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Prioritizing Alternative Fuels for Co-firing in an Indonesian Cement Plant: A Techno-Economic Analysis Using Integrated AHP-TOPSIS

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ABSTRACT

The cement industry faces a dual challenge stemming from global decarbonization requirements and fossil fuel price volatility. Increasing environmental regulatory pressure and sustainability targets compel cement producers to accelerate the energy transition through the substitution of alternative fuels (co-firing). This study aims to identify the factors influencing alternative fuel selection for cement production, determine the optimal fuel option for PT Semen ABC, West Java, and establish a ranking of the best alternative fuels by balancing technical and economic considerations. Using an MCDM framework, this research integrates the AHP to weight decision criteria and the TOPSIS method to rank the alternatives. Six materials were evaluated: rice husk, sawdust, wood chips, rice husk pellets, carbon rubber, and RDF. The AHP results indicate that technical quality dominates decision preferences at 56.5% (calorific value: 28.26%; moisture content: 28.16%), exceeding the influence of material price, transportation cost, supplier capacity, and the number of suppliers. Based on the TOPSIS analysis, carbon rubber ranks first as the most ideal solution, achieving the highest preference value (V = 0.7266), with a calorific value of 6.363 kcal/kg and a moisture content of 2.44%. The subsequent ranking is: rice husk pellets, rice husk, RDF, wood chips, and sawdust, with sawdust identified as the least-recommended fuel. This study concludes that kiln operational stability, which is strongly affected by material quality, constitutes the primary priority compared with procurement cost and supplier capability. Empirical research on integrated AHP–TOPSIS MCDM using techno-economic assessments based on operational data from Indonesian cement plants remains scarce. Most prior studies emphasize co-firing in power plants, making this application to the cement sector a key novel contribution.

1. Introduction

Currently, global investors focus not only on corporate profitability but also on non-financial factors, particularly environmental aspects. Climate change, driven by the greenhouse effect, causes environmental damage and global warming. Climate-related risks affect activities across the value chain and impact economic outcomes. Sustainability-oriented companies should not only demonstrate target fulfillment through financial contributions but also show the changes they have made as part of their corporate efforts to improve the planet [1]. Previous research reported a clear correlation between climate change and rising industrial CO_2 emissions [2]. The IEA estimates that the cement sector contributes about 7% of global CO_2 emissions [3]. In Indonesia, data from the Ministry of Environment and Forestry indicate that the cement industry accounts for more than 6.7% of national greenhouse-gas emissions. Technological innovation is therefore critical to improving cement-production efficiency and reducing environmental impacts; the IEA projects that renewable energy could cut cement-sector CO_2 emissions by up to 30% by 2030.

Cement manufacturing is highly energy-intensive [4]: 50–60% of production costs are spent on energy, with thermal energy alone accounting for 20–25%. Previous research showed that using sawdust waste as an alternative fuel can reduce CO_2 emissions by 14.6% [5]. However, biomass co-firing would require 4–9 million tonnes/year, while supply remains limited [6]. Key barriers include high upfront investment, inconsistent waste supply, and regulatory frameworks that remain insufficiently supportive [7]. With the potential increase in demand for alternative fuels, problems arise regarding limited sources, high prices, and a limited number of suppliers. Given these constraints, it is necessary to select alternative fuels that are competitively priced, high-quality, and available in sufficient quantities to meet the fuel requirements of high-energy-consuming plants. The correct and effective selection of materials will optimize processes, lower production costs, and reduce emissions from these factories.

Therefore, a systematic and structured approach is required to evaluate and select the most suitable alternative fuels. The Multi-Criteria Decision Making (MCDM) method, using the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), can assist in this decision-making process. Previous research applied MCDM to select alternative fuels for co-firing in power plants, whereas this study extends the approach to the cement industry, which has markedly different technical specifications [8], [9]. Previous research discussed supplier selection based on price and logistics within their respective regions; in contrast, this research provides a more industry-specific perspective for comparable cement facilities located in West Java, acknowledging that alternative fuels are highly location-dependent in terms of availability, cost, and logistics [10], [11], [12]. Moreover, while [13] and [14] relied on external experts to assign criteria weights—and [15], [8], and [10] derived weights through literature review and expert consultation—this study determines criteria weights using stakeholders directly involved in the cement plant's alternative-fuel utilization system, supported by actual operational data.

The phenomenon of optimal alternative fuels is complex due to conflicting techno-economic criteria. A structured decision-support framework is lacking at plant ABC, leading to potentially suboptimal choices. This study aims to identify the factors influencing the selection of alternative fuels for cement production and to determine the optimal fuel option for PT. Semen ABC, West Java, and establish a ranking of the best alternative fuels by balancing technical and economic considerations.

2. Research Methodology

2.1. Materials

The research was conducted at the ABC cement plant located in West Java, with an observation period spanning from 2023 to 2025. The six alternative fuels used are rice husks, sawdust, wood chips, rice husk pellets, carbon rubber, and RDF waste. These six alternative fuels were selected because they make a substantial contribution as substitutes for coal. Collectively, they account for approximately 80% of the alternative fuels procured by the purchasing team. Other fuels were not included due to their limited delivery volumes and irregular utilization.

This study employs Multi-Criteria Decision Making (MCDM), first introduced by Michael Scott Morton in 1971, to select the best alternative from conflicting criteria [16].

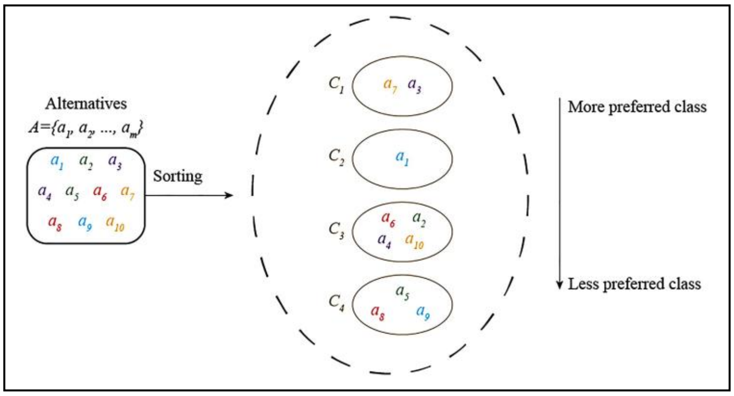

Fig. 1. Scheme of decision making from various alternatives [16]

Fig. 1 illustrates a sorting (classification) procedure in which a set of alternatives $A = \{a_1, a_2, \ldots, a_{10}\}$ is evaluated and then assigned to ordered preference classes C_1, C_2, C_3, and C_4. The classes are ranked from most preferred (C_1) to least preferred (C_4), meaning each alternative is placed into the appropriate category according to its overall preference level rather than being strictly ranked one by one [16].

According to previous research, the Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method used to rank decision alternatives and identify the most preferred option. AHP is widely applied because it structures complex problems into a hierarchical framework, decomposing criteria into progressively detailed sub-criteria [17]. According to previous research, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is based on the principle that the best alternative is the one with the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution. The application process of this method includes creating a decision matrix, normalizing data, assigning weights to each criterion, and calculating the relative closeness of each alternative to the ideal solution. One of the main advantages of TOPSIS is its ability to provide clear and easily interpretable rankings of alternatives, even in complex decision-making problems [18].

Based on previous research, comparing MCDM methods (AHP, TOPSIS, PROMETHEE, ELECTRE), this study uses a combination of AHP and TOPSIS, as AHP is effective for hierarchically determining criterion weights. In contrast, TOPSIS is used to rank alternatives based on closeness to the ideal solution [19].

2.2. Procedures

The following is the research flow:

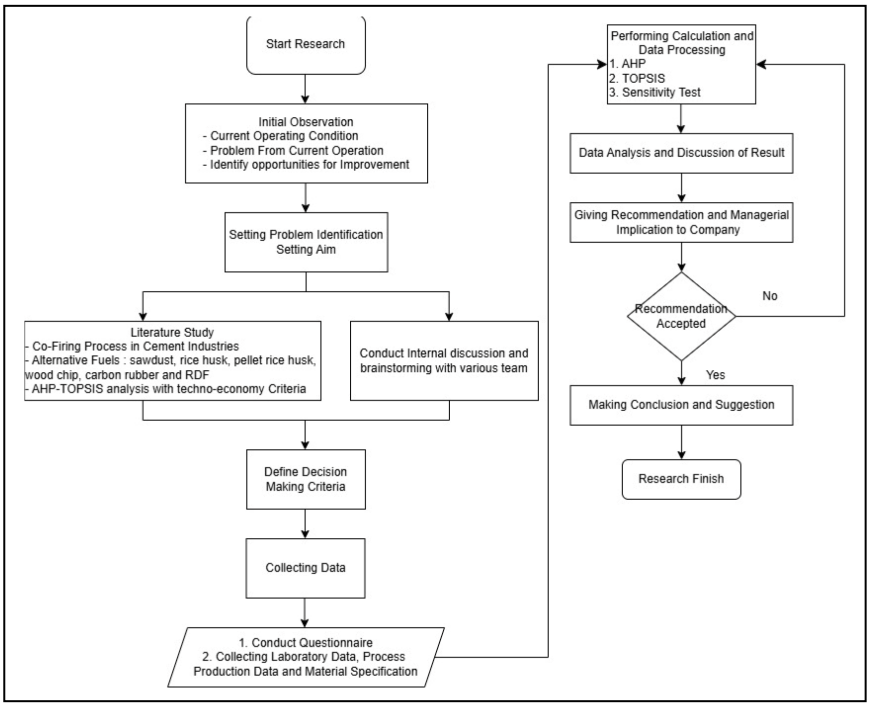

Fig. 2. Research flowchart

Fig. 2 summarizes a research process that begins with observing current operations to identify problems and opportunities for improvement. The study then sets the research objectives, reviews relevant literature, and conducts internal discussions to define decision criteria. Data are collected through questionnaires and operational/laboratory records, then analyzed using AHP, TOPSIS, and a sensitivity test. The results are discussed to produce recommendations and managerial implications; if the recommendations are not accepted, the analysis is revised and repeated. Once accepted, the study concludes with conclusions and practical suggestions.

The criteria selected align with techno-economic studies to find optimal alternative fuels, as shown in Fig. 3:

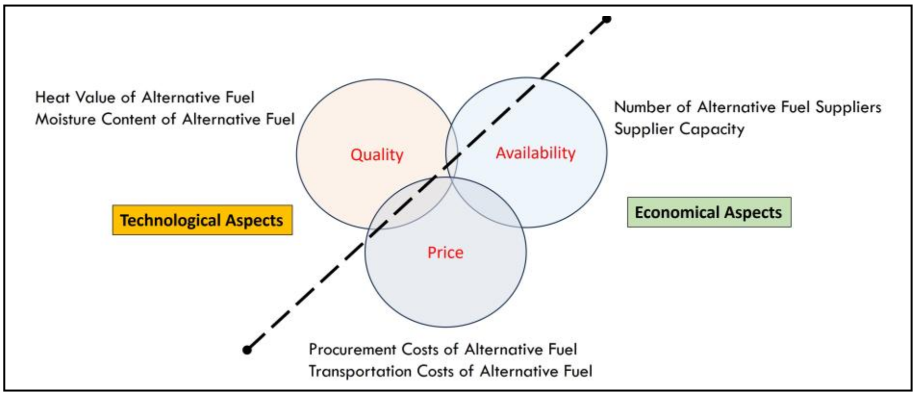

Fig. 3. Criteria Selected in Research

Fig. 3 presents a techno-economic framework for selecting alternative fuels in the cement industry by jointly prioritizing technological and economic considerations. The core criteria comprise quality, availability, and cost/price. From the technological perspective, fuel quality is assessed using parameters such as heating value and moisture content, which determine combustion suitability and process stability. From an economic perspective, availability is evaluated by the number of suppliers and their capacity to ensure continuity of supply. At the same time, cost is defined as the total delivered cost, including procurement and transportation expenses. The overlap among the three criteria indicates that the preferred option is an optimal trade-off: it must meet technical requirements, be reliably available, and remain economically competitive. The following is a hierarchical structure of criteria for determining alternative fuels, which is presented in Fig. 4 as follows:

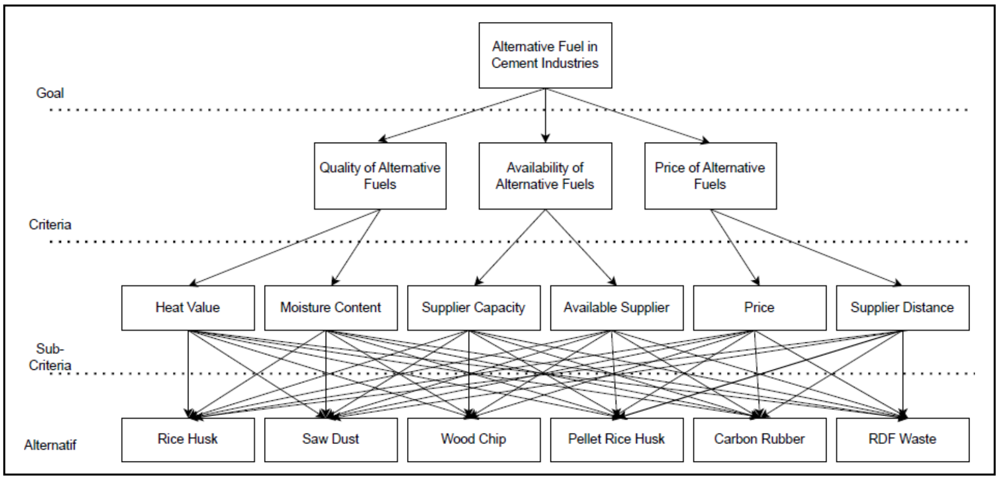

Fig. 4. Hierarchical Structure

Fig. 4 shows an AHP-style decision hierarchy for selecting alternative fuels in the cement industry. The goal is to select the most suitable alternative fuel, evaluated against three main criteria: fuel quality, availability, and cost. These are translated into sub-criteria: quality is measured by heating value and moisture content; availability by supplier capacity and number of suppliers; and cost by procurement and transportation costs. The candidate alternatives assessed against all sub-criteria are rice husk, sawdust, wood chips, rice husk pellets, carbon rubber, and RDF waste.

Data collection was conducted by distributing questionnaires to Echelon 4 and Echelon 3 officials as respondents and by collecting secondary data, including field documentation, technical reports, material analysis results, and other supporting data from the literature and SOPs required for the research. The data processing in this study involves primary data (questionnaire and laboratory results) and secondary data (literature). Material sampling data from 2023– 2025 was collected to calculate averages for quality, tonnage, and the number of suppliers delivering to the ABC cement plant. Primary data obtained from questionnaires were processed and calculated using the AHP-TOPSIS method. With the AHP method, data are processed through pairwise comparisons to determine the weight of each criterion. These weighting results are then used in the TOPSIS calculations.

1) AHP METHOD

The AHP method begins by determining the criteria, sub-criteria, and alternatives to be achieved.

1. A pairwise comparison matrix is created to depict the level of importance of each element or criterion relative to the goal using a ratio scale. These opinions are obtained from respondents who were previously given questionnaires to select the most appropriate criteria.

Table 1. Paired Matrix Scale in the AHP Method

Scale	Influence	Meaning
1	Equally Important	Both criteria have the same contribution
3	Moderate	One criterion is slightly more important than the other
5	Strong	One criterion is more important than the others
7	Very strong	One criterion is much more important than the other
9	Extreme	One criterion is absolutely more important than the others
2,4,6,8		The mean value between scales

An example of a paired matrix is as follows:

$$\text{Matrix} = \begin{bmatrix} X_{11} & \cdots & X_{1j} \\ \vdots & \ddots & \vdots \\ X_{i1} & \cdots & X_{ij} \end{bmatrix} \quad (1)$$

2. Calculation of the sum of each column of the pairwise comparison matrix.

$$C_{ij} = \sum_{i=1}^{n} X_{ij} \quad (2)$$

3. Performing normalized pairwise comparison calculations.

$$\dot{X}_{ij} = \frac{X_{ij}}{C_{ij}} \begin{pmatrix} X_{11} & \cdots & X_{1j} \\ \vdots & \ddots & \vdots \\ X_{i1} & \cdots & X_{ij} \end{pmatrix} \quad (3)$$

$$\dot{X}_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \begin{pmatrix} X_{11} & \cdots & X_{1j} \\ \vdots & \ddots & \vdots \\ X_{i1} & \cdots & X_{ij} \end{pmatrix} \quad (4)$$

where, $\dot{X}ij$ is the matrix component in the i-th row and j-th column, normalized by the number of matrix components in the j-th column.

4. Perform an average calculation of the values in each row to determine the criteria weight.

$$\dot{Y}_{ij} = \frac{\sum_{j=1}^{n} \dot{X}_{ij}}{n} \quad (5)$$

where, $\dot{Y}ij$ is a component of the weighted criteria matrix, so that the weighted criteria matrix is obtained as:

$$Y_{ij} = \begin{pmatrix} \dot{Y}_{11} \\ \vdots \\ \dot{Y}_{i1} \end{pmatrix} \quad (6)$$

5. Perform consistency vector (Cv) by multiplying the pairwise comparison matrix (Xij) by the weighted matrix (Yij).

$$\begin{pmatrix} X_{11} & \cdots & X_{1j} \\ \vdots & \ddots & \vdots \\ X_{i1} & \cdots & X_{ij} \end{pmatrix} x \begin{pmatrix} \dot{Y}_{11} \\ \vdots \\ \dot{Y}_{i1} \end{pmatrix} = \begin{pmatrix} Cv_{11} \\ \vdots \\ Cv_{i1} \end{pmatrix} \quad (7)$$

6. Performing eigenvalue calculations.

$$CV_{i1} = \frac{1}{\dot{Y}_{i1}}\left[X_{11}\dot{Y}_{i1} + \cdots + X_{1j}\dot{Y}_{i1}\right] \tag{8}$$

Performing maximum eigenvalue calculations.

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} Cv_{ij} \tag{9}$$

7. Calculate *the Consistency Index* (CI) by means of

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{10}$$

Consistency Ratio (CR) calculations by means of

$$R = \frac{CI}{RI} \tag{11}$$

The Random Index (RI) is a reference value used to calculate the Consistency Ratio (CR). The RI depends on the matrix size (n), which is the number of criteria being compared. The RI values for the matrix sizes are shown in Table 2.

Table 2. Random Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

If the CR value is ≤ 0,1 the matrix is considered consistent and acceptable.

If the CR value is > 0.1, the matrix is deemed inaccurate and requires correction.

2) TOPSIS METHOD

Following the AHP-based weighting results, the solutions are ranked from best to worst. The steps in the TOPSIS calculation are as follows:

1. Performing normalized decision matrix calculations

This is done by calculating the performance rating of each alternative AI on each normalized criterion Kj.

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{12}$$

Where:

value i= 1,2,3,….m and value j= 1,2,3….n

Xij = initial value of the i-th alternative on the j-th criterion

2. Calculate the normalized decision matrix weighting.

$$y_{ij} = w_j \cdot r_{ij} \tag{13}$$

Where:

value i= 1,2,3,….m and value j= 1,2,3….n

Wij = weight of the j-th criterion

3. Determining Positive Ideal Solution (A^+) and Negative Ideal Solution (A^-)

The positive ideal solution (A^+) is the best value of a criterion for the value of its alternative solution, and the positive ideal solution (A^-) is the worst value of a criterion for the value of its alternative solution. The value of this ideal solution is obtained based on the weighting of the best and worst normalized decision matrices

$$A^+ = (y_1^+, y_2^+, y_3^+, \ldots., y_n^+,) \quad (14)$$

$$A^- = (y_1^-, y_2^-, y_3^-, \ldots., y_n^-,) \quad (15)$$

4. Calculating Alternative Distances to the Ideal Solution (D) Positive and Negative

This alternative distance calculation uses *the Euclidean distance* between the alternatives' values and the ideal solution values for each criterion.

Alternative distance (Ai) to the positive ideal solution distance (D^+)

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - y_j^+\right)^2} \quad (16)$$

Alternative distance (Ai) to the positive ideal solution distance (D^-)

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - y_j^-\right)^2} \quad (17)$$

5. Calculate the Preference Value for each alternative

The preference value or closeness coefficient is calculated using the formula:

$$V_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (18)$$

The value of Vi will be between 0 and 1. The closer the value is to 1, the better the alternative solution.

6. Sort the best alternatives

Alternatives are ranked by their highest preference value. The alternative with the highest Vi value is the best, and the one with the lowest is the worst according to the TOPSIS analysis. The final phase involves conducting a sensitivity analysis to assess the robustness of the rankings derived from the AHP-TOPSIS method to variations in criterion weights. Subsequently, the study proceeds with data analysis and discussion, formulates conclusions and suggestions, and culminates in strategic recommendations for the company.

3. Results and Discussion

3.1. Alternative Fuel for Cement Factory as follows

Cement Plant ABC has used alternative fuels since 2015 and subsequently upgraded its feeding system and diversified fuel sources to reduce CO_2 emissions and energy costs while maintaining kiln stability and clinker quality; therefore, fuel acceptance is governed primarily by calorific value, moisture content, and homogeneity, as standardized in the plant's SOP. In practice, biomass such as rice husk and sawdust is favored for its availability, yet moisture variability reduces effective heat input and absorbs kiln energy for evaporation, necessitating strict quality control and blending; rice husk is also used as a porous carrier to enable feeding of liquid/sludge wastes. Woodchips offer the largest supply volume but typically have high moisture content and may introduce soil contamination, increase ash, and potentially disturb clinker chemistry. To enhance combustion stability, rice husk is densified into pellets with lower moisture content and a higher calorific value, which can be co-stored and co-fired with coal, albeit with supply-chain concentration risk. Beyond biomass, recovered carbon black (rCB) from tire pyrolysis is considered highly promising due to high carbon content, high calorific value, very low moisture, and the potential to substitute coal by roughly 15% on a heat basis. Municipal-waste-derived RDF must be sorted, shredded, and dried to improve uniformity (commonly <50 mm) and ensure continuous feeding compatible with systems such as Vecoplan/Hotdisk; its energy contribution remains strongly dependent on moisture and composition, making specification control essential for stable kiln operation.

3.2.Techno-Economic Analysis of the Utilization of Alternative Fuels in Factories

Techno-economic analysis of alternative fuel utilization at the ABC cement plant is a strategic step to address two main challenges: industrial decarbonization and high fossil fuel price volatility.

Table 3. Analysis of technology and fuel economy at the ABC cement plant

Material	Moisture Content (%)	Heat Value (kcal/kg)	Price (IDR/Ton)	Available Supplier	Supplier Capacity (Ton/Month)	Supplier Distance (km)	Location
Coal Sub-Bituminous*	30-35	4.200 - 5.500	Rp 750,000	>10	>10.000	>500	Borneo, Sumatra
Rice Husk	22.09	2.558	Rp 385,000	6	4.096	60	Bogor, Sukabumi, Cianjur
Sawdust	33.01	2.854	Rp 622,000	6	2.240	75	Bogor, Sukabumi, Ciawi
Wood chip	36.54	2.759	Rp 850,000	5	7.912	40	Bogor, Sukabumi
Pellet rice husk	6.02	3.602	Rp 1,200,000	2	5.314	130	Bogor, Subang
Carbon rubber	2.44	2.44	Rp 775,000	4	1.323	90	Bogor, Serang
Shredded RDF	34.24	34.24	Rp 700,000	14	6.053	40	Jakarta, Bogor

*Coal Type: HBA II

The combined technical and economic factors (Table 3) indicate key parameters for selection. Considerations must include compatibility with existing technology, the ability to replace coal, and competitive pricing. Rice husk offers a distinct cost advantage; however, its application is limited by a low calorific value. Conversely, sawdust and wood chips, despite benefitting from high supplier availability, are less effective due to high acquisition costs, low calorific value, and high moisture content. Meanwhile, pellets and carbon rubber demonstrate superior technical quality, yet high prices and a limited supplier base constrain their feasibility. Among the alternatives, Refuse-Derived Fuel (RDF) offers the greatest potential due to its high calorific value and extensive supplier network. Nevertheless, achieving material homogeneity remains a critical challenge, primarily due to the lack of household-level waste segregation.

3.3.Analytic Hierarchy Process (AHP) Analysis Results

1) Questionnaire for determining the AHP of alternative fuels

Respondents were Echelon III and IV officials at the ABC cement plant, selected for their direct involvement in operational process management and field implementation related to alternative fuel use. Although they came from diverse backgrounds, all were relevant to the study objectives. The questionnaire collected data from 16 respondents, whose composition is presented in Table 10. The questionnaire was administered online via Google Forms. Respondents evaluated paired criteria using the Saaty importance scale (1–9), indicating the relative importance of each criterion with respect to the primary objective. The questionnaire was administered online using *Google Forms*.

Table 4. Composition of questionnaire respondents

Sections in ABC Cement Factory	Number of Respondents
Production Department	7
AF Handling Section	2
Laboratory Section	3
Purchasing and Warehouse Department	3
Expert Team	1
Total	16

2) Paired Matrix Creation

Responses for each pairwise comparison matrix were aggregated using the geometric mean, which preserves the reciprocal property required in AHP and is less sensitive to extreme values than the arithmetic mean. The aggregated results were then used to construct the pairwise comparison matrix (Table 5) to determine the relative importance of the criteria with respect to the primary objective.

Table 5. Paired matrix of alternative fuel selection

Criteria	Heat Content	Water Content	Price	Transportation Costs	Number of Suppliers	Supplier Capacity
Heat Content	1.00	1.59	1.67	2.43	3.55	2.70
Water content	0.63	1.00	2.30	2.80	3.56	4.17
Price	0.60	0.43	1.00	1.46	3.93	2.55
Transportation costs	0.41	0.36	0.68	1.00	1.85	1.50
Number of Suppliers	0.28	0.28	0.25	0.54	1.00	0.73
Supplier Capacity	0.37	0.24	0.39	0.67	1.36	1.00
Total	3.29	3.90	6.30	8.90	15.26	12.65

3) Determination of alternative fuel criteria weights using AHP

The matrix calculation results in Table 11 were then normalized by dividing each column by its total. The normalized results were then summed for each row for each criterion. The total number of criteria in the same row was then divided by 6 to obtain the criterion weights according to the AHP calculation.

Table 6. Normalization of the pairwise matrix and AHP weight results for each criterion

Criteria	Heat Content	Water Content	Price	Transport. Costs	Number of Suppliers	Supplier Capacity	Eigenvector	Weight Criteria
Heat Content	0.30	0.41	0.26	0.27	0.23	0.21	0.283	28.3%
Water content	0.19	0.26	0.37	0.31	0.23	0.33	0.282	28.2%
Price	0.18	0.11	0.16	0.16	0.26	0.20	0.179	17.9%
Transportation costs	0.13	0.09	0.11	0.11	0.12	0.12	0.113	11.3%
Number of Suppliers	0.09	0.07	0.04	0.06	0.07	0.06	0.064	6.4%
Supplier Capacity	0.11	0.06	0.06	0.08	0.09	0.08	0.080	8.0%
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	100.0%

From Table 6, AHP results clearly show that technical criteria dominate the decision, with calorific value (28.3%) and moisture content (28.2%) ranked highest; together, they account for 56.5% of the total importance, indicating that respondents prioritize fuel technical performance over other criteria. In contrast, economic criteria rank lower price third (17.9%), with transport cost following (11.3%), so the economic dimension contributes ~29.2% in aggregate, well below the combined technical weight. This prioritization is rational for a cement plant because fuel heat and moisture directly determine kiln combustion performance, which influences flame/heat stability, combustion efficiency, and clinker quality. Poor combustion will lower clinker quality by increasing free lime content and reducing alite crystals, thereby reducing cement compressive strength. Moreover, the plant's alternative-fuel combustion system is highly sensitive to moisture content. The particle size can be mechanically controlled, but moisture cannot, and high moisture reduces usable heat release. Pre-drying is typically avoided because it increases costs and undermines the fuel's economic attractiveness. Increasing moisture lowers flame temperature and radiative heat transfer because a substantial fraction of combustion energy is consumed as the latent heat of evaporation. It even notes that achieving 80% radiation factor requires limiting moisture to less 15% for efficient kiln use. Therefore, even though energy costs are high and price matters, they do not outweigh technical criteria in AHP, because cheap fuel with high moisture or low calorific value can increase fuel consumption and cause operational disturbances, raising total long-term costs and risking stable operation and product quality. Hence, respondents may accept slightly higher prices if kiln stability and clinker quality are maintained.

Table 7. Calculation of consistency ratio

Criteria	Heat Content	Water Content	Price	Transport Costs	Number of Suppliers	Supplier Capacity	Weighted Sum Value	Eigen Vector	Eigen Value
Heat Content	0.28	0.45	0.30	0.27	0.23	0.22	1.75	0.28	6.18
Water Content	0.18	0.28	0.41	0.32	0.23	0.33	1.75	0.28	6.21
Price	0.17	0.12	0.18	0.17	0.25	0.20	1.09	0.18	6.08
Transportation Costs	0.12	0.10	0.12	0.11	0.12	0.12	0.69	0.11	6.11
Number of Suppliers	0.08	0.08	0.05	0.06	0.06	0.06	0.39	0.06	6.09
Supplier Capacity	0.10	0.07	0.07	0.08	0.09	0.08	0.48	0.08	6.06
Total	0.93	1.10	1.13	1.00	0.97	1.01			

Table 7 shows a λmax value of 6.121 and a CR value of 0.0194 (1.94%). According to Saaty (1980), a CR value <0.10 (10%) is considered consistent. Thus, the results of the respondents' assessments via the questionnaire in this study are highly valid and reliable. Respondents at the plant prefer fuels with superior technical characteristics, even if the price is slightly higher, provided these fuels maintain their contribution to operational stability and product quality.

Price ranks third at 17.9%, followed by transportation costs at 11.3%. In aggregate, the economic dimension accounts for approximately 29.2% of the overall priority weighting. At the ABC cement plant, energy expenditure constitutes a significant proportion of total production costs. The moderate weight assigned to transportation costs indicates that, while the proximity of fuel sources and logistical efficiency are taken into account, they remain subordinate to technical quality specifications and fuel acquisition costs. These four criteria demonstrate that the ABC cement plant strives to achieve cost efficiency without compromising the minimum technical requirements of an alternative fuel.

3.4.Analysis Results of TOPSIS

To determine the optimal ranking of alternative fuels for the ABC cement plant, the TOPSIS method was used. TOPSIS measures the relative performance of alternatives against positive and negative ideal solutions simultaneously. Specifically, the positive ideal solution maximizes benefit criteria and minimizes cost criteria, whereas the negative ideal solution does the opposite.

Table 8. Positive and negative criteria in fuel alternatives for the ABC cement factory

	Benefit Criteria (+)			Cost Criteria (-)		
Material	**Heat Value (kcal/kg)**	**Avaliable Suppliers**	**Supplier Capacity (tons/month)**	**Moisture Content (%)**	**Price (IDR/Ton)**	**Supplier Distance (km)**
Rice Husk	2.558	6	4.096	22.09	Rp 385,000	60
Sawdust	2.854	6	2.240	33.01	Rp 622,000	75
Wood Chips	2.759	5	7.912	36.54	Rp 850,000	40
Pellets Rice Husk	3.602	2	5.314	6.02	Rp 1,200,000	130
Carbon Rubber	6.363	4	1.323	2.44	Rp 775,000	90
Shredded RDF	3.825	14	6.053	34.24	Rp 700,000	40

1) Weighted Matrix Normalization

Using the AHP-derived weights, the normalized decision matrix (Table 9) was computed and then weighted (Table 10) to determine the ideal solutions. Normalization is performed by dividing the criterion by the square root of the total value of that criterion across all alternatives. This is done to ensure that the assigned values are equal.

Table 9. Normalization of the alternative fuel weight matrix for the ABC cement factory

Material	Heat Value (kcal/kg)	Avaliable Suppliers	Supplier Capacity (Tons/month)	Moisture Content (%)	Price (IDR/Ton)	Supplier Distance (km)
Rice Husk	0.269	0.339	0.333	0.344	0.198	0.310
Sawdust	0.300	0.339	0.182	0.514	0.320	0.388
Wood Chips	0.290	0.283	0.644	0.569	0.437	0.207
Pellets Rice Husk	0.379	0.113	0.432	0.094	0.617	0.672
Carbon Rubber	0.669	0.226	0.108	0.038	0.398	0.465
Shredded RDF	0.402	0.791	0.493	0.533	0.360	0.207

Table 10. Weighted normalized matrix of alternative fuels for the ABC cement factory

Material	Heat Value (kcal/kg)	Avaliable Suppliers	Supplier Capacity (tons/month)	Moisture Content (%)	Price (IDR/Ton)	Supplier Distance (km)
AHP Weight	0.283	0.064	0.080	0.282	0.179	0.113
Rice Husk	0.076	0.022	0.027	0.097	0.035	0.035
Sawdust	0.085	0.022	0.015	0.145	0.057	0.044
Wood Chips	0.082	0.018	0.051	0.160	0.078	0.023
Pellets Rice Husk	0.107	0.007	0.035	0.026	0.111	0.076
Carbon Rubber	0.189	0.014	0.009	0.011	0.071	0.053
Shredded RDF	0.114	0.050	0.039	0.150	0.064	0.023
Min	0.076	0.007	0.009	0.011	0.035	0.023
Max	0.189	0.050	0.051	0.160	0.111	0.076

In Table 10, the normalized value is multiplied by the weights previously calculated using the AHP method. The higher the value, the greater the contribution, according to respondents from the ABC cement factory.

2) Positive Ideal Solution and Negative Ideal Solution

Positive Ideal Solution (A+) is the maximum (largest) optimum value of a criterion for several alternative solution values in one criterion. Negative Ideal Solution (A-) is the minimum (smallest) optimum value of a criterion for several alternative solution values in one criterion.

Table 11. Positive and negative ideal solutions of alternative fuel criteria for the ABC cement factory

Ideal Solution	Heat Value	Number of Suppliers	Capacity per month (tons)	Water content (%)	Price (Rupiah)	Supplier Distance (km)
Attribute	Max	Max	Max	Min	Min	Min
Positive Ideal (A+)	0.189	0.050	0.051	0.011	0.035	0.023
Negative Ideal (A-)	0.076	0.007	0.009	0.160	0.111	0.076
Attribute	Min	Min	Min	Max	Max	Max

3) Alternative Distances to Ideal Solution

Ideal Solution Distance (D) is the Euclidean distance between the alternative value and the ideal solution value for each criterion.

Table 12. Alternative distances to the ideal solution for alternative fuels for the ABC cement factory

Material	Positive Ideal Solution Distance (D+)	Negative Ideal Solution Distance (D+)
Rice Husk	0.4176	0.1089
Sawdust	0.1787	0.0665
Wood Chips	0.1916	0.0761
Pellets Rice Husk	0.1324	0.1398
Carbon rubber	0.0726	0.1930
Shredded RDF	0.1616	0.0960

4) Preference Value for Alternatives

The preference value (V) is calculated based on the distance of the alternatives to the positive and negative solutions. The calculation results are sorted from largest to smallest, so that the alternative with the highest preference value is the best, while the alternative with the lowest is the worst.

Table 13. Alternative fuel preference values of the ABC cement factory

Material	V Value	Ranking
Rice Husk	0.4244	3
Sawdust	0.2713	6
Wood Chips	0.2843	5
Pellets Rice Husk	0.5136	2
Carbon Rubber	0.7266	1
Shredded RDF	0.3726	4

Table 14. Alternative fuel ranking of the ABC cement plant

Ranking	Alternative Fuels
1	Carbon Rubber
2	Pellets Rice Husk
3	Rice Husk
4	Shredded RDF
5	Wood Chips
6	Sawdust

3.5.Interpretation of AHP-TOPSIS Results of Alternative Fuels for Cement Factories

1) Ranking Overview and Dominance of Quality Factors

The results of the AHP and TOPSIS calculations indicate that the quality factor is the primary determinant in selecting alternative fuels to replace coal. The ranking analysis reveals that carbon rubber ranks first with a preference value (V) of 0.7266, followed by rice husk pellets (0.5136) and rice husk (0.4244).

2) Analysis of Top-Ranked Alternatives

Carbon rubber's primary advantage lies in two key parameters prioritized in the AHP analysis: its high calorific value of 6,363 kcal/kg—surpassing RDF and other biomass—and its exceptionally low moisture content of 2.44%, substantially lower than that of other biomass-based fuels, which typically exceed 20%. Ranking second, rice husk pellets exhibit excellent technical specifications despite being the most expensive option among available alternatives, even surpassing coal in cost. It has a very low moisture content (approximately 6.02%) and a moderate calorific value (3,602 kcal/kg), which provides a distinct advantage over other biomass fuels. Meanwhile, rice husk ranks third as a highly viable option; although characterized by moderate moisture and calorific values, it is the most cost-effective alternative. Furthermore, it benefits from a large supplier base with significant delivery capacity. The consistent availability of stock constitutes a major strategic advantage for its utilization.

3) Analysis of Lower-Ranked Alternatives (RDF, Wood Chips, Sawdust)

The low rankings of wood chips, sawdust, and RDF indicate that, despite competitive pricing and abundant supply, their high moisture content (ranging from 30% to 36%) significantly reduced their preference values. In the TOPSIS analysis, high moisture content increases the geometric distance from the ideal solution, rendering these materials high-risk for operations despite their logistical advantages. Specifically, while RDF shows promise due to vast sourcing potential and increasing waste volumes, it has not yet qualified as the optimal alternative fuel due to quality inconsistencies. Improvements are required regarding moisture reduction and material homogeneity to minimize impurities. Similarly, although wood chips have a large supply capacity, their quality remains suboptimal due to high moisture content, low calorific value, and high costs relative to other biomass. Moreover, the presence of impurities, such as soil, can degrade clinker quality by altering its chemical composition through the introduction of excess silica or alumina. Furthermore, wood chips are occasionally sourced from whole trees felled specifically for fuel; this practice contradicts circular economy principles and reduces the population of trees available for CO_2 sequestration. Comparable limitations apply to sawdust, where high moisture content, low calorific value, and high cost limit its effectiveness.

3.6.Sensitivity Test of Calculation Result

Sensitivity tests conducted by varying AHP weights showed that the model is robust. Even with simulated changes to the weight criteria (increasing the importance of price), Carbon Rubber consistently remained the top recommendation (Table 17).

Table 15. Simulation of changes in AHP criteria weights

Criteria	Criteria Weight (%)	New Criteria Weight (%)
Heat Content	28.26%	28.26%
Water Content	28.16%	17.93%
Price	17.93%	28.16%
Transportation Costs	11.29%	11.29%
Number of Suppliers	6.36%	6.36%
Supplier	7.99%	7.99%
Total	100%	100%

Table 16. TOPSIS Preference Values

Material	Initial V Value	Simulation V Value
Rice Husk	0.4244	0.5029
Sawdust	0.2713	0.3832
Wood Chips	0.2849	0.3463
Pellets Rice Husk	0.5136	0.3701
Carbon Rubber	0.7266	0.6565
Shredded RDF	0.3726	0.4688

Table 17. Alternative Fuel Rankings

Ranking	Initial Fuel	Simulation Fuel
1	Carbon Rubber	Carbon Rubber
2	Pellets Rice Husk	Rice Husk
3	Rice Husk	Shredded RDF
4	Shredded RDF	Sawdust
5	Wood Chips	Pellers Rice Husk
6	Sawdust	Wood Chips

Carbon rubber is considered superior because it provides a high, consistent heat contribution to the kiln—averaging 6,363 kcal/kg — with a very low moisture content (~2.44%). This performance surpasses that of sub-bituminous coal (5,000–5,500 kcal/kg) and could reduce coal consumption. Although its supply capacity is relatively limited (±1,323 tons/month across four suppliers), its higher energy density reduces the tonnage required to meet the target heat input, making the volume constraint more tolerable. These findings are consistent with the AHP results, which identify calorific value (28.26%) and moisture content (28.16%) as the top priorities, while price (17.9%) and supplier capacity (~8%) are assigned lower weights. Consequently, carbon rubber remains the best alternative, achieving the highest TOPSIS score (V = 0.7266).

The study indicates that RDF offers high supply potential from municipal waste streams and can support fossil-fuel substitution; however, its quality is inconsistent because RDF is typically produced from mixed, multi-source feedstocks with variable composition and contaminants. Consequently, its calorific value is strongly governed by moisture content and dominant fractions (e.g., plastic type, wood), resulting in a wide range of heating values and a marked decline at high moisture levels. This variability can be reduced through upstream-to-downstream policies that strengthen source separation and expand and standardize pre-treatment facilities (sorting–shredding–drying) to improve homogeneity and meet particle-size specifications. So, it should implement quality standards and establish partnership mechanisms with local governments to ensure a continuous supply and compliance with fuel specifications. In a broader framing, improving RDF governance advances the circular economy by diverting residual waste from landfills and valorizing it as energy. At the same time, end-of-life tire processing into carbon rubber extends material circularity. It contributes to coal displacement, which, by implication, could support energy security by reducing dependence on coal, and aligns with national waste-management objectives that promote RDF utilization. Acknowledge limitations: geographical specificity to West Java suppliers; assumptions about price stability; scope 3 emissions from fuel transport not considered.

Previous studies have extensively investigated recovered carbon rubber, which has been identified as a candidate fuel or co-firing material in industrial processes [20], [21], [22]. [23] reported that using carbon rubber in limited proportions does not increase NOx and SOx emissions, provided that the blending ratio with coal is maintained at approximately 15–20%. At higher substitution levels, however, [24] found that sulfur emissions limit the broader use of carbon rubber during combustion, potentially leading to exceedances of regulatory thresholds. In addition, [25] and [21] noted that the high ash content of carbon rubber (approximately 10–20%) can adversely affect the composition of the resulting clinker. To address these limitations, [24] proposed blending carbon rubber with solid biomass, such as peat and rice husk. Their results showed that adding 15% rice husk reduced SOx emissions by 52%. This reduction was attributed to the lower ash content of biomass and its capacity to immobilize sulfur into the clinker. Sawdust also exhibits low ash content with relatively high silica composition; therefore, the resulting ash may positively influence clinker quality through the formation of alite crystals. [26] Further reported that SOx emissions from carbon rubber can be mitigated by co-firing it with biomass pellets made from sawdust and algae, emphasizing that biomass is a carbon-neutral fuel. Taken together with the findings of Slyusarsky et al. (2023), these results are consistent with the AHP–TOPSIS ranking, which indicates that recovered carbon rubber should be blended with pellets and rice husk (ranked second and third, respectively) to reduce the associated negative impacts.

4. Conclusion

The research results indicate that material quality takes priority over economic and logistical considerations. This shows that fuel quality and combustion process stability in the kiln are the management's main factors in selecting fuel, rather than just price and supplier factors. The optimal alternative fuel, based on the criteria, is Carbon Rubber, valued for its high heat output. The objective priority ranking for alternative fuels is as follows: Rank 1: Carbon Rubber (Main priority, highly recommended). Rank 2: Rice Husk Pellets. Rank 3: Rice Husk. Rank 4: Refuse-Derived Fuel (RDF). Rank 5: Wood Chips. Rank 6: Sawdust (Not recommended). Suggestions for further research include exploring dynamic MCDM with fluctuating prices, integrating Life Cycle Assessment (LCA), or expanding the study to other cement plants in Indonesia. For Company Management: The recommended technical actions can be consolidated into a single procurement and fuel-management strategy: Shift alternative-fuel procurement from price-based to quality-based selection (calorific value and moisture), apply blending by pairing abundant low-quality fuels with limited high-quality fuels to stabilize kiln operation, renegotiate costly high-quality fuels (e.g., rice husk pellets) through long-term contracts and more flexible penalties, and prioritize long-term contracts with carbon rubber suppliers to secure a consistent high-quality supply. For Policymakers: Develop standards for RDF quality and incentivize tire pyrolysis for carbon rubber production to support the circular economy.

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References

[1] J. Pucker-Singer, C. Aichberger, J. Zupancic, C. Neumann, D. N. Bird, G. Jungmeier, A. Gubina, and A. Tuerk, “Greenhouse gas emissions of stationary battery installations in two renewable energy projects,” *Sustainability (Switzerland)*, vol. 13, no. 11, Jun. 2021, doi: 10.3390/su13116330.

[2] A. Valavanidis, “Extreme weather events exacerbated by the global impact of climate change. A glimpse of the future, if climate change continues unabated,” *Scientific Review*, Feb 2023.

[3] Global Cement and Concrete Association, *Cement Industry Net Zero Progress Report 2024/25: An Update of Global Action and Progress of the GCCA and Its Member Companies*. London, U.K.: Global Cement and Concrete Association, 2024.

[4] N. A. Madlool, R. Saidur, M. S. Hossain, and N. A. Rahim, "A critical review on energy use and savings in the cement industries," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 4, pp. 2042–2060, May 2011, doi: 10.1016/J.RSER.2011.01.005.

[5] A. Z. Nugraha, E. I. Wiloso, and M. Yani, "Pemanfaatan serbuk gergaji sebagai substitusi bahan bakar pada proses pembakaran - kiln di pabrik semen dengan pendekatan life cycle assessment (LCA)," *Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan (Journal of Natural Resources and Environmental Management)*, vol. 8, no. 2, pp. 188–198, Aug 2018, doi: 10.29244/jpsl.8.2.188-198.

[6] Putra Adhiguna, "Indonesia's biomass cofiring bet : beware of the implementation risks," *Ieefa*, pp. 1-34, Feb 2021.

[7] A. Hasanbeigi, L. Price, and E. Lin, "Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 6220–6238, Oct 2012, doi: 10.1016/J.RSER.2012.07.019.

[8] F. B. D. Filho, L. V. M. deSousa, E. E. S. Lora, J. C. E. Palacio, P. T. Borges, R. M. Barros, R. L. Jaen, M. R. Erra, and Q. R. Quintero, "A methodology for the feasibility assessment of using crop residues for electricity production through GIS-MCD and its application in a case study," *Agriculture (Switzerland)*, vol. 15, no. 3, Feb 2025, doi: 10.3390/agriculture15030334.

[9] H. Howari, M. Parvez, O. Khan, A. Alhodaib, A. Mallah, and Z. Yahya, "Multi-objective optimization for ranking waste biomass materials based on performance and emission parameters in a pyrolysis process—an AHP–TOPSIS approach," *Sustainability (Switzerland)*, vol. 15, no. 4, Feb 2023, doi: 10.3390/su15043690.

[10] D. A.Wimantika and A. Hidayatno, "Advancing Indonesia's net zero goals through sustainable biomass supplier selection: insights from multi-criteria decision analysis," *Journal of Technology and Policy in Energy and Electric Power*, vol. 1, no. 2, Jun 2025, doi: 10.33322/jtpeep.v1i2/124.

[11] M. H. Manik, "Addressing the supplier selection problem by using the analytical hierarchy process," *Heliyon*, vol. 9, no. 7, Jul 2023, doi: 10.1016/j.heliyon.2023.e17997.

[12] R. A. Kubde, M. A. Bhura, and M. E. Student, "Supplier selection and evaluation in dairy industry using analytical hierarchy process," *Anvesha*, vol. 4, no. 1, Jun 2011.

[13] I. Fachri and Y. A. Hidayat, "A conceptual framework for the selection of biomass alternatives for coal co-firing using multi-criteria decision making (MCDM) approach," *IGSC*, vol. 5, no. 1, pp. 86-97, Oct 2025.

[14] A. Mardani, A. Jusoh, E. K. Zavadskas, F. Cavallaro, and Z. Khalifah, "Sustainable and renewable energy: An overview of the application of multiple criteria decision-making techniques and approaches," *Sustainability*, vol. 7, no. 10, pp. 13947-13984, Oct. 2015, doi: 10.3390/su71013947.

[15] A. Mokhtar and M. Nasooti, "A decision support tool for cement industry to select energy efficiency measures," *Energy Strategy Reviews*, vol. 28, pp. 100458, Mar 2020, doi: 10.1016/J.ESR.2020.100458.

[16] P. A. Alvarez, A. Ishizaka, and L. Martínez, "Multiple-criteria decision-making sorting methods: A survey," *Expert Syst. Appl.*, vol. 183, pp. 115368, Nov 2021, doi: 10.1016/J.ESWA.2021.115368.

[17] B. W. Taylor, *Introduction to Management Science*, 13th ed. Boston, MA, USA: Pearson, 2018.

[18] B. Uzun, D. U. Ozsahin, H. Gokcekus, and J. LaMoreaux, *Professional practice in earth sciences application of multi-criteria decision analysis in environmental and civil engineering*, England: Springer International Publishing, 2021.

[19] I. Emovon and O. S. Oghenenyerovwho, "Application of MCDM method in material selection for optimal design: A review," *Results in Materials*, vol. 7, pp. 100115, Sep 2020, doi: 10.1016/J.RINMA.2020.100115.

[20] B. N.-Smaragdakis, Z. Cepic, N. Senk, J. Doric, and L. Z. Radovanović, "Use of scrap tires in cement production and their impact on nitrogen and sulfur oxides emissions," *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, vol. 38, no. 4, pp. 485–493, Feb 2016, doi: 10.1080/15567036.2013.787473.

[21] I. Gökalp, O. Kaya, S. Keçecioglu, and D. Boden, "A techno-economic feasibility analysis for the gasification of scrap tires for energy generation in Turkey," *Detritus*, vol. 7, pp. 68–75, Sep 2019, doi: 10.31025/2611-4135/2019.13843.

[22] M. V. F. de Araújo, "Coprocessamento de pneus inservíveis na indústria cimenteira," *Scientia Tec*, vol. 5, no. 2, Dec 2018, doi: 10.35819/scientiatec.v5i2.3020.

[23] S. Saini, B. R. Bamniya, G. V Ramakrishna, and D. M. Kumawat, "Study of pollution load in environment during co-processing of solid waste (carbon black) in cement rotary kiln," *Poll. Res.*, vol. 36, no. 3, pp. 645–650, 2017.

[24] K. Slyusarsky, A. Tolokolnikov, A. Gubin, A. Kaltaev, A. Gorshkov, A. Asilbekov, and K. Larionov, "Ignition and emission characteristics of waste tires pyrolysis char co-combustion with peat and sawdust," *Energies (Basel)*, vol. 16, no. 10, May 2023, doi: 10.3390/en16104038.

[25] S. M. R. Costa, D. Fowler, G. A. Carreira, I. Portugal, and C. M. Silva, "Production and upgrading of recovered carbon black from the pyrolysis of end-of-life tires," *Materials*, vol. 15, no. 6, Mar 2022, doi: 10.3390/ma15062030.

[26] C. T. Dube and H. Baloyi, "Co-combustion of tyre waste char and biomass blends using thermogravimetric-mass spectrometric analysis," *S. Afr. J. Sci.*, vol. 121, no. 5–6, May 2025, doi: 10.17159/sajs.2025/18082.