. Using mitigation strategies focusing on optimizing fuels, raw materials, and production methods can reduce these emissions. Research has focused on developing strategies to mitigate these impacts, including optimizing material use with industrial by-products such as (fly ash and slag) as alternative raw materials and traditional fuels with alternative fuels, such as biomass and waste-derived fuels, to improve energy efficiency, move toward a more sustainable future [25–27]. These substitutions reduce reliance on natural resources and lower emissions. Despite progress in developing sustainable cement production, the optimal approach remains unclear, especially in region-specific contexts like South Africa, where comprehensive, comparative ranking studies using integrated methodologies are limited. Additionally, developing novel cementitious materials, such as blended cement, can reduce clinker content, the most emissions-intensive component of cement [28,29].

Cement types, such as Portland, Portland Composite, Composite and Pozzolanic (CEM I, CEM II, CEM III, CEM IV and CEM V), vary in composition, production processes and environmental impact, requiring comparative analysis. A critical evaluation of the impact of these cement types is necessary to promote sustainable construction practices that reduce climate change effects, conserve resources, and protect ecosystem integrity. The environmental impact of cement production has been investigated across its entire lifecycle, using life cycle assessment (LCA) from raw material extraction to disposal [29–31]. LCA quantifies metrics such as global warming potential, acidification, resource depletion, etc., providing insights into more sustainable production methods [17,32–35]. Several studies have investigated the complexities of cement production and its impacts on the environment and humans, a critical concern for policymakers across the public and private sectors [32,36,37]. LCA studies highlight the need to balance performance, cost, and sustainability, particularly in developing regions like South Africa, where infrastructure demands clash with decarbonization goals.

Several approaches have been proposed to mitigate the environmental impact of cement production. One effective method is to substitute industrial waste materials with alternative raw materials and fuel sources [25–28,38]. This method reduces the consumption of natural resources and lowers GHG emissions [13]. Additionally, the development of novel cementitious materials has shown improvement by incorporating waste-based components, which reduce the overall carbon footprint of cement production [29]. Transitioning to sustainable cement production requires integrating LCA-driven insights methods with pragmatic policy and industrial innovation. The integration of LCA and multi-criteria

decision-making (MCDM) methods is crucial for ranking and evaluating different cement types. The MCDM is a set of techniques used to assess and prioritize alternatives by integrating multiple conflicting criteria to support complex decision-making and identify the most suitable alternative [39,40].

Despite the availability of general LCA–MCDM applications, few studies have focused on South African cement types using objective entropy weighting with dual MCDM techniques. This study fills that gap by offering a localized, reproducible ranking of cement alternatives, providing practical guidance for sustainable material selection in industrial and policy contexts. Existing studies have largely focused on global or generalized datasets, with limited attention to South Africa's unique production conditions and environmental constraints. This study introduces a region-specific LCA–MCDM framework using entropy-weighted COPRAS and ARAS to identify and rank the most sustainable cement types, offering new methodological and contextual insights. This study offers a novel methodological contribution by integrating midpoint LCA with two robust MCDM methods, Complex Proportional Assessment (COPRAS) and Additive Ratio Assessment (ARAS), enhanced with entropy-based weighting to reduce subjective bias. Unlike previous studies that either apply LCA in isolation or rely on subjective decision-making frameworks, this research systematically links environmental impact data with structured, objective prioritization techniques. It delivers a region-specific sustainability ranking of seven cement types used in South Africa, addressing the current lack of comparative, data-driven evaluations tailored to local production practices. The inclusion of entropy weighting improves transparency and reliability, while the combined LCA–MCDM model enables holistic assessment across multiple environmental categories. This approach not only enhances analytical rigor but also provides actionable insights to support policymakers, manufacturers, and stakeholders in selecting environmentally optimal cement alternatives.

Integrating these methods will help the stakeholders evaluate and rank cement alternatives by prioritizing low-carbon materials and energy-efficient technologies. Also, it will enable and guide stakeholders in adopting context-specific solutions, thereby promoting sustainable construction practices. Therefore, this paper integrates hybrid methodologies LCA-MCDM, i.e., COPRAS and ARAS, weighted with entropy weight methods to assess, select and rank cement types (alternatives) in South Africa based on environmental impacts and criteria relevance, enabling informed, sustainability-driven decision-making for the sector. Also, this study addresses the following core research question: What are the most sustainable cement alternatives within the South African context, considering a comprehensive life cycle assessment and the reconciliation of environmental, economic, and social objectives?

The remainder of this paper is organized as follows: Section 2 presents the literature review. Section 3 presents the methodology, including the integrated Life Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM) framework, with detailed descriptions of the COPRAS and ARAS methods, entropy weighting, and system boundaries, outlines the data sources, LCA modeling assumptions, and analytical parameters. Section 4 provides the results and discussion, highlighting LCA midpoint impacts, entropy-based criteria weighting, and the ranking of cement alternatives using MCDM techniques, low entropy weight for global warming potential and sensitivity analysis of MCDM results. Section 5 concludes the study with key findings, practical implications for sustainable cement production, and recommendations for future research.

2. Literature Review

In determining the preferred environmentally sustainable methods for cement production, it is critical to evaluate multiple environmental criteria across production stages.

MCDM provides a robust framework for selecting or ranking preferred alternatives based on multiple criteria. LCA is a crucial methodology for assessing the environmental impacts of cement production from raw material extraction to end-of-life disposal, throughout the cement lifecycle, when determining the most preferred environmentally sustainable methods. Integrating MCDM and LCA is critical for advancing sustainable cement production, as their combined method addresses both qualitative preferences and quantitative performance, thereby improving decision-making by providing a comprehensive evaluation of sustainability assessments in cement production [41,42]. The integration of LCA and MCDM methodologies provides a reliable and comprehensive assessment of sustainability in cement production, combining quantitative lifecycle analysis with adaptive multi-criteria decision support. LCA provides a detailed evaluation of the environmental impacts across all stages of the cement production process, thereby enabling the identification of impact hotspots and potential improvements [13].

MCDM methods have gained traction in production processes, providing robust frameworks for material selection, sustainability assessment, and performance optimization [42–47]. Different types of MCDM methods, including COPRAS, ARAS, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), multi-objective optimization based on ratio analysis (MOORA), analytic network process (ANP), multi-attribute utility analysis (MUA), data envelopment analysis (DEA), VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), elimination of choice translating reality (ELECTRA), etc., have become increasingly important in the cement industry to balance environmental and economic criteria with technical requirements, thereby providing reliable multi-criteria decision-making solutions. These methods incorporate various criteria in decision-making by integrating the views of different stakeholders through mathematical modeling to evaluate, rank and compare alternatives [48].

Meanwhile, the MCDM method is a flexible methodology that can change to evolving conditions or priorities over time [49,50]. MCDM considers multiple factors, such as environmental, economic, and social factors, to ensure sustainability assessment [51]. MCDM helps facilitators in decision-making by evaluating the trade-offs and synergies between multiple variables for sustainable material production [52]. LCA has been widely used as a tool to assess the environmental impacts of cement production and its alternatives, with a view to improving material use and reducing emissions [29]. Yang, Fan [53] performed the LCA and partial Life Cycle Costing comparing the environmental impacts of six grades of cement strength in China. Their study showed that higher-grade cement not only increased resource consumption and emission levels but also had a better economic outcome. The authors concluded that the environmental impacts and economic costs of the materials were mainly due to emissions from long-distance material transport. Pushkar and Verbitsky [54] used the LCA framework to evaluate five blended cement composites in Israel, including limestone powder, fly ash and ground granulated blast furnace slag (GGBFS). According to their study, the use of supplementary cementitious materials (SCMs) reduces the environmental impacts and economic costs compared to Portland cement, depending on how allocation methods are performed and which alternative is used.

In the literature, numerous studies have applied MCDM methods to optimize cement production processes. For instance, Gökcekuş, Ghaboun [55] evaluate several factors such as the homogeneity of the raw materials, amount of fuel consumed, amount of dust emitted, quality, CO_2 emissions produced and production costs of the cement using the Fuzzy Preference Ranking Organization Method for Enrichment Evaluation (F-PROMETHEE) method, highlighting the environmental impact and economic advantages of dry-process in the cement production. Similarly, Bathrinath, Nagesh [56] employed the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to analyze 18 key factors

that influence the CMI cement, highlighting the critical role of capital investment, quality control and equipment maintenance in cement production efficiency, suggesting awareness for industry optimization. Marinelli and Janardhanan [57] applied MCDM, the best-worst method (BWM), to provide insight into the necessity of implementation of energy-efficient and low-carbon practices to mitigate the environmental impact of cement production, particularly in high-production regions like India. Similarly, Hossain, Poon [58] applied the LCA model to assess the energy consumption and potential impacts of global warming on different cement types in Hong Kong. They proposed two eco-friendly approaches to mitigate these impacts and identified fossil fuel combustion and raw material transportation as major contributors to GHG emissions. Hossain, Poon [59] demonstrated the benefits of fly ash-based eco-blocks in reducing global warming potential. The results showed a 17–20% reduction in GHG emissions and a 26–32% reduction in energy use. These studies collectively emphasize the importance of region-specific approaches and the right materials to reduce the impact of cement on the environment.

Many MCDM methods, such as TOPSIS, EDAS, COPRAS, ARAS, and AHP, combined with LCA, have been explored in various cement production processes [3,42,60,61]. For instance, Akintayo, Babatunde [60] conducted a comparative analysis of ten cement production methods using LCA and MCDM techniques to evaluate and rank ten different methods of cement production, highlighting the environmental impacts across 18 impact categories. The study identifies GGBFS as the optimal alternative, with ranking scores of 0.9094 and 1.7228 for EDAS and TOPSIS methods, respectively. Kurda, de Brito [45] developed an MCDM model to evaluate cementitious materials, considering mechanical properties, environmental impact, and cost-effectiveness. Their approach highlighted the viability of non-traditional materials in reducing emissions without compromising durability. Similarly, Suárez Silgado, Calderón Valdiviezo [62] assessed recycled materials in concrete production in Catalonia, Spain, through the LCA-MCDM method, using LCA to assess environmental impacts and VIKOR to identify the best alternatives that balance economic and environmental benefits. Putra, Teh [3] used LCA-MCDM integration methods to determine the sustainability and rank three cement production plants in Western Indonesia. They evaluated the social, economic and environmental impacts using the LCA and AHP to identify the most sustainable plant. Arukala, Pancharathi [61] used TOPSIS to rank five different concretes made from traditional cement OPC, fly ash, metakaolin, GGBS and composite cement at a particular grade to select the best sustainable cementitious material. The results showed that fly ash-based concrete has emerged as the preferred alternative. Yoris-Nobile, Esther [42] compared low-clinker cement and geopolymer mortars for their application in 3D printing, focusing on their environmental impact, mechanical properties, and cost-effectiveness using the LCA-MCDM methodologies, LCA to evaluate the environmental impact and TOPSIS and WASPAS to select the most suitable dosages. They concluded that geopolymer mortars had a higher environmental impact primarily due to the use of sodium hydroxide. Low-clinker cement mortars ranked highest due to their lower environmental impact and material costs.

Sustainability decision-making often involves uncertainty and subjective judgments. Fuzzy multi-criteria decision-making (MCDM) methods address this challenge by incorporating fuzzy set theory into traditional MCDM, enabling the handling of vague criteria and linguistic assessments [63]. Fuzzy MCDM approaches, such as fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), fuzzy PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), and fuzzy AHP (Fuzzy Analytic Hierarchy Process), have gained grip in sustainability evaluations of cementitious materials due to their ability to model uncertainty and expert subjectivity. These methods offer robust decision-support tools under vague or imprecise conditions, particularly in com-

plex multi-criteria sustainability contexts involving environmental and technical trade-offs. These techniques allow experts to use terms like high or low for criteria importance or performance and have been widely employed in sustainability contexts, for example, in choosing sustainable suppliers and materials, because type-1 fuzzy sets effectively represent human subjectivity in multi-criteria frameworks [63]. Over the last decade, numerous fuzzy MCDM methods, such as fuzzy TOPSIS, fuzzy AHP, fuzzy PROMETHEE and advanced fuzzy extensions (interval type-2 fuzzy sets, intuitionistic fuzzy sets, etc.) have been applied to improve decision-making in the cement sector and broader sustainable engineering problems [64–67]. In the cement industry, fuzzy MCDM methods are utilized to evaluate materials, processes, and strategies against sustainability criteria. This method has guided the selection and ranking of alternative cementitious materials [64], optimized maintenance and production strategies to balance economic and environmental goals [65] and in building materials selection [66].

For instance, Falqi, Ahmed [64] used a fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) based framework to rank alternative cement and sustainable concrete siliceous materials, such as nano-cement, fly ash, slag and recycled aggregate by evaluating their contribution to sustainability across multiple criteria based on environmental and technical performance. Such a fuzzy TOPSIS method identifies the material closest to the ideal sustainable solution while farthest from the worst solution, helping decision-makers select optimal cementitious materials under uncertainty. Ighravwe and Oke [65] used fuzzy entropy weight and Fuzzy PROMETHEE to optimize and rank maintenance sustainability strategies in a cement plant. They compared the results with a fuzzy TOPSIS method. The fuzzy PROMETHEE analysis helped highlight differences in maintenance decisions under various criteria, illustrating its value for improving sustainability in cement plant operations and its recommendations aligned closely with a parallel fuzzy TOPSIS analysis. Reddy, Murthy [66] applied fuzzy AHP as an MCDM method to select building materials in Hanamkonda, India, considering criteria such as quality, cost, and location-specific availability, and ranked alternatives like cement, bricks, and tiles based on client preferences and project location. The study identified Portland pozzolana cement as the most suitable cement type under sustainable considerations. Similarly, interval type-2 fuzzy sets, which provide a higher-order fuzzy modeling of uncertainty, have been introduced in cement-sector decisions. Çebi and Otay [67] developed a fuzzy TOPSIS method with interval type-2 fuzzy sets to select a cement factory location, addressing the high uncertainty in site selection factors. Their approach identified the best factory site by handling ambiguous expert judgments more flexibly than standard fuzzy (type-1) methods.

Beyond cement, fuzzy MCDM assists sustainable engineering decisions such as project selection, clean technology prioritization, and green supplier evaluation under uncertainty [68,69]. Roy, Das [70] extended the CODAS decision method with interval-valued intuitionistic fuzzy sets to handle incomplete information in material selection problems. Their framework was demonstrated for selecting sustainable automotive parts and optimal bricks for an eco-friendly building project. The intuitionistic fuzzy approach, considering both membership and non-membership degrees, improved reliability in assessing social, environmental, and economic criteria, and a sensitivity analysis showed the stability of the fuzzy rankings. Lolli, Ishizaka [71] combined a new group fuzzy PROMETHEE and traditional environmental criteria of life cycle assessments with social and economic criteria to evaluate alternative waste treatment solutions against sustainability criteria in municipal waste management. By involving multiple decision-makers and fuzzy preference modeling, the approach identified the best waste treatment option considering environmental, economic, and social impacts. Similarly, Hendiani and Walther [63] introduced a novel fuzzy MCDM in the sustainability performance evaluation of supply chain decisions by

using interval-valued intuitionistic fuzzy (IVIF) information. Studies consistently find that combining fuzzy logic with MCDM techniques yields more realistic and inclusive evaluations of sustainability criteria. In this study, we employ LCA and MCDM to select and rank seven different cement types in South Africa based on environmental impacts.

3. Methodology

This study employs an integrated methodological framework combining LCA and MCDM to evaluate sustainability. Merging this framework allows the environmental assessments of the LCA into the structured decision-making capabilities of the MCDM method. LCA quantifies environmental impacts across the entire product lifecycle, from raw material extraction to end-of-life disposal or recycling [72,73]. MCDM facilitates the assessment of multiple criteria, enabling decision-makers to compare environmental impacts alongside economic and social factors [49]. Combining LCA data with the COPRAS-ARAS (MCDM) framework, stakeholders can make informed choices. COPRAS weighs beneficial and non-beneficial criteria [74–76]. ARAS ranks alternatives using weighted ratios. These methods balance cost, emissions, and performance [77].

3.1. Integrating LCA into COPRAS-ARAS MCDM for Cement Types Assessment

This study evaluates seven South African cement types using LCA and MCDM. LCA quantifies environmental impacts, while MCDM (COPRAS and ARAS) ranks alternatives using criteria from LCA. The entropy method determines criteria weights to reduce subjectivity. COPRAS-ARAS is applied to LCA midpoint categories to rank cement types by environmental impact, as illustrated in Figure 1. The study presents an evidence-based LCA-MCDM method to identify sustainable cement alternatives, enhance analytical rigor, and support transparent, balanced, long-term decision-making.

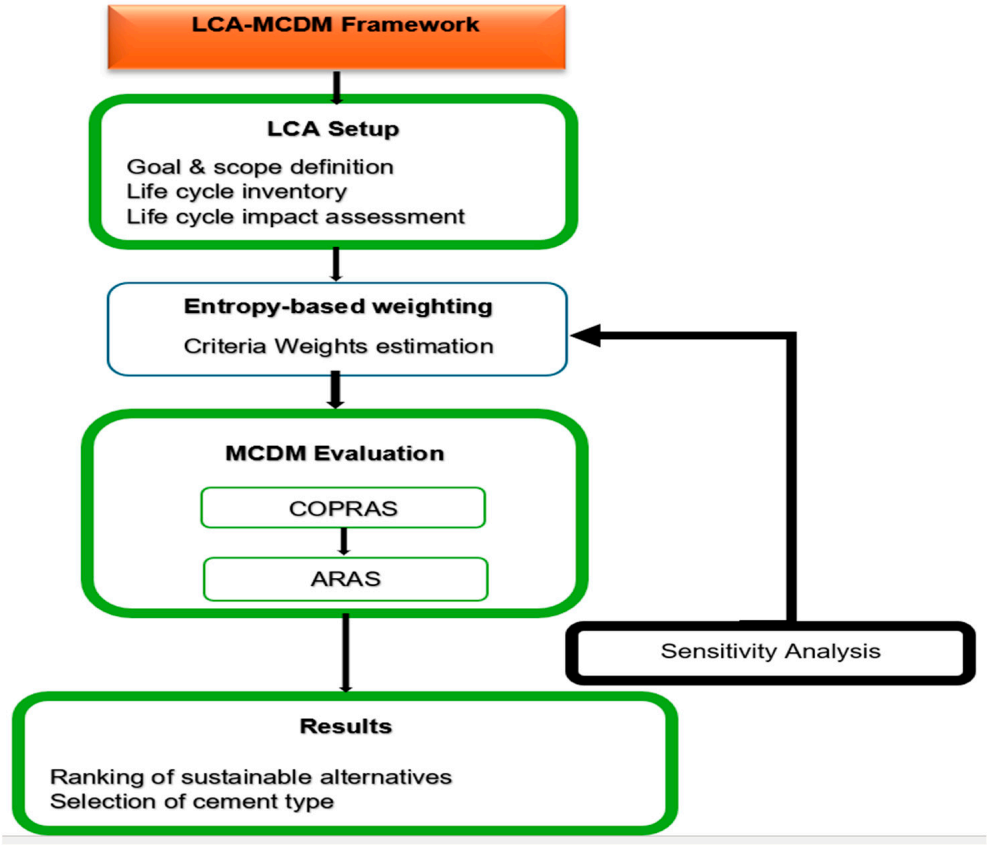


Figure 1. LCA-MCDM framework for sustainability assessment of cement production.

3.2. Life Cycle Assessment

LCA is a standardized methodology for evaluating the environmental, economic, and social impacts of products across their entire lifespan ("cradle-to-grave") [72]. The International Organization for Standardization ISO governs LCA guidelines ISO 14044 [78] and aggregates input-output data to inform decision-making, especially in cement production. Analyzing LCA data is complex due to exchanges between impact categories, making decision-making difficult. Experts may combine weighted results into one score or prioritize critical impacts. Using methods like ReCiPe 2016 (H) midpoint, LCA aligns with ISO standards and assesses environmental impacts. It includes four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation [78,79].

3.2.1. Goal and Scope Definition

The first stage of the LCA involves stating the purpose of the study, its application, and methodology. In cement production, it defines the objective, assessing the environmental impacts of different processes. This study uses a cradle-to-gate LCA to evaluate seven cement types, using 1 kg of cement as the functional unit, enabling comparisons of cement types for sustainability assessments. System boundaries include raw material, clinker production, fuel, electricity, and transportation, as illustrated in Figure 1. Impacts are assessed at each stage to identify sustainable alternatives. This ensures transparency and enables comparison between production routes. The specific details of each process may vary depending on the plant and the type of cement being produced.

Raw material stage: This involves activities such as mining and preparing materials like limestone, clay, gypsum, slag, and fly ash, which are essential components in cement production.

Clinker production stage: This is the high-temperature process where raw materials are chemically transformed into clinkers. This stage was modeled using dry kiln processes with preheater/precalciner systems.

Fuel usage stage: This includes thermal energy provided by the combustion of fossil fuels (e.g., coal, petcoke) in the kiln during clinker production, contributing significantly to greenhouse gas emissions.

Electricity usage stage: This includes electrical energy consumed during all processing stages, including grinding, heating, material handling and other auxiliary plant processes. Electricity consumption was modeled using the South African grid mix, which is primarily coal-based. Kiln systems were modeled as dry-process kilns with preheater and precalciner units to reflect industry-standard technology.

Transportation stage: The system includes the transport of raw materials and fuels to the cement plant. Average haul distances for South African cement operations are estimated at 60–100 km for raw materials and 100–150 km for fuel sources. Transport was modeled using diesel-powered trucks (Euro V standard), as documented in Ecoinvent.

3.2.2. Inventory Analysis

The second stage, Life Cycle Inventory (LCI), involves collecting and quantifying data on inputs (materials, energy) and outputs (emissions, waste) within system boundaries. In cement production, inputs include limestone, clay, gypsum, fly ash, and slag, along with their extraction and transport. Energy inputs include electricity and thermal energy from coal, natural gas, and alternative fuels. Emissions such as CO_2, NO_x, SO_2, and particulate matter are recorded, as is water use. Due to the unavailability of site-specific industrial data, this study utilized secondary datasets from Ecoinvent v3.8 within SimaPro 9.2.0.1 software. The LCI data in Table S9 is used to model the environmental impacts of the seven cement types. Ecoinvent offers regionally representative and internationally standardized

life cycle inventory data for cement production processes. Also, it provides geographically relevant and process-specific data, making it suitable for assessing cement production scenarios in South Africa. The study also used data from published literature and South African industry reports to supplement process parameters when needed. This database was selected due to its extensive, validated, and geographically adaptable datasets suitable for cement processes and associated upstream activities.

3.2.3. Impact Assessment

In the third stage, the environmental impacts, was characterized using the ReCiPe 2016 Midpoint (H) method, which is widely accepted for midpoint-level assessments and aligned with ISO 14044 standards to quantifies 18 midpoint impact categories such as Global Warming Potential (GWP), Acidification Potential (AP), Fossil Resource Scarcity, Freshwater Ecotoxicity, Human Toxicity (carcinogenic and non-carcinogenic), and Water Consumption. The GWP is a primary concern due to significant carbon dioxide emissions generated during clinker production, while AP arises from the release of NO_x and SO_2 into the atmosphere. This model was selected due to its robust coverage of midpoint categories and alignment with international LCA standards. This stage is essential for identifying environmental hotspots and understanding the broader implications of each production method. This approach effectively categorizes impact indicators, providing a detailed understanding of the environmental impact of cement production.

3.2.4. Interpretation

The final stage of the LCA methodology is interpretation. This phase involves analyzing and validating the results from the inventory and impact assessment stages to ensure consistency and relevance. In cement production, interpretation facilitates the identification of the most environmentally impactful stages and processes, enabling stakeholders to draw informed conclusions. It allows comparisons of the different production scenarios and provides evidence-based recommendations for process improvements. The conclusions drawn must align with the original goal and scope of the study and be clearly documented for stakeholders and decision-makers.

3.3. Multi-Criteria Decision-Making (MCDM)

The MCDM is a structured method for evaluating and ranking multiple alternatives by balancing quantitative and qualitative criteria [80,81]. It addresses complex decision-making by offering a logical framework to reconcile priorities and improve accountability. The MCDM problem is represented as a decision matrix (Equation (1)), where alternatives are assessed using normalized criteria values and weights. COPRAS and ARAS methods are used for their simplicity and adaptability, while other techniques like AHP, TOPSIS, and VIKOR offer advantages depending on complexity and data availability [82–84].

In this study, the entropy method is used to determine criterion weights, reducing subjectivity by quantifying uncertainty in datasets. These weights are integrated with COPRAS-ARAS to compute priority scores for seven cement-type alternatives in South Africa. This combined approach ensures transparency, supports informed policy-making, and provides a comprehensive view of sustainability, balancing favorable and unfavorable attributes in selecting optimal alternatives.

3.3.1. Entropy Method

The entropy-based objective weighting method relies on unbiased data, addressing the limitations of subjective weighting methods [85]. It quantifies the amount of valid information in the data [86], using a step-by-step procedure to determine the weight of

each criterion based on its information content. The following steps are the fundamental procedure of the Entropy objective weighting method.

Step 1: Normalization of the array decision matrix

The normalization of the array decision matrix (performance indices) to obtain the project outcomes P_{lj}, using Equation (1).

$$P_{lj} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (1)$$

where P_{lj}, represents the normalized value of the data of the **array** decision matrix. The value of x_{ij} is the performance value of the i^{th} alternative with respect to the j^{th} criterion.

Step 2: Computation of the normalization of entropy values

Computation of the **normalization** of entropy values of project outcomes using Equation (2)

$$E_j = -\mathbf{k}\sum_{i=1}^{m} P_{ij}\, \mathbf{1}n\, {}_{P_{ij}} \quad (2)$$

where $\mathbf{K} = \mathbf{1}/\mathbf{1}n(m)$.

n, represents number of criteria and m number of alternatives.

Step 3: Calculation of the Entropy objective weight

Calculating the entropy objective weight w_j, based on the entropy concept using Equation (3).

$$w_j = \frac{1 - \mathbf{E}_j}{\sum_{j=1}^{n}(1 - E_j)} \quad (3)$$

where $\sum_{j=1}^{n} w_j = \mathbf{1}$, w_j represents normalized weight for criterion j.

3.3.2. Preference Ranking

This paper employs two MCDM methodologies, COPRAS and ARAS, to develop a unified index for ranking and selecting the most suitable alternatives for their robustness in handling heterogeneous data and transparency in ranking.

Complex Proportional Assessment (COPRAS) Method

The COPRAS method is a widely used MCDM that evaluates alternatives by considering the proportional influence of beneficial and non-beneficial criteria [75,87]. It begins with constructing a decision matrix, normalizing data, assigning criteria weights, and computing utility scores to rank alternatives [74,88–90]. COPRAS distinguishes between maximizing and minimizing criteria, offering direct rankings based on positive and negative attribute sums [91]. It is a well-established method for ranking alternatives based on multiple, often conflicting, criteria [74]. By incorporating both beneficial and non-beneficial criteria with relevant weights, COPRAS supports more informed and transparent decisions [88,89]. This study uses COPRAS to rank seven cement-type alternatives in South Africa based on quantitative and qualitative criteria [92]. The application of COPRAS in this context involves the following methodological steps:

Step 1: Development of the initial Decision Matrix.

The decision matrix (Equation (4)) is a matrix table that outlines the assessment criteria for each alternative within the decision-making process. This matrix incorporates both qualitative and quantitative values, offering a comprehensive summary of each alternative's attributes and thereby streamlining informed decision-making. For each alternative i and criterion j, the normalized decision value is given by (Equation (4)).

$$x = [x_{ij}]_{mxn} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (4)$$

for i = 1, 2, . . ., m, j= 1, 2, . . ., n.

Where value x_{ij} is the performance value of the i^{th} alternative with respect to the j^{th} criterion, m is the number of alternatives and n is the number of criteria [87].

Step 2: Normalization of the decision matrix.

Criteria values are normalized to eliminate unit disparities (Equation (5)). It standardizes all evaluation criteria to a common scale, ensuring each criterion is given equal weight and consideration during assessment. Since criteria may have different units, normalization facilitates comparison and evaluation. The decision matrix is carried out using Equation (5).

$$R = [r_{ij}]_{mxn} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (5)$$

r_{ij} is the normalized score for alternative i and criterion j.

Step 3: Calculate the weighted normalized decision matrix.

Each normalized decision matrix value is multiplied by the corresponding weight of the criterion (obtained in the Entropy method) in Equation (6). The decision-maker determines the weights and reflects the relative importance of each criterion.

$$\begin{gathered} D = [y_{ij}]_{mxn} = r_{ij} \times w_j \\ i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n \end{gathered} \quad (6)$$

where y_{ij} is the weighted normalized score

Step 4: Weighted sum of the normalized decision matrix

This step identifies the beneficial S_{+i} and non-beneficial S_{-i} criteria of each alternative by summing them across all criteria. The calculation of these criteria is performed using Equations (7) and (8).

$$\text{Beneficial criteria } S_{+i} \sum_{j=1}^{n} y_{+ij} \quad (7)$$

$$\text{Non-beneficial criteria } S_{-i} \sum_{j=1}^{n} y_{-ij} \quad (8)$$

where S_{+i} is the sum of weighted beneficial criteria for alternative i and S_{-i}.

Represents the sum of weighted non-beneficial criteria for alternative i.

Step 5: Determining the relative weight of each alternative.

The step determined the relative importance (Q_i) of each alternative by evaluating its beneficial and non-beneficial criteria through Equation (9). The higher Q_i value indicates a higher priority or rank for the alternative [87,88]. Alternatives are ranked based on their overall scores.

$$Q_i = S_{+i} + \frac{S_{-min} \sum_{i=1}^{m} S_{-i}}{S_{-i} \sum_{i=1}^{m} (S_{-min} / S_{-i})} (i = 1, 2, \dots, m) \quad (9)$$

where S_{-min} is the smallest value of S_{-i} among **all alternatives** and (Q_i) is calculated using Equation (9) [39,93].

Step 6: Ranking the alternatives

This step ranks the alternatives in descending order of their relative significance based on their calculated utility degree [74]. The relative significance (Q_i) and utility degree U_i for each alternative, which establishes their priority hierarchy, are determined using Equation (10).

$$U_i = \left\lfloor \frac{Q_i}{Q_{max}} \right\rfloor \times 100\% \quad (10)$$

A higher utility degree U_i indicates a more favorable alternative.

Additive Ratio Assessment Method (ARAS)

ARAS evaluates alternatives by comparing their weighted normalized values to the ideal (optimal) solution using weighted ratios [77]. It uses a linear additive model to calculate the optimality score for each alternative. The normalized criterion values are weighted and summed, with the higher scores thereby indicating excellent performance. The ARAS method is particularly effective for multi-criteria problems with maximum and minimum objectives [94]. The ARAS method can be utilized to solve MCDM problems [77,95] in the following steps:

Step 1: The initial decision matrix development.

Include an ideal (optimal) alternative $i = 0$ with the best performance values. For all alternatives i (including the ideal) and each criterion j, the decision matrix is defined by x_{ij}.

$$x = \begin{bmatrix} x_{01} & \dots & x_{0j} & \dots & x_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \dots & x_{ij} & \dots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \dots & x_{mj} & \dots & x_{mn} \end{bmatrix}; \; i = \overline{0, m}; \; j = \overline{1, n} \quad (11)$$

where m represents the number of alternatives and n is the number of criteria, x_{ij} is the value representing i performance value alternative in terms of the j criterion, x_{01} represents the best value of j the criterion.

Step 2: Calculation of a normalized decision matrix

$$\textbf{Beneficial criteria } \overline{x_{ij}} = \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}} \quad (12)$$

$$\textbf{Non-beneficial criteria } x_{ij} = \frac{1}{x_{ij}^*}; \; \overline{x_{ij}} = \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}} \quad (13)$$

x_{ij}^* represents the normalized and weighted performance **value** of alternative i with respect to criterion j.

Step 3: Calculation of weighted normalized decision matrix.

$$\hat{x}_{ij} = \overline{x_{ij}} w_j \quad (14)$$

where w_j, represent the weight of the j criterion and $\overline{x_{ij}}$, represent the normalized rating of the j criterion.

Step 4: S_i-Optimality function for i alternative

$$S_i = \sum_{j=1}^{n} \hat{x}_{ij}; \; i = \overline{0, m}, \quad (15)$$

where S_i, represent the value of the optimality function of the i alternative. There is a need to differentiate between the sum of the beneficial and non-beneficial criteria.

Step 5: Calculation of the utility degree for each alternative

$$K_i = \frac{S_i}{S_0} \quad (16)$$

where S_0 is the optimality function value of the ideal alternative. Higher K_i indicates better performance.

In this study, the MCDM problem is formulated using Equation (1), where the criteria and their respective weights are determined using the Entropy method to assess their relative significance in cement-type sustainability. These weighted criteria are integrated with the COPRAS and ARAS methods to calculate the overall priority score and identify the most sustainable cement alternative.

3.3.3. Sensitivity Analysis

The sensitivity analysis process and equations applied in your MCDM study using ARAS and COPRAS, particularly with entropy-weighted criteria:

Step 1: Original Weighted Score Calculation

The weighted performance score S_i for each alternative i is calculated using the original normalized decision matrix x_{ij} and entropy-derived weights w_j:

$$S_i = \sum_{j=1}^{n} x_{ij} \times w_j \tag{17}$$

where x_{ij} is the normalized performance of alternative i under criterion j, w_j is weight of criterion j (from entropy method) and n is number of criteria.

Step 2: Perturbation of Weights

Each weight w_j is adjusted by a perturbation factor α (e.g., ±25%, ±50%, ±75%):

$$w_j^{(\propto)} = w_j \times \propto \tag{18}$$

where $w_j^{(\propto)}$ represents the perturbed weight of criterion j after applying a shift factor α.

Step 3: Normalization of Perturbed Weights

This ensures that the weights remain proportional and valid in the MCDM model. After perturbation, the new weights are normalized so that:

$$\sum_{\mathbf{j=1}}^{\mathbf{n}} \mathbf{w_j^{(\propto)}} = \mathbf{1} \tag{19}$$

$$w_j^{(normalized)} = \frac{\mathbf{w_j^{(\propto)}}}{\sum_{j=1}^{n} \mathbf{w_j^{(\propto)}}} \tag{20}$$

$w_j^{(normalized)}$ is the normalized weight after applying the perturbation. The perturbed weights must be normalized so they sum to 1.

Step 4: Recalculation of Weighted Scores

The new weighted performance score for each alternative under the perturbed weight scenario is:

$$S_i^{(\propto)} = \sum_{j=1}^{n} x_{ij} \times w_j^{(normalized)} \tag{21}$$

This value represents how well alternative i performs under the specific perturbation scenario.

Step 5: Conversion to Utility Percentage

The utility degree K_i of each alternative is calculated by dividing its score by the maximum score among all alternatives:

$$K_i = \left(\frac{S_i}{S_{max}} \right) \times \mathbf{100} \tag{22}$$

where S_{max} **is** $max(S_i)$.

This expresses each alternative's performance as a percentage of the best-performing alternative.

Step 6: Ranking of Alternatives

Alternatives are ranked in **descending order** based on their utility values K_i. The highest K_i receives Rank 1, indicating the most preferred alternative.

3.4. Justification of MCDM Method Selection

In sustainability assessments, integrating LCA with MCDM yields more balanced decisions by accounting for trade-offs among multiple environmental impacts [47]. This study employs an entropy-weighted MCDM approach with COPRAS and ARAS to rank different sustainable cement-type alternatives in South Africa while minimizing subjective biases. This selection is grounded in the methods' robustness, transparency, and their proven applicability to environmental decision-making problems involving conflicting criteria and large quantitative datasets. Also, their effectiveness in handling both beneficial and non-beneficial criteria, which is critical in sustainability assessment and a common characteristic of the life cycle midpoint impact categories. Entropy weighting is employed as an objective weighting method to reduce human subjectivity. It derives weights directly from the data variability across alternatives, making it particularly appropriate for LCA-based criteria where expert-driven subjective weights could introduce inconsistency or bias [85,96]. This approach reduces **subjective bias** compared to expert-based methods like AHP, which can be inconsistent when applied to environmental impact criteria derived from normalized LCA values. Also, this impartial weighting is valuable in environmental evaluations, where stakeholder opinions might skew outcomes and has been applied in sustainability ranking studies to reflect unbiased indicator significance [97]. For instance, an entropy COPRAS model was used to compare EU countries' sustainable development performance [97], demonstrating this approach's practical relevance.

The selection of the COPRAS and ARAS is for their effectiveness and transparency in sustainability evaluations. COPRAS computes a utility value for each alternative and ranks alternatives by simultaneously considering maximizing (beneficial) and minimizing (non-beneficial) criteria, enabling direct comparisons of relative sustainability [74,75]. It provides a direct proportional ranking based on performance utilities, offering interpretability and efficiency in computation. The ARAS method uses a **basic approach** where all criteria contribute additively and are weighted to produce the final performance score [77]. It aligns well with the nature of LCA outputs, which are cumulative impact scores. Both methods have been successfully employed in environmental and construction material decision-making contexts [98,99] and directly aggregate weighted criteria without reliance on an arbitrary ideal or compromise factor, potentially reducing method bias. Hezer, Gelmez [100] concluded in their study that the COPRAS method obtained the most compatible and closest results to the results of the Deep Knowledge Group report compared to the TOPSIS and VIKOR methods.

Methods like TOPSIS and VIKOR are widely used in MCDM studies, and they are more sensitive to the ideal/anti-ideal solution assumptions and normalization effects. TOPSIS focuses on geometric and rank alternatives by distances to an ideal solution, but can exhibit rank reversal if alternatives change, which can influence LCA data. VIKOR introduces a compromise ranking based on group utility and regret, which may not align with additive LCA impacts without additional scaling adjustments that affect the result [101]. Nonetheless, each MCDM technique has its assumptions and limitations, and comparative analyses note that every method has distinct strengths and weaknesses in sustainability assessments [101,102]. Recognizing these differences, this study acknowledges that rankings could change under different methods or weighting schemes. Comparative studies

often find largely consistent results across methods like TOPSIS and COPRAS, with only minor deviations, yet specific methods, such as VIKOR or COPRAS, have shown high sensitivity to input variations that might alter the rank order [101]. To address the concern regarding methodological bias, the study employed a sensitivity analysis, applying a range of perturbations (±25%, ±50%, and ±75%) to the entropy weights to validate the robustness of our ranking. The rankings across both COPRAS and ARAS remained largely stable, consistently identifying the most sustainable cement alternative. By varying criteria weights and even comparing alternative MCDM approaches, we ensure the top cement option remains optimal under plausible uncertainty. This consistency provides strong evidence of methodological robustness and low bias.

4. Results and Discussions

This section draws the results of the analyses of the LCA mid-point characterization, criteria weighting and MCDM method of cement production. This study integrates environmental impact data into MCDM to evaluate and rank different cement-type alternatives in the South African cement industry. The selection of criteria within the MCDM framework was a detailed process associated with the environmental impacts of seven different cement types. The choice was based on production volume, commercial availability, and relevance in the South African construction market. These types, ranging from traditional Portland cement (CEM I) to blended and pozzolanic alternatives (CEM II, CEM III), reflect the most commonly produced and used formulations across the country. The selection also considered diversity in clinker content and SCMs to enable a comparative sustainability assessment. This ensures that the results are representative, practical, and aligned with industry practices and decarbonization goals. The chosen criteria align with sustainability objectives and effectively represent the cement life cycle from cradle to gate. These criteria were impact indicators from the LCA process. Comprehensive LCA results for seven cement types produced in South Africa are summarized in Table S1.

4.1. Results of LCA

As shown in Supplementary Table S1, CEM I (Traditional Portland Cement) exhibited the highest GWP, with emissions reaching 0.99 kg CO_2 eq of cement. CEM II/B-L followed this at 0.86 kg CO_2 eq. CEM III/A recorded the lowest emissions in GWP (0.57 kg CO_2 eq) and fossil resource depletion (0.09 kg oil eq), indicating a significantly reduced carbon footprint compared to Portland Cement, attributable to its high slag content. Despite its lower GWP and fossil resource depletion, CEM III/A showed comparatively higher values in other categories, such as terrestrial ecotoxicity (1.31 kg 1,4-DCB eq), human non-carcinogenic toxicity (0.63 kg 1,4-DCB eq), and freshwater ecotoxicity (0.03 kg 1,4-DCB eq). Similarly, an increase in limestone content in CEM II/B-L contributed to reductions in specific environmental impact. Fly ash-based cement, including CEM II/B-V and CEM II/A-V, showed significant improvements in global warming potential, toxicity (Human carcinogenic and Human non-carcinogenic) and fossil resources.

However, these high toxicity indicators suggest trade-offs that must be considered when evaluating environmental performance holistically. The LCA offers a data-driven evaluation of the environmental benefits associated with cement alternatives incorporating high proportions of industrial by-products, namely slag, fly ash, and limestone, when compared to traditional Portland Cement. The analysis reveals that GGBFS-based cement emerged as the most environmentally preferable option. It exhibited the lowest impact across multiple categories, including GWP, Stratospheric ozone depletion, human toxicity indicators, fossil resource use, and water usage, underscoring its potential as a low-impact, circular economy-aligned solution. These results substantiate the strategic advantage of

substituting clinker-intensive formulations with SCMs. Specifically, the use of GGBFS emerges as an effective decarbonization pathway within the cement sector. The evidence supports the accelerated transition towards low-impact binder systems as a critical lever for advancing environmental sustainability in construction materials. The LCIA results were further integrated into the MCDM framework using the COPRAS and ARAS methods to rank and determine the most sustainable cement alternative. Tables S2–S8 present a detailed analysis of the MCDM results.

4.2. Weight of Criteria

The entropy method assigns weights to study prioritized weight determination based on the characteristics of the available data (diversity and variance) to determine the preferred cement-type alternatives in South Africa. The highest prioritized weighted criterion is Mineral Resource Scarcity, with an entropy weight of 64.83% as shown in Figure 2, indicating that material efficiency is the most vital factor in selecting an environmentally preferred cement type. This dominant weight reflects both the high variability and regional relevance of raw material extraction impacts in South Africa. Cement production in the country relies heavily on the mining of limestone, shale, gypsum, and other finite environmental inputs. The significant entropy weight assigned to Mineral Resource Scarcity indicates that this criterion strongly differentiates among cement alternatives, particularly between high-clinker Portland cements and blended formulations that use slag or fly ash, highlighting the importance of minimizing raw material depletion and promoting circular practices.

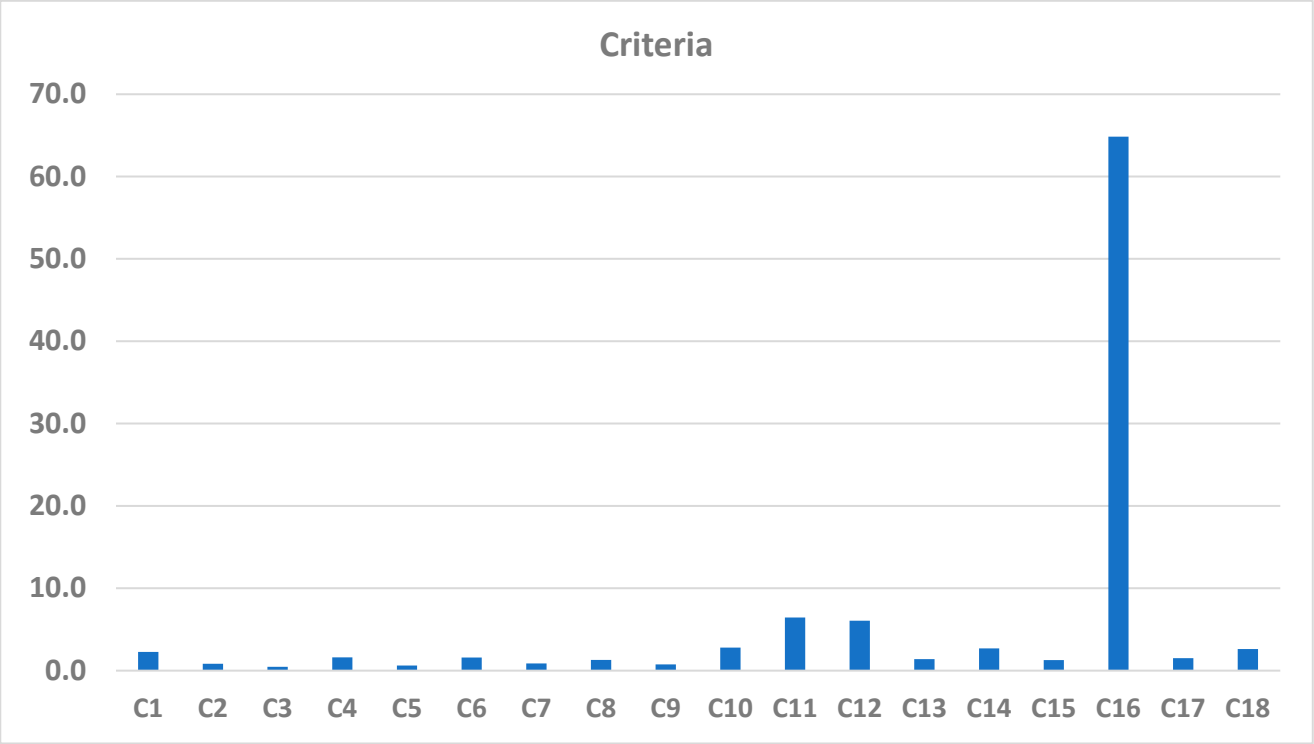


Figure 2. Weight of criteria.

The prioritized criteria, such as freshwater ecotoxicity (6.44%) and land use (1.29%), reflect growing environmental concerns about aquatic contamination and biodiversity loss in cement-intensive regions. Fly ash, slag, and other industrial by-products used as SCMs may introduce trace metals and organic pollutants during the production and disposal stages. These emissions can threaten freshwater ecosystems, explaining their increased weight when variation exists across alternatives. Similarly, land use impacts are driven

by raw material quarrying, habitat disturbance and occupation due to mining, storage, and plant operations, impacts that are highly variable across alternatives and critical in the South African context, where quarry sites often overlap with vulnerable ecosystems.

Interestingly, traditional global-impact categories such as GWP (2.27%), Fossil Resource Scarcity (1.51%), and Water Consumption (2.63%) received relatively low prioritized weights. This is not due to their unimportance but rather their limited variability across cement types in the dataset. For example, most cement alternatives showed similar carbon intensities due to the consistent use of similar fuels and SCM blends, resulting in high entropy values and thus low normalized weights. While cement production contributes nearly 8% of global CO_2 emissions [103], this suggests that the compared methods may have similar GHG profiles. Nonetheless, reducing emissions through fuel switching, carbon capture, and energy efficiency remains essential for long-term climate targets [104]. Studies have shown that water consumption in cement production can range from 0.14 to 1.28 L/kg of cement [105].

Mid-ranked prioritized criteria such as Human Non-Carcinogenic Toxicity (2.71%) and Terrestrial Ecotoxicity (2.79%) reflect the importance of pollutant emissions (e.g., NO_x, SO_2, heavy metals) and their varying presence in different cement compositions [106]. These emissions pose occupational and community health risks, mainly when low-quality fuels or secondary materials are used. The entropy weighting outcomes in this study emphasize localized, variable-impact categories over globally prominent but homogeneous ones. While global warming remains critical in sustainability agendas, its consistent profile across alternatives reduces its statistical influence in entropy-based MCDM. Decision-makers are thus encouraged to combine these objective weights with expert judgment or policy relevance to balance local variability with broader environmental priorities.

4.3. Result of MCDM Analysis

Table S2 presents the LCA results for the evaluated cement-type alternatives alongside the corresponding criteria weights using the entropy method. As detailed in Table S2, the entropy criteria weights show 18 clear environmental and human health impact categories, with weights reflecting their relative significance in sustainability decision-making. With a high weight of 64.83%, Mineral Resource Scarcity emerges as by far the most influential criterion. This result indicates that differences in raw material consumption among the compared cement production methods dominate the decision. Optimizing raw material usage, particularly the reduction of limestone in clinker production, is paramount. Emphasis should be placed on SCMs to reduce dependence on non-renewable mineral resources. South African cement strategies must aim to enhance circular economy practices through resource-efficient production models. Freshwater ecotoxicity (6.44%) is attributable to the potential release of chemical emissions, heavy metals and other hazardous pollutants during the production process. Cement production can release toxic substances into water bodies, primarily through kiln dust and leachate containing heavy metals. In fact, cement plants are known to release effluents that deteriorate water quality and cause toxins to accumulate in an aquatic ecosystem.

Land Use is another emphasized criterion, though its weight is only about 1.29%. However, land use is an essential context for sustainability because cement production in South Africa relies on large limestone quarries. Given the important water resource depletion and potential pollution from wastewater linked to cement production, water consumption prioritization at 2.63%, highlighting its critical role in selecting the most sustainable cement-type alternatives in cement production. Wastewater generated during cement production can contain heavy metals, chemicals, and other pollutants, which can contaminate water sources if not appropriately treated. Fossil resource scarcity holds

moderate significance at 1.51%. This supports the gradual replacement of coal with alternative fuels such as biomass, RDF, or industrial by-products. Though process constraints exist, fuel switching presents a viable pathway to reduce fossil dependency and associated impacts. GWP, surprisingly, with a weight of 2.27%, is less prioritized compared to mineral resource use. Although CO_2 emissions are a known cement challenge, this outcome reflects the relative impact in the dataset. Nonetheless, strategies like low-carbon binders, energy efficiency, and carbon capture remain central to decarbonization. The remaining criteria have comparatively lower weights. While important, their marginal contributions suggest that immediate sustainability efforts should focus on material resource efficiency, toxicity reduction, and ecological preservation.

In addition to the weighted criteria, Table S3 presents the normalized decision metrics for each cement-type alternative across all 18 impact categories. These normalized values represent the relative performance of each alternative for each impact category. The normalized matrix was multiplied by the respective weights, resulting in the weighted normalized decision matrix shown in Table S4 by integrating both the magnitude of each impact and the relative importance of the corresponding criterion using the COPRAS method, focusing on the environmental impacts of various cement-type alternatives. Data Normalization Standardize the LCA data for each impact category across all cement alternatives to ensure comparability. In this paper, the impact categories serve as the decision criteria, while the different cement types represent the alternatives. The analysis ranks alternatives for cement types based on 18 midpoint impact categories from the LCA. This matrix captures both the magnitude of each impact and the relative significance of the corresponding criterion, with factors such as water consumption, fresh ecotoxicity and land use receiving higher emphasis. Table 1 presents the most and least preferred for each criterion.

Table 1. Results of the MCDM method.

Cement Types	ARAS			COPRAS		
	Si	Ki	Rank	Qi	Ui	Rank
CEM I	0.1588	0.5266	4	0.17	74.27	4
CEM II/A-S	0.0720	0.2389	5	0.08	35.40	5
CEM II/A-V	0.1936	0.6421	2	0.21	89.06	2
CEM II/B-S	0.0642	0.2130	6	0.07	29.37	6
CEM II/B-L	0.1827	0.6061	3	0.19	84.19	3
CEM II/B-V	0.2188	0.7257	1	0.23	100.00	1
CEM III/A	0.0584	0.1937	7	0.05	22.06	7

The most preferred corresponds to the highest weighted normalized value (highest utility degree of environmental impact), while the least preferred is represented by the lowest value (lowest utility scores). These two reference points establish the bounds for evaluating the relative positioning of each cement-type alternative. In terms of environmental impact, the criteria were weighted equally to contribute to an equitable assessment of the cement-type alternatives. The application of COPRAS and ARAS methodologies in this study highlights the importance of COPRAS-ARAS MCDM methodologies for evaluating different cement-type alternatives. Both methods identified CEM II/B-V as the most preferred cement type alternative, achieving the highest utility degree of 100 (COPRAS) and the highest utility score of 0.7257 (ARAS), therefore highlighting the potential of fly ash-based cement. This superior ranking is attributed to the technical composition of CEM II/B-V, particularly its high fly ash content and lower clinker ratio, which significantly

reduce energy consumption and CO_2 emissions. These features contribute to its strong environmental performance across multiple impact categories, enhancing its sustainability compared to other alternatives.

Although CEM III/A cement demonstrated the highest potential for CO_2 emission reduction, it was ranked as the least preferred alternative, with the lowest utility scores of 22.06 (COPRAS) and 0.1937 (ARAS), indicating comparatively higher environmental impacts. These results highlight the critical role of LCA-MCDM integration in balancing environmental impact and identifying the best cement type. Despite the use of different mathematical formulations in COPRAS and ARAS, both methods merge as the top-ranked method for ranking cement-type alternatives, which demonstrated strong agreement in their rankings, supporting the strength and reliability of the selected alternatives. Also, the identification of the same preferred alternatives by both methods provides essential validation of the results across the two MCDM approaches.

4.4. LCA Characterization Results at the Midpoint Method

This section presents a comprehensive analysis of the midpoint characterization results of the most preferred cement type (CEM II/B-V) and the least preferred cement type (CEM III/A). The study was conducted using SimaPro 9.2.0.1, a widely recognized LCA software, in accordance with the ReCiPe 2016 Midpoint (H) method. The data inputs from the Ecoinvent v3.8 established LCI databases were used to model and reflect cement production conditions relevant to the South African context. Figure 3 illustrates the midpoint characterization results for CEM II/B-V cement, the most preferred cement type alternative in this study. The analysis highlights stage-specific contributions to environmental impact categories, with process details varying depending on plant operations and cement composition. The analysis showed that the clinker production stage is the most significant contributor to global warming impacts, accounting for 73.42% of the total, primarily due to CO_2 emissions from the calcination process and fossil fuel combustion.

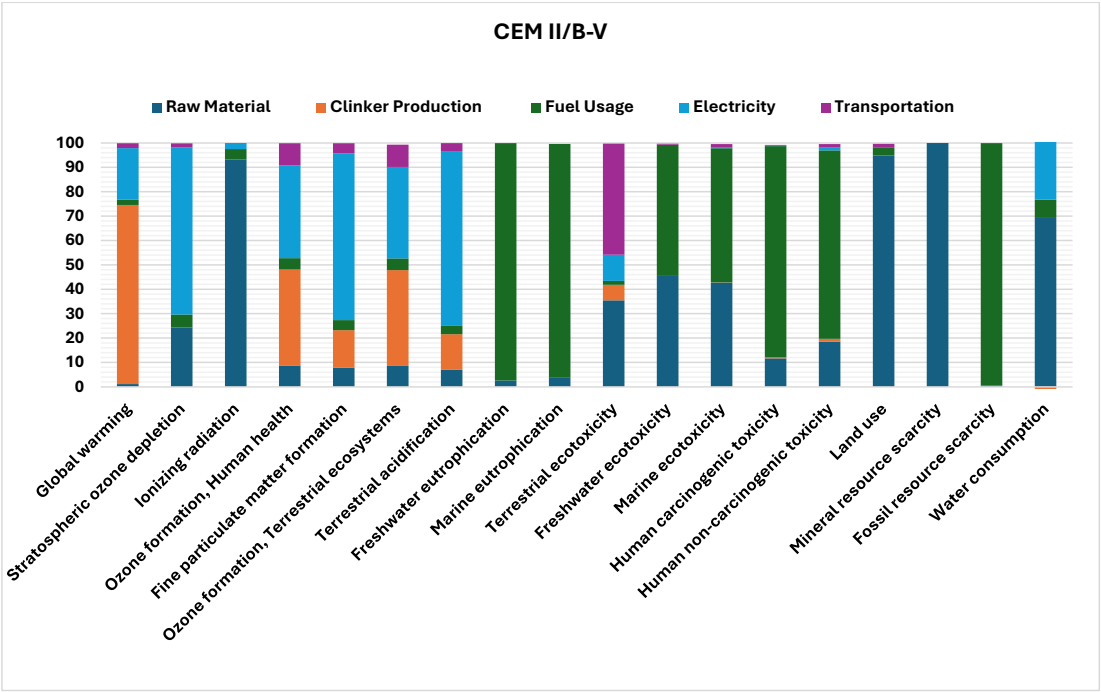


Figure 3. The midpoint characterization of the CEM II/B-V cement.

The electricity usage stage accounts for the highest contribution to stratospheric ozone depletion at 68.59%, primarily due to emissions of halocarbons from fossil fuel-

dependent power generation, followed by contributions from the raw material extraction and processing stage (24.27%), fuel usage (5.34%), and the transportation stage (1.61%). Additionally, the raw material extraction and processing stage significantly influences multiple environmental impact categories. This stage contributes 1.13% to global warming emissions and is the primary source of several other impacts, including mineral resource scarcity (100%) due to the extraction of finite resources like limestone and clay, ionizing radiation (93.17%), land use (94.82%), and water consumption (69.61%).

Fuel usage stage significantly contributes to a range of environmental impact categories, including freshwater ecotoxicity (53.79%) and marine ecotoxicity (55.05%). This is linked to heavy metal discharges during fuel processing and combustion. Human non-carcinogenic toxicity (77.29%) and Human carcinogenic toxicity (86.67%) are attributable to polycyclic aromatic hydrocarbons and particulate emissions, marine eutrophication (95.64%), freshwater eutrophication (97.38%) are driven by phosphorus and nitrogen from fuel impurities and fossil resource scarcity (99.38%), reflecting reliance on non-renewable hydrocarbons for kiln heating.

Figure 4 presents a detailed midpoint characterization of CEM III/A cement, the least preferred cement type, highlighting the contribution of each production stage to various environmental impacts. The clinker production stage dominates GWP, contributing 62.83% of emissions, primarily due to CO_2 release during limestone calcination, followed by the Electricity usage stage, which accounts for 23.32% due to grid energy use for grinding and auxiliary processes. The fuel usage stage contributes 4.46%, the raw material extraction and processing stage (6.56%), and transportation (2.56%) contribute minimally by comparison. For stratospheric ozone depletion, the electricity and raw material stages are the primary contributors, responsible for 63.47% and 26.95%, respectively, due to halocarbon emissions from energy production and mining equipment, while fuel usage and transportation contribute 6.83% and 2.33%. Also, the fuel usage stage dominates the source of freshwater eutrophication (89.41%) and marine eutrophication (85.56%). The raw material extraction and processing stage contributed the lowest to these categories (10.28% and 13.35%, respectively). The electricity usage stage (60.07%) is the most significant contributor to fine particulate matter formation, attributable to NO_x and SO_x emissions from coal-fired power plants. Followed by raw materials (15.24%) due to quarrying dust, clinker production (10.67%) attributed to the kiln particulate emissions, fuel usage stage (8.30%), and transportation stage (4.76%).

The raw material extraction and processing stage is identified as the primary contributor to several environmental impact categories. This includes ionizing radiation (92.88%) primarily from uranium and thorium in limestone and clay deposits released during quarrying and crushing activities, terrestrial ecotoxicity (62.72%), freshwater ecotoxicity (77.90%), marine ecotoxicity (76.24%) attributed to heavy metal leaching into ecosystems, human non-carcinogenic toxicity (58.14%) due to particulate matter and volatile organic compound emissions during material handling, land use (93.96%) driven by habitat fragmentation and soil degradation from quarrying operations, mineral resource scarcity (100%) resulting from the extraction of finite geological resources (e.g., limestone, clay), and water consumption (46.13%), associated with slurry preparation, dust suppression, and equipment cooling.

This study integrates LCA with criteria weighting analysis to assess sustainable cement production, focusing on GWP, terrestrial ecotoxicity, and human health impacts. We evaluated seven cement types across 18 environmental impact categories. The results showed that traditional Portland Cement (CEM I) has the highest environmental impacts, especially in GWP (0.99 kg CO_2 eq), resource depletion, and toxicity, primarily due to the calcination of limestone and the energy-intensive clinker production process at 1400–1450 °C. Key contributors to these impacts include kiln exhaust gas recirculation, calciners in cyclone pre-

heaters, and fossil fuel combustion. In contrast, low-clinker alternatives such as CEM III/A and CEM II/B-V demonstrated significantly reduced environmental impacts. The slag-based cement CEM III/A recorded a lower GWP (0.57 kg CO_2eq) and reduced carcinogenic toxicity and fossil fuel depletion. Similarly, fly ash-based cement (CEM II/A-V and CEM II/B-V) showed improved performance in GWP and toxicity categories. The slag-based cement exhibited the most suitable environmental profile within multiple categories. This study emphasizes the importance of LCA in identifying low-clinker alternatives and validating the environmental superiority of slag-based cement, positioning GGBFS adoption as a strategic pathway to support the cement sector with circular economy principles.

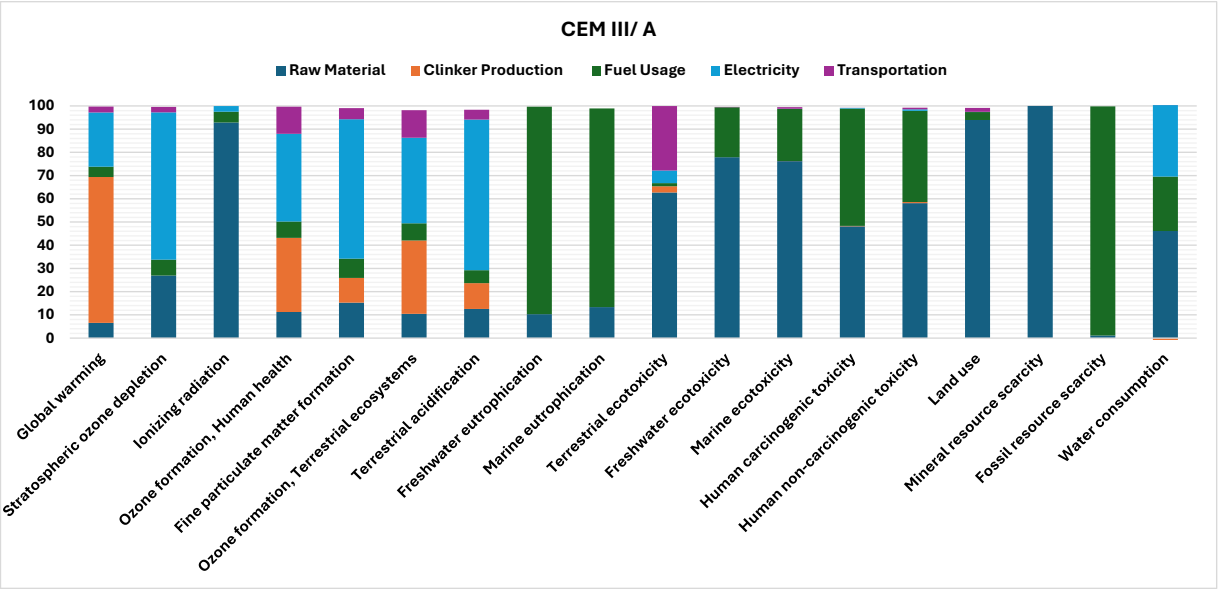


Figure 4. The midpoint characterization of the CEM III/A cement.

Also, the results support the importance of using clinker substitutes, such as industrial by-products (slag and fly ash), to reduce the environmental impact of cement production. It also supports a policy-driven approach toward low-carbon cement, highlighting the potential of CCS technologies and process optimization. The adoption of CEM III/A presents a promising alternative and represents a scalable and actionable pathway toward a more sustainable construction industry. Further research is needed to address the environmental impacts linked to its raw material sourcing.

4.5. Low Entropy Weight for Global Warming Potential

In sustainability assessments integrating LCA and MCDM, entropy weighting provides an objective approach to assigning importance to impact criteria based on data variability. Within this framework, the GWP, a critical climate-related indicator, was assigned a low entropy weight in this study. Though initially counterintuitive, this outcome reflects the fundamental properties of entropy-based weighting and the nature of the dataset rather than a dismissal of the environmental significance of GWP. Entropy weighting emphasizes criteria that provide greater discriminatory information across decision alternatives. As noted by Zhu, Tian [107], criteria with low variance yield higher entropy (closer to 1), indicating uniformity, and thus receive lower weights since they contribute less to differentiating between options. Similarly, the CRITIC method uses each criterion's standard deviation (variance) to assign weight [108]. Criteria with greater dispersion, ie, with lower entropy, are seen as more informative and are assigned higher weights [108]. Both the entropy and the CRITIC methods mathematically treat criteria with greater variance [107,108], therefore highlighting what differs most across options.

In the context of cement production, many low-clinker or blended cements (e.g., CEM II/B-V, CEM III/A) are explicitly designed to reduce CO_2 emissions. However, they may all achieve similar reductions in GWP per unit of product due to shared reliance on SCMs like fly ash or slag. This clustering leads to a narrow range of GWP values across alternatives, reducing the entropy. In South African cement LCA datasets, the GWP of cement types typically shows modest variation across mixes. For example, Ige, Olanrewaju [30] and Akintayo, Olanrewaju [109] reported 0.993 kg CO_2 eq for Portland cement, while blended cements (slag- or ash-content) reduce this modestly between 0.57 and 0.64 kg CO_2 eq [28,29]. Though environmentally relevant, this absolute difference is modest. The entropy weighting method interprets such consistency as minimal information gain, resulting in low weights for GWP. Further, the studies noted that raw-material extraction accounted for over 90% of the freshwater scarcity and 73% of water-use impacts, compared to GWP, which is 1.2% [28–30,109]. Similarly, ecotoxicity impacts, driven by trace metals like Pb, Cr, and Cd from raw material inputs, showed substantial variability [110]. These wide value ranges naturally lead to higher entropy weights. Therefore, a low entropy weight for GWP in this study does not reduce its environmental importance. Instead, it indicates homogeneous GWP profiles across evaluated alternatives and the structure of entropy-based objective weighting. To ensure balanced decision-making, entropy-weighted models may benefit from integration with expert-informed or context-specific weighting frameworks.

4.6. Sensitivity Analysis of MCDM Results

To test the robustness of the MCDM methodology applied in this study, a complete sensitivity analysis was conducted by systematically perturbing the entropy-derived weights applied to the environmental impact criteria (C1–C18). Each weight was randomly adjusted by increasing or decreasing by 25%, 50%, and 75% from the original entropy-derived values. The perturbed weights were normalized to ensure they summed to 1 in each scenario and used to recalculate the weighted performance scores for each cement type for both the ARAS and COPRAS methods. Figure 5 shows the sensitivity analysis results of the COPRAS method.

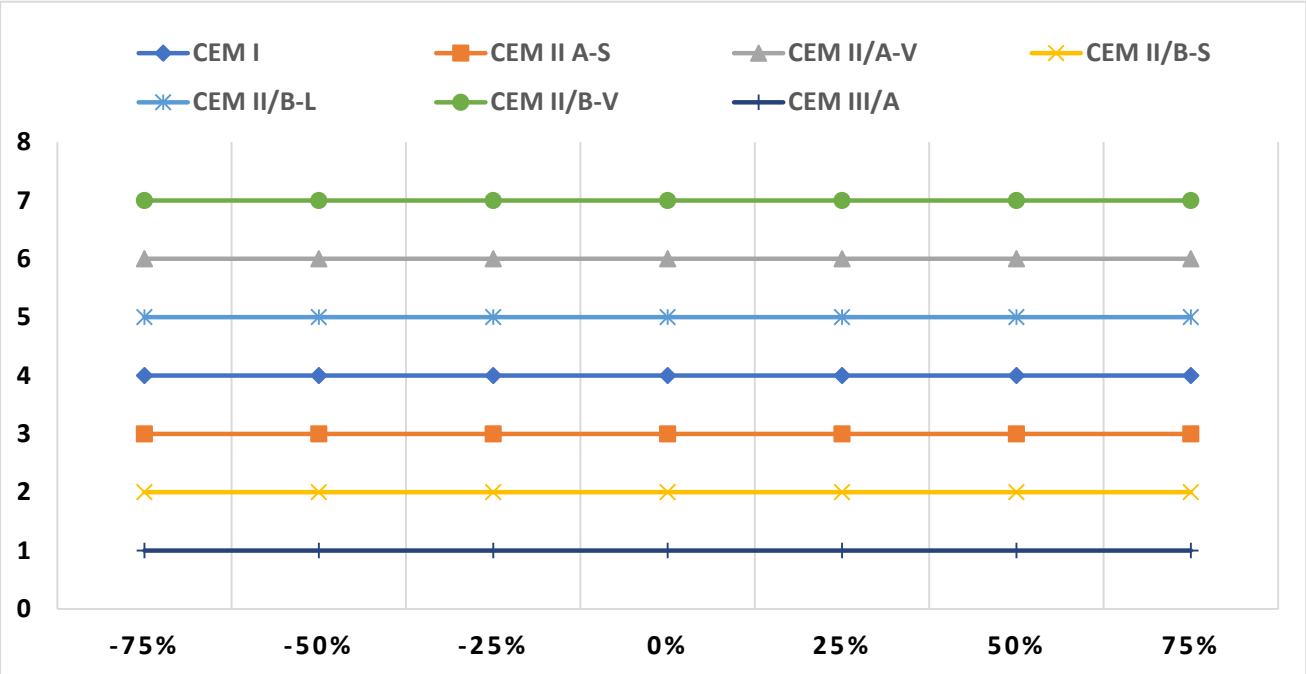


Figure 5. Sensitivity analysis results (COPRAS method).

The sensitivity analysis of the COPRAS rankings showed remarkable consistency across all perturbation scenarios. CEM II/B-V consistently remained the most sustainable cement alternative regardless of weight adjustments. Other alternatives, such as CEM II/A-V, CEM II/B-L and CEM I, also maintained high sustainability rankings, while CEM II A-S and CEM II/B-S also ranked low sustainability rankings, and CEM III/A remained the least preferred in most cases. These results confirm that the COPRAS-based selection of CEM II/B-V as the most sustainable cement alternative is robust and not sensitive to moderate changes in weighting assumptions.

Similarly, in Figure 6, the ARAS-based sensitivity analysis confirmed that CEM II/B-V consistently ranked highest in all tested scenarios, regardless of weight variations. Its utility scores remained dominant across ±25%, ±50%, and ±75% changes to the criteria weights. CEM II/A-V, CEM II/B-L and CEM I followed closely in rank, affirming their favorable environmental profiles. Conversely, CEM II A-S and CEM II/B-S consistently received the lowest sustainability rankings and CEM III/A remained the least preferred. This performance consistency further reinforces the validity of ARAS in selecting CEM II/B-V as the top-performing alternative in sustainable cement production.

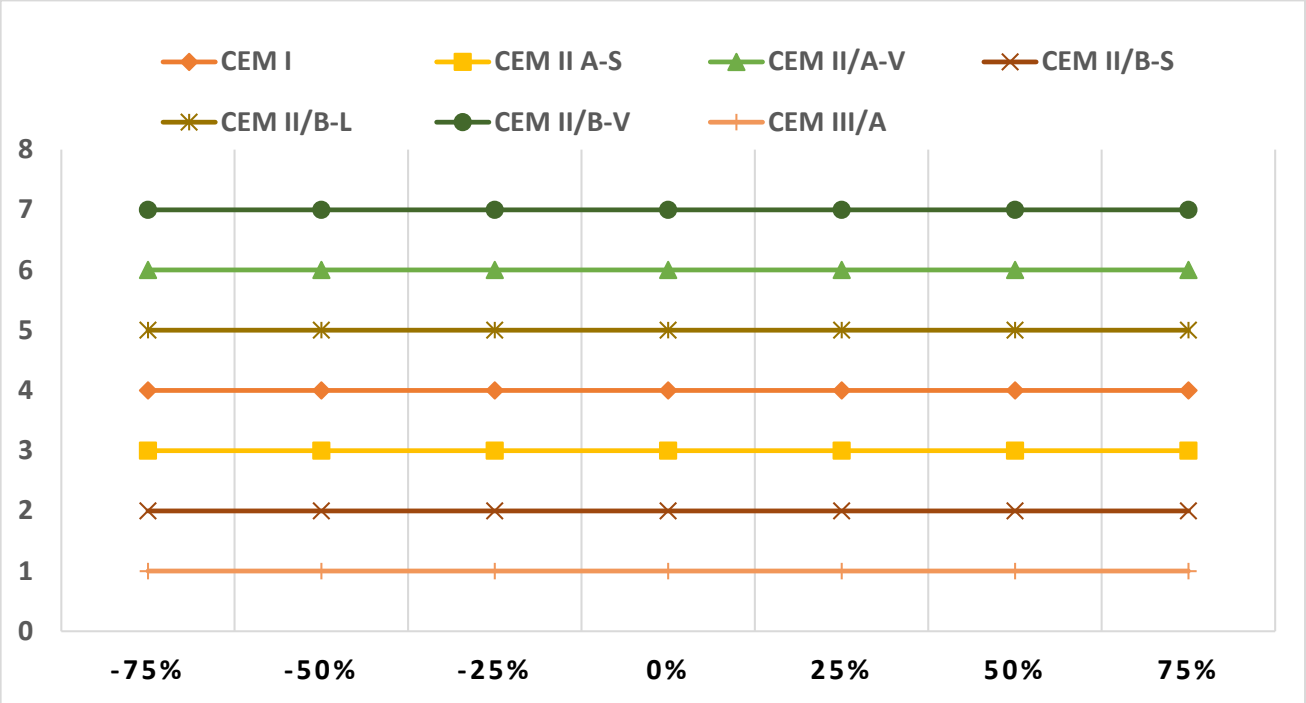


Figure 6. Sensitivity Analysis Results (ARAS Method).

The sensitivity analysis demonstrates the methodological soundness and reliability of both MCDM approaches used in this study. These results confirm that the integration of entropy-based weighting with ARAS and COPRAS produces robust, repeatable results across a wide range of perturbation conditions. The stability of CEM II/B-V's ranking across all test scenarios in both COPRAS and ARAS confirms its status as the most environmentally sustainable cement alternative in the South African context. These findings support its prioritization in policy, procurement, and production strategies aimed at reducing environmental impacts in the construction sector.

5. Conclusions

This study highlights the value of integrating LCA and MCDM methods to evaluate the environmental sustainability of cement alternatives produced in South Africa. LCA

quantified impacts across five production stages and 18 midpoint categories, while entropy-weighted COPRAS and ARAS methods ranked alternatives using structured decision criteria. The results indicate that blending traditional Portland Cement with SCMs such as GGBFS, fly ash, and limestone delivers significant environmental benefits. CEM III/A (slag-based) showed a 50% reduction in GWP compared to CEM I, but ranked lowest overall due to higher impacts in ionizing radiation, terrestrial ecotoxicity, and water consumption. By contrast, fly ash-based CEM II/B-V consistently ranked as the most sustainable alternative (COPRAS: 100.00; ARAS: 0.7257), offering reduced emissions and resource depletion. This result reflects its superior balance of environmental, technical, and economic performance, driven by its fly ash content, which reduces clinker reliance and associated emissions. CEM II/A-V and CEM II/B-L followed closely in the rankings, further highlighting the potential of using alternative binders and optimizing production processes to improve sustainability. Clinker production and raw material extraction were identified as major environmental hotspots, underscoring the need for process innovation and alternative raw material use. Although this study relied on secondary data (Ecoinvent via SimaPro), which may introduce regional uncertainties, the framework remains robust across a wide range of perturbations. Sensitivity analysis confirmed the stability of rankings despite variations in criteria weights.

This study focuses on environmental performance due to data availability but acknowledges that holistic sustainability must include economic and social dimensions. Future work will incorporate life cycle costing (LCC), social LCA, and endpoint modeling to assess impacts on human health and ecosystems. The generalizability of this approach makes it adaptable for other geographic contexts with similar SCM availability, offering guidance for transitioning toward net-zero cement systems globally. While this study is specific to South Africa, the integrated LCA–MCDM framework can be adapted to other regions with similar clinker substitution practices and SCM availability. However, applicability may be limited by local variations in energy sources, raw material composition, and production technologies, which influence life cycle impact profiles. Further studies should also explore additional SCMs, such as silica fume and magnesium oxide, and incorporate endpoint modeling to quantify damage to human health and ecosystems. Expanding the framework with socio-economic factors and applying it in diverse geographic contexts using primary data will improve relevance and strengthen its utility for sustainable decision-making in the cement industry.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/sci7030085/s1, Table S1: Environmental impact category values of the different cement types; Table S2: Decision matrix; Table S3: Normalized Decision Matrix (COPRAS) of alternatives with respect to impact category; Table S4: Weighted Normarlized Decision Matrix (COPRAS) of alternatives with respect to impact category; Table S5: Result (COPRAS method); Table S6: Normalized decision matrix (ARAS) of alternatives with respect to impact category; Table S7: Weighted normalized decision matrix (ARAS) of alternatives with respect to impact category; Table S8: Result (ARAS Method); Table S9: Inventory Dataset (from Ecoinvent and SimaPro); Table S10: Parameters.

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Nomenclature

Abbreviation	Definition
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
MCDM	Multi-Criteria Decision-Making
COPRAS	Complex Proportional Assessment
MOORA	Multi-Objective Optimization Based on Ratio Analysis
ARAS	Additive Ratio Assessment
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DEA	data Envelopment analysis
ELECTRA	Elimination of Choice Translating Reality
VIKOR	Multi-Criteria Optimization And Compromise Solution
MUA	Multi-Attribute Utility Analysis
ANP	Analytic Network Process
Fuzzy TOPSIS	Fuzzy Technique for Order Preference by Similarity to Ideal Solution
AHP	Analytic Hierarchy Process
Fuzzy AHP	Fuzzy Analytic Hierarchy Process
Fuzzy PROMETHEE	Fuzzy Preference Ranking Organization Method for Enrichment Evaluation
IT2FS	Interval Type-2 Fuzzy Sets
IVIF	Interval-Valued Intuitionistic Fuzzy
IFS	Intuitionistic Fuzzy Sets
CODAS	Combinative Distance Assessment
GWP	Global Warming Potential
GHG	Greenhouse Gas
SCMs	Supplementary Cementitious Materials
GGBFS	Ground Granulated Blast Furnace Slag
ISO	International Organization for Standardization
SimaPro	LCA Modeling Software by PRé Consultants
ReCiPe	LCA Impact Assessment Methodology
DCBeq	Dichlorobenzene Equivalent (used in toxicity metrics)

References

1. Verma, Y.K.; Mazumdar, B.; Ghosh, P. Thermal energy consumption and its conservation for a cement production unit. *Environ. Eng. Res.* **2021**, *26*, 200111. [CrossRef]
2. Zhang, Z.; Lin, B. Energy conservation and emission reduction of Chinese cement industry: From a perspective of factor substitutions. *Emerg. Mark. Financ. Trade* **2019**, *55*, 967–979. [CrossRef]
3. Putra, M.A.; Teh, K.C.; Tan, J.; Choong, T.S.Y. Sustainability assessment of Indonesian cement manufacturing via integrated life cycle assessment and analytical hierarchy process method. *Environ. Sci. Pollut. Res.* **2020**, *27*, 29352–29360. [CrossRef]
4. Ahmed, M.; Bashar, I.; Alam, S.T.; Wasi, A.I.; Jerin, I.; Khatun, S.; Rahman, M. An overview of Asian cement industry: Environmental impacts, research methodologies and mitigation measures. *Sustain. Prod. Consum.* **2021**, *28*, 1018–1039. [CrossRef]
5. Cruz Juarez, R.I.; Finnegan, S. The environmental impact of cement production in Europe: A holistic review of existing EPDs. *Clean. Environ. Syst.* **2021**, *3*, 100053. [CrossRef]
6. IEA. *Technology Roadmap—Low-Carbon Transition in the Cement Industry*; World Business Council for Sustainable Development (WBCSD): Geneva, Switzerland; International Energy Agency (IEA): Paris, France, 2018.
7. Schneider, M. The cement industry on the way to a low-carbon future. *Cem. Concr. Res.* **2019**, *124*, 105792. [CrossRef]

8. Huntzinger, D.N.; Eatmon, T.D. A life-cycle assessment of Portland cement manufacturing: Comparing the traditional process with alternative technologies. *J. Clean. Prod.* **2009**, *17*, 668–675. [CrossRef]
9. Proaño, L.; Sarmiento, A.T.; Figueredo, M.; Cobo, M. Techno-economic evaluation of indirect carbonation for CO_2 emissions capture in cement industry: A system dynamics approach. *J. Clean. Prod.* **2020**, *263*, 121457. [CrossRef]
10. Andrew, R.M. Global CO_2 emissions from cement production. *Earth Syst. Sci. Data* **2018**, *10*, 195–217. [CrossRef]
11. 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]
12. Ige, O.E.; Von Kallon, D.V.; Desai, D. Carbon emissions mitigation methods for cement industry using a systems dynamics model. *Clean Technol. Environ. Policy* **2024**, *26*, 579–597. [CrossRef]
13. Ige, O.E.; Olanrewaju, O.A.; Duffy, K.J.; Collins, O.C. A review of the effectiveness of Life Cycle Assessment for gauging environmental impacts from cement production. *J. Clean. Prod.* **2021**, *324*, 129213. [CrossRef]
14. Guo, Y.; Luo, L.; Liu, T.; Hao, L.; Li, Y.; Liu, P.; Zhu, T. A review of low-carbon technologies and projects for the global cement industry. *J. Environ. Sci.* **2024**, *136*, 682–697. [CrossRef]
15. Mamchii, O. *Largest Cement Producers in the World*; Best Diplomats: New York, NY, USA, 2024.
16. Mokhtar, A.; Nasooti, M. A decision support tool for cement industry to select energy efficiency measures. *Energy Strategy Rev.* **2020**, *28*, 100458. [CrossRef]
17. Soomro, M.; Tam, V.W.Y.; Jorge Evangelista, A.C. (Eds.) 2—Production of cement and its environmental impact. In *Recycled Concrete*; Woodhead Publishing: Cambridge, UK, 2023; pp. 11–46.
18. Khan, Z.A.; Salami, B.A.; Hussain, S.A.; Hasan, M.A.; Al-Ramadan, B.; Rahman, S.M. Dynamics of Greenhouse Gas Emissions from Cement Industries in Saudi Arabia-Challenges and Opportunities. *IEEE Access* **2023**, *11*, 125631–125647. [CrossRef]
19. Anderson, T.R.; Hawkins, E.; Jones, P.D. CO_2, the greenhouse effect and global warming: From the pioneering work of Arrhenius and Callendar to today's Earth System Models. *Endeavour* **2016**, *40*, 178–187. [CrossRef]
20. Andrew, R.M. Global CO_2 emissions from cement production, 1928–2017. *Earth Syst. Sci. Data* **2018**, *10*, 2213–2239. [CrossRef]
21. Li, H.; Wang, L.; Zhang, Y.; Yang, J.; Tsang, D.C.; Mechtcherine, V. Biochar for sustainable construction industry. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 63–95.
22. Turner, L.K.; Collins, F.G. Carbon dioxide equivalent (CO_2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Constr. Build. Mater.* **2013**, *43*, 125–130. [CrossRef]
23. Miccoli, S.; Finucci, F.; Murro, R. Assessing project quality: A multidimensional approach. In *Advanced Materials Research*; Trans Tech Publications: Zürich, Switzerland, 2014.
24. Miccoli, S.; Finucci, F.; Murro, R. Criteria and procedures for regional environmental regeneration: A European strategic project. In *Applied Mechanics and Materials*; Trans Tech Publications: Zürich, Switzerland, 2014; pp. 401–405.
25. Aranda Usón, A.; López-Sabirón, A.M.; Ferreira, G.; Llera Sastresa, E. Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options. *Renew. Sustain. Energy Rev.* **2013**, *23*, 242–260. [CrossRef]
26. Zieri, W.; Ismail, I. Alternative fuels from waste products in cement industry. In *Handbook of Ecomaterials*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 1–24. [CrossRef]
27. Abdul-Wahab, S.A.; Al-Dhamri, H.; Ram, G.; Chatterjee, V.P. An overview of alternative raw materials used in cement and clinker manufacturing. *Int. J. Sustain. Eng.* **2021**, *14*, 743–760. [CrossRef]
28. Ige, O.E.; Olanrewaju, O.A. Comparative Life Cycle Assessment of Different Portland Cement Types in South Africa. *Clean Technol.* **2023**, *5*, 901–920. [CrossRef]
29. Ige, O.; Desai, D.; Kallon, D. Environmental Impact of Blended Cement Produced with Ground-Granulated Blast Furnace Slag Substitution in the South African Cement Industry. In Proceedings of the 5th African International Conference on Industrial Engineering and Operations Management, Johannesburg/Pretoria, South Africa, 23–25 April 2024; IEOM Society International: Southfield, MI, USA; pp. 843–853.
30. Ige, O.E.; Olanrewaju, O.A.; Duffy, K.J.; Collins, O.C. Environmental Impact Analysis of Portland Cement (CEM1) Using the Midpoint Method. *Energies* **2022**, *15*, 2708. [CrossRef]
31. Ristimäki, M.; Säynäjoki, A.; Heinonen, J.; Junnila, S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy* **2013**, *63*, 168–179. [CrossRef]
32. Palermo, G.C.; Castelo Branco, D.A.; Fiorini, A.C.O.; de Freitas, M.A.V. Comparative life cycle assessment of three 2030 scenarios of the Brazilian cement industry. *Environ. Monit. Assess.* **2022**, *194*, 153. [CrossRef]
33. Stafford, F.N.; Raupp-Pereira, F.; Labrincha, J.A.; Hotza, D. Life cycle assessment of the production of cement: A Brazilian case study. *J. Clean. Prod.* **2016**, *137*, 1293–1299. [CrossRef]
34. García-Gusano, D.; Garraín, D.; Herrera, I.; Cabal, H.; Lechón, Y. Life Cycle Assessment of applying CO_2 post-combustion capture to the Spanish cement production. *J. Clean. Prod.* **2015**, *104*, 328–338. [CrossRef]
35. García-Gusano, D.; Herrera, I.; Garraín, D.; Lechón, Y.; Cabal, H. Life cycle assessment of the Spanish cement industry: Implementation of environmental-friendly solutions. *Clean Technol. Environ. Policy* **2015**, *17*, 59–73. [CrossRef]

36. Ma, F.; Sha, A.; Yang, P.; Huang, Y. The Greenhouse Gas Emission from Portland Cement Concrete Pavement Construction in China. *Int. J. Environ. Res. Public Health* **2016**, *13*, 632. [CrossRef]
37. Busola, D.O.; Oludolapo, A.O. Life Cycle Assessment of Ordinary Portland Cement (OPC) Using both Problem Oriented (Midpoint) Approach and Damage Oriented Approach (Endpoint). In *Product Life Cycle*; Antonella, P., Fabio De, F., Eds.; IntechOpen: Rijeka, Croatia, 2021; Chapter 3.
38. Kunche, A.; Mielczarek, B. Application of System Dynamic Modelling for Evaluation of Carbon Mitigation Strategies in Cement Industries: A Comparative Overview of the Current State of the Art. *Energies* **2021**, *14*, 1464. [CrossRef]
39. Zavadskas, E.K.; Zenonas, T.; Kildienė, S. State of art surveys of overviews on MCDM/MADM methods. *Technol. Econ. Dev. Econ.* **2014**, *20*, 165–179. [CrossRef]
40. Langemeyer, J.; Gómez-Baggethun, E.; Haase, D.; Scheuer, S.; Elmqvist, T. Bridging the gap between ecosystem service assessments and land-use planning through Multi-Criteria Decision Analysis (MCDA). *Environ. Sci. Policy* **2016**, *62*, 45–56. [CrossRef]
41. 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]
42. Yoris-Nobile, A.I.; Esther, L.-A.; Slebi-Acevedo, C.J.; Elena, B.-F.; Sara, A.-C.; Irune, I.-V.; Castro-Fresno, D. Life cycle assessment (LCA) and multi-criteria decision-making (MCDM) analysis to determine the performance of 3D printed cement mortars and geopolymers. *J. Sustain. Cem.-Based Mater.* **2023**, *12*, 609–626. [CrossRef]
43. Mokhtar, A.; Nasouti, M.; Shahrestani, D.A. Prioritizing Energy Efficiency Measures in the Cement Industry using decision making techniques. In Proceedings of the 10th International Energy Conference, Tehran, Iran, 26–27 August 2014.
44. Shmlls, M.; Abed, M.; Fořt, J.; Horvath, T.; Bozsaky, D. Towards closed-loop concrete recycling: Life cycle assessment and multi-criteria analysis. *J. Clean. Prod.* **2023**, *410*, 137179. [CrossRef]
45. Kurda, R.; de Brito, J.; Silvestre, J.D. CONCRETop—A multi-criteria decision method for concrete optimization. *Environ. Impact Assess. Rev.* **2019**, *74*, 73–85. [CrossRef]
46. Soni, A.; Chakraborty, S.; Kumar Das, P.; Kumar Saha, A. Materials selection of reinforced sustainable composites by recycling waste plastics and agro-waste: An integrated multi-criteria decision making approach. *Constr. Build. Mater.* **2022**, *348*, 128608. [CrossRef]
47. 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]
48. Taherdoost, H.; Madanchian, M. Multi-criteria decision making (MCDM) methods and concepts. *Encyclopedia* **2023**, *3*, 77–87. [CrossRef]
49. Azhar, N.A.; Radzi, N.A.M.; Wan Ahmad, W.S.H.M. Multi-criteria Decision Making: A Systematic Review. *Recent Adv. Electr. Electron. Eng.* **2021**, *14*, 779–801. [CrossRef]
50. 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]
51. 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]
52. 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*, 42. [CrossRef]
53. Yang, D.; Fan, L.; Shi, F.; Liu, Q.; Wang, Y. Comparative study of cement manufacturing with different strength grades using the coupled LCA and partial LCC methods—A case study in China. *Resour. Conserv. Recycl.* **2017**, *119*, 60–68. [CrossRef]
54. Pushkar, S.; Verbitsky, O. Effects of different allocation approaches for modeling mineral additives in blended cements on environmental damage from five concrete mixtures in Israel. *Mater. Struct.* **2016**, *49*, 4401–4415. [CrossRef]
55. Gökcekuş, 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.
56. Bathrinath, S.; Nagesh, S.M.; Dinesh, V.; Sri Ram Ganesh, M.; 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*; Natarajan, E., Vinodh, S., Rajkumar, V., Eds.; Springer Nature: Singapore, 2023; pp. 489–498.
57. 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]
58. Hossain, M.U.; Poon, C.S.; Lo, I.M.C.; Cheng, J.C.P. Comparative LCA on using waste materials in the cement industry: A Hong Kong case study. *Resour. Conserv. Recycl.* **2017**, *120*, 199–208. [CrossRef]
59. Hossain, M.U.; Poon, C.S.; Lo, I.M.C.; Cheng, J.C.P. Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach. *Int. J. Life Cycle Assess.* **2016**, *21*, 70–84. [CrossRef]

60. 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. [CrossRef]
61. Arukala, S.R.; Pancharathi, R.K.; Anand Raj, P. A Qualitative and Quantitative Approach to Prioritize Sustainable Concrete Using TOPSIS. In *Advances in Sustainable Construction Materials*; Pancharathi, R.K., Sangoju, B., Chaudhary, S., Eds.; Springer: Singapore, 2020; pp. 159–169.
62. Suárez Silgado, S.; Calderón Valdiviezo, L.; Gassó Domingo, S.; Roca, X. Multi-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: The case of Catalonia (Spain). *Resour. Conserv. Recycl.* **2018**, *133*, 120–131. [CrossRef]
63. Hendiani, S.; Walther, G. Towards sustainable futures: Rethinking supplier selection through interval-valued intuitionistic fuzzy decision-making. *Int. J. Prod. Econ.* **2025**, *285*, 109620. [CrossRef]
64. Falqi, I.I.; Ahmed, M.; Mallick, J. Siliceous Concrete Materials Management for Sustainability Using Fuzzy-TOPSIS Approach. *Appl. Sci.* **2019**, *9*, 3457. [CrossRef]
65. Ighravwe, D.E.; Oke, S.A. A multi-hierarchical framework for ranking maintenance sustainability strategies using PROMETHEE and fuzzy entropy methods. *J. Build. Pathol. Rehabil.* **2017**, *2*, 9. [CrossRef]
66. Reddy, L.S.; Murthy, N.R.D.; Srikanth, M.; Sunil, S.; Reddy, P.; Keerthana, D.M. Selection of Building Materials Using Fuzzy Analytical Hierarchy Process. *Open Civ. Eng. J.* **2024**, *18*, e18741495311020. [CrossRef]
67. Çebi, F.; Otay, İ. Multi-Criteria and Multi-Stage Facility Location Selection under Interval Type-2 Fuzzy Environment: A Case Study for a Cement Factory. *Int. J. Comput. Intell. Syst.* **2015**, *8*, 330–344. [CrossRef]
68. Mohagheghi, V.; Mousavi, S.M.; Shahabi-Shahmiri, R. Sustainable project portfolio selection and optimization with considerations of outsourcing decisions, financing options and staff assignment under interval type-2 fuzzy uncertainty. *Neural Comput. Appl.* **2022**, *34*, 14577–14598. [CrossRef]
69. Syan, C.S.; Ramsoobag, G. Maintenance applications of multi-criteria optimization: A review. *Reliab. Eng. Syst. Saf.* **2019**, *190*, 106520. [CrossRef]
70. Roy, J.; Das, S.; Kar, S.; Pamučar, D. An Extension of the CODAS Approach Using Interval-Valued Intuitionistic Fuzzy Set for Sustainable Material Selection in Construction Projects with Incomplete Weight Information. *Symmetry* **2019**, *11*, 393. [CrossRef]
71. Lolli, F.; Ishizaka, A.; Gamberini, R.; Rimini, B.; Ferrari, A.M.; Marinelli, S.; Savazza, R. Waste treatment: An environmental, economic and social analysis with a new group fuzzy PROMETHEE approach. *Clean Technol. Environ. Policy* **2016**, *18*, 1317–1332. [CrossRef]
72. Hauschild, M.Z. Introduction to LCA Methodology. In *Life Cycle Assessment: Theory and Practice*; Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 59–66.
73. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. *Life Cycle Assessment*; Springer Nature: Cham, Switzerland, 2018; Volume 2018.
74. Karaca, C.; Ulutaş, A.; Yağar Yamaner, G.; Topal, A. The selection of the best Olympic place for Turkey using an integrated MCDM model. *Decis. Sci. Lett.* **2019**, *8*, 1–16. [CrossRef]
75. Janhavi Chaidhanya, G.; Ramachandran, M.; Ramu, K.; Murugan, A. Understanding the Performance of Micro and Small Entrepreneurs by (COPRAS). *REST J. Data Anal. Artif. Intell.* **2022**, *1*, 33–40. [CrossRef]
76. Zapolskytė, S.; Vabuolytė, V.; Burinskienė, M.; Antuchevičienė, J. Assessment of Sustainable Mobility by MCDM Methods in the Science and Technology Parks of Vilnius, Lithuania. *Sustainability* **2020**, *12*, 9947. [CrossRef]
77. Zavadskas, E.K.; Turskis, Z. A new additive ratio assessment (ARAS) method in multicriteria decision-making. *Ukio Technol. Ir Ekon. Vystym.* **2010**, *16*, 159–172. [CrossRef]
78. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO (International Organization for Standardization): Geneva, Switzerland, 2006.
79. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO (International Organization for Standardization): Geneva, Switzerland, 2006.
80. Keshavarz Ghorabaee, M.; Zavadskas, E.K.; Olfat, L.; Turskis, Z. Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). *Informatica* **2015**, *26*, 435–451. [CrossRef]
81. Juanpera, M.; Blechinger, P.; Ferrer-Martí, L.; Hoffmann, M.M.; Pastor, R. Multicriteria-based methodology for the design of rural electrification systems. A case study in Nigeria. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110243. [CrossRef]
82. Saaty, T.L. The analytic hierarchy process (AHP). *J. Oper. Res. Soc.* **1980**, *41*, 1073–1076.
83. Opricovic, S.; Tzeng, G.-H. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *Eur. J. Oper. Res.* **2004**, *156*, 445–455. [CrossRef]
84. Singh, A.; Malik, S.K. Major MCDM Techniques and their application—A Review. *IOSR J. Eng.* **2014**, *4*, 15–25. [CrossRef]
85. Wang, E.; Alp, N.; Shi, J.; Wang, C.; Zhang, X.; Chen, H. Multi-criteria building energy performance benchmarking through variable clustering based compromise TOPSIS with objective entropy weighting. *Energy* **2017**, *125*, 197–210. [CrossRef]
86. Wang, Z.; Zhan, W. Dynamic Engineering Multi-criteria Decision Making Model Optimized by Entropy Weight for Evaluating Bid. *Syst. Eng. Procedia* **2012**, *5*, 49–54. [CrossRef]

87. Hosseinzadeh Lotfi, F.; Allahviranloo, T.; Pedrycz, W.; Shahriari, M.; Sharafi, H.; Razipour GhalehJough, S. The Complex Proportional Assessment (COPRAS) in Uncertainty Environment. In *Fuzzy Decision Analysis: Multi Attribute Decision Making Approach*; Hosseinzadeh Lotfi, F., Allahviranloo, T., Pedrycz, W., Shahriari, M., Sharafi, H., Razipour GhalehJough, S., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 291–308.
88. Okunevičiūtė Neverauskienė, L.; Novikova, M.; Kazlauskienė, E. Factors determining the development of intelligent transport systems. *Bus. Manag. Econ. Eng.* **2021**, *19*, 229–243. [CrossRef]
89. Organ, A.; Yalçın, E. Performance evaluation of research assistants by COPRAS method. *Eur. Sci. J.* **2016**, *12*, 102–109.
90. Taherdoost, H.; Mohebi, A. A Comprehensive Guide to the COPRAS method for Multi-Criteria Decision Making. *J. Manag. Sci. Eng. Res.* **2024**, *7*, 1–14. [CrossRef]
91. Kaklauskas, A.; Zavadskas, E.K.; Trinkunas, V. A multiple criteria decision support on-line system for construction. *Eng. Appl. Artif. Intell.* **2007**, *20*, 163–175. [CrossRef]
92. Ighravwe, D.E.; Oke, S.A. An integrated approach of SWARA and fuzzy COPRAS for maintenance technicians' selection factors ranking. *Int. J. Syst. Assur. Eng. Manag.* **2019**, *10*, 1615–1626. [CrossRef]
93. Viteikiene, M.; Zavadskas, E.K. Evaluating the sustainability of vilnius city residential areas. *J. Civ. Eng. Manag.* **2007**, *13*, 149–155. [CrossRef]
94. Karabašević, D.; Stanujkić, D.; Urošević, S. The MCDM Model for Personnel Selection Based on SWARA and ARAS Methods. *Management* **2015**, *20*, 43–52. [CrossRef]
95. Karabasevic, D.; Paunkovic, J.; Stanujkic, D. Ranking of companies according to the indicators of corporate social responsibility based on SWARA and ARAS methods. *Serbian J. Manag.* **2016**, *11*, 43–53. [CrossRef]
96. Xu, D.; Li, W.; Shen, W.; Dong, L. Decision-Making for Sustainability Enhancement of Chemical Systems under Uncertainties: Combining the Vector-Based Multiattribute Decision-Making Method with Weighted Multiobjective Optimization Technique. *Ind. Eng. Chem. Res.* **2019**, *58*, 12066–12079. [CrossRef]
97. MASCA, M.; GENÇ, T. Sustainable Development Performance Analysis by Entropy-Based Copras Method: An Application in The European Union Countries. *Rev. Manag. Econ. Eng.* **2024**, *23*, 122–130. [CrossRef]
98. Goswami, S.S.; Behera, D.K. Solving Material Handling Equipment Selection Problems in an Industry with the Help of Entropy Integrated COPRAS and ARAS MCDM techniques. *Process Integr. Optim. Sustain.* **2021**, *5*, 947–973. [CrossRef]
99. Goswami, S.S.; Behera, D.K. Implementation of ENTROPY-ARAS decision making methodology in the selection of best engineering materials. *Mater. Today Proc.* **2021**, *38*, 2256–2262. [CrossRef]
100. Hezer, S.; Gelmez, E.; Özceylan, E. Comparative analysis of TOPSIS, VIKOR and COPRAS methods for the COVID-19 Regional Safety Assessment. *J. Infect. Public Health* **2021**, *14*, 775–786. [CrossRef] [PubMed]
101. Malefaki, S.; Markatos, D.; Filippatos, A.; Pantelakis, S. A Comparative Analysis of Multi-Criteria Decision-Making Methods and Normalization Techniques in Holistic Sustainability Assessment for Engineering Applications. *Aerospace* **2025**, *12*, 100. [CrossRef]
102. Aytekin, A. Comparative Analysis of the Normalization Techniques in the Context of MCDM Problems. *Decis. Mak. Appl. Manag. Eng.* **2021**, *4*, 1–25. [CrossRef]
103. Shah, I.H.; Miller, S.A.; Jiang, D.; Myers, R.J. Cement substitution with secondary materials can reduce annual global CO_2 emissions by up to 1.3 gigatons. *Nat. Commun.* **2022**, *13*, 5758. [CrossRef]
104. Clark, G.; Davis, M.; Shibani; Kumar, A. Assessment of fuel switching as a decarbonization strategy in the cement sector. *Energy Convers. Manag.* **2024**, *312*, 118585. [CrossRef]
105. Nydrioti, I.; Moutsaki, M.-M.; Leounakis, N.; Grigoropoulou, H. Implementation of the water footprint as a water performance indicator in industrial manufacturing units located in Greece: Challenges and prospects. *Environ. Sci. Pollut. Res.* **2024**, *31*, 803–819. [CrossRef]
106. Etim, M.-A.; Babaremu, K.; Lazarus, J.; Omole, D. Health Risk and Environmental Assessment of Cement Production in Nigeria. *Atmosphere* **2021**, *12*, 1111. [CrossRef]
107. Zhu, Y.; Tian, D.; Yan, F. Effectiveness of Entropy Weight Method in Decision-Making. *Math. Probl. Eng.* **2020**, *2020*, 3564835. [CrossRef]
108. Krishnan, A.R.; Kasim, M.M.; Hamid, R.; Ghazali, M.F. A Modified CRITIC Method to Estimate the Objective Weights of Decision Criteria. *Symmetry* **2021**, *13*, 973. [CrossRef]
109. Akintayo, B.D.; Olanrewaju, O.A.; Olanrewaju, O.I. Life Cycle Assessment of Ordinary Portland Cement Production in South Africa: Mid-Point and End-Point Approaches. *Sustainability* **2024**, *16*, 3001. [CrossRef]
110. Olowoyo, J.O. Trace Metals in Soil and Plants around a Cement Factory in Pretoria, South Africa. *Pol. J. Environ. Stud.* **2015**, *24*, 2087–2093. [CrossRef] [PubMed]

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