Assessing sustainability critical success factors in the UAE cement industry using the fuzzy analytic hierarchy process

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Abstract

Purpose – The United Arab Emirates (UAE) cement industry is a vital contributor to national development, but faces significant sustainability challenges due to high energy consumption, carbon emissions, and resource depletion. This study aims to identify and prioritise critical success factors (CSF) that drive sustainability adoption in the sector using the fuzzy analytic hierarchy process (FAHP).

Design/methodology/approach – Through a mixed-method approach integrating literature review, expert opinions and stakeholder inputs, CSF are categorised into environmental, social and economic dimensions. The study employs advanced statistical tools, including exploratory factor analysis (EFA) for factor identification, Kaiser–Meyer–Olkin (KMO) and Bartlett's tests for data adequacy, Cronbach's alpha for reliability assessment, the relative importance index (RII) for ranking CSF, and the Kruskal–Wallis test for hypothesis validation.

Findings – Key findings highlight several important sustainability enablers, such as waste recycling technology used (ENV3), demand for green/sustainable products (SOC1), Lean Six Sigma (LSS) tools and methods that are assigned to solve problems that arise (ECO4). The research provides a strategic roadmap for industry leaders and policymakers, aligning sustainability efforts with the UAE's green economy vision. While the study focuses on the UAE cement industry, findings offer broader implications for similar industries globally. However, reliance on expert inputs may introduce subjectivity, and future research should incorporate real-time industry data for enhanced validation. By leveraging FAHP and robust statistical analysis, this study delivers a comprehensive framework to facilitate sustainability adoption, enhance decision-making and contribute to long-term environmental and economic resilience in cement manufacturing.

Practical implications – This article offers valuable, real-world insights to guide the UAE cement industry towards a more sustainable future. First, by identifying and prioritising CSFs such as waste recycling technologies and LSS tools, it provides a guide for regulators to create focused policies and incentives that encourage the most impactful sustainability practices. Second, the clear ranking of these factors gives UAE cement companies a benchmark for assessing their progress across all three pillars of sustainability. Finally, the study highlights the necessity for UAE cement industry practitioners to prioritise operational improvements using LSS tools and robust, real-time resource monitoring.

Originality/value – This study advances sustainability literature by integrating the FAHP with empirical statistical validation, offering a rigorous method for prioritising CSF in industrial sustainability. It contributes to a structured framework that bridges multi-criteria decision-making theory with practical implementation strategies, particularly within resource-intensive sectors like cement manufacturing.

Keywords Sustainability, UAE, Cement industry, Environmental, Social, Economic, FAHP, Critical success factors, Lean six sigma

Paper type Research article

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1. Introduction

The cement industry is a cornerstone of the UAE construction sector, playing a crucial role in the nation’s economic development. As a significant contributor to infrastructure growth, the industry is essential for national progress. The cement industry is one of the primary energy-intensive industries in the UAE. Cement manufacturing, an energy-intensive process, accounts for approximately 12–15% of a country’s total energy consumption, with the UAE’s cement manufacturers consuming 467,000 Tons of Oil Equivalent (TOE) annually. However, this industrial segment also poses substantial environmental challenges, being a significant source of carbon emissions, energy consumption and natural resource depletion. Figure 1 shows the diverse routes of cement industry pollution and its possible impact on the environment. The urgency to mitigate these impacts has never been greater, especially in light of the UAE’s commitments to global sustainability goals and its vision for a green economy.

The global cement industry has increasingly adopted sustainable practices to reduce its environmental footprint. With its ambitious sustainability agendas, such as the UAE Vision 2021 and the UAE Green Agenda 2030, the UAE actively seeks to align its industrial practices with these goals. Despite some advancements, the UAE cement industry still faces significant hurdles in fully integrating sustainable practices. This context sets the stage for critically examining the factors that can drive sustainable transformation within this sector. Transitioning to sustainability in the UAE cement industry is challenging. For manufacturing organisations, it is challenging to understand and identify the critical success factors that can facilitate successful implementations (Swarnakar *et al.*, 2020). These factors can provide a blueprint for overcoming barriers and highlight strengths for achieving a more sustainable operational framework. A key innovation of this study lies in its integration of MCDM methodologies, particularly the FAHP, into the realm of the cement industry. This novel approach underscores the research’s commitment to leveraging advanced decision-making tools to address sustainability challenges comprehensively. Additionally, EFA is employed, enhancing the robustness of CSF identification and validation.

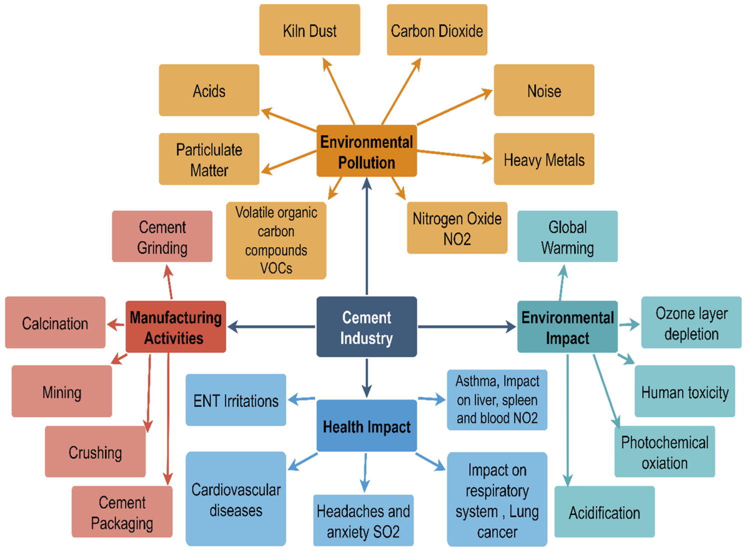

Figure 1. Diverse routes of cement industry pollution and its possible impacts. *Source: Authors’ work*

Modern organisations are in search of initiatives that will help them become sustainable and provide a competitive advantage to remain a continuous stakeholder in the global market (Yadav *et al.*, 2021). This study uniquely incorporates the three pillars of sustainability: environmental, economic and social factors. This holistic perspective ensures a balanced approach to sustainable transformation. Furthermore, the identified enablers of sustainability are rigorously verified through expert opinions from industry stakeholders, adding credibility and practical relevance to the findings. The significance of this study lies in its potential to transform the UAE cement industry into a model of sustainability. By identifying and analysing these CSF, the study provides valuable insights that can guide industry leaders, policymakers, and environmental advocates. The findings will not only help in formulating strategic initiatives for sustainability but also contribute to the broader discourse on sustainable industrial practices in the region. By combining FAHP and EFA, the study addresses uncertainties and subjective judgments in evaluating CSF, marking a pioneering effort in cement industry sustainability research.

Despite the cement industry's critical role in the UAE's economic and infrastructural development, there remains a notable deficiency in comprehensive, context-specific research that systematically identifies and prioritises the CSF for sustainable transformation within this sector. While global advances in sustainability and the adoption of decision-making tools like FAHP (Lachheb and Benlakouiri, 2025) have been explored in other industries and regions, their application tailored to the unique economic, environmental and social conditions of the UAE cement industry is limited. Moreover, existing studies often treat sustainability dimensions in isolation, neglecting the integrated perspective of the environmental, economic and social pillars that are essential for holistic progress. This research gap hinders the development of actionable, evidence-based strategies that can effectively guide policymakers, industry leaders and stakeholders in overcoming specific regional barriers. It is worth mentioning that a significant research gap is the underutilization of these MCDM techniques, which are not explicitly applied in the cement industry. Especially when originating from the LSS viewpoint or from the sustainability viewpoint. Moreover, such a study is not addressed region-wise, especially when considering all three pillars together. No study has encompassed this novel approach using the MCDM method. The literature reveals that these research gaps exist, and this study aims to address them. Therefore, this study's innovative integration of MCDM techniques with expert validation offers a crucial and timely contribution. It addresses these gaps by delivering a nuanced, multidimensional framework to drive sustainable practices uniquely suited to the UAE cement industry's challenges and opportunities.

The literature review explores existing research on sustainability in the cement industry, focusing on the fuzzy analytic hierarchy process and identifying the relevant CSF discussed by researchers. This section establishes the foundation for understanding the role of these decision-making techniques in enhancing sustainability. The methodology section outlines the research design, discussing data collection and analysis methods to ensure transparency and replicability. The results section presents findings from the FAHP, identifying key factors that influence sustainability in the cement sector. These findings are interpreted in the discussion, with strategic recommendations to guide stakeholders in improving sustainability practices. The conclusion summarises the research's key insights and suggests areas for future study to advance sustainability in the cement industry. The findings from this study underscore the significance of various factors, such as technological advancements (Santos and Sant'Anna, 2024), economic incentives, and Lean Six Sigma tools, in promoting sustainable practices. By systematically evaluating and ranking the CSF, this research offers a detailed roadmap for industry leaders and policymakers. The innovative combination of MCDM methodology, the inclusion of all three sustainability pillars and industry expert validation collectively position this study as a significant advancement in the domain. The actionable insights will enhance sustainability adoption, positioning the UAE cement industry as a model for sustainable industrial practices in the region.

2. Literature review

The cement industry plays a pivotal role in global infrastructure development but faces significant challenges related to environmental sustainability, energy efficiency and operational optimisation. A comprehensive literature review reveals active research on sustainability innovations (e.g., low-carbon binders and circular-economy approaches), lean manufacturing practices applied to cement plants and production performance enhancement through digital optimisation and AI-driven control (Volaity *et al.*, 2025). Studies highlight that the industry's substantial carbon footprint (Khaiyum *et al.*, 2023) accounts for a large share of global CO_2 emissions and is a major target for decarbonization efforts. A study conducted by Beguedou *et al.* (2023) emphasised the need for substituting clinker, adopting alternative fuels and waste co-processing, deploying carbon capture, utilisation and storage (CCUS) technologies and increasing the use of supplementary cementitious materials (SCMs) such as fly ash, blast-furnace slag and calcined clays to reduce clinker consumption (Scott, 2025). The following sections present a detailed literature review on the environmental, social and economic CSF for sustainability in the cement industry.

2.1 Environmental CSF for sustainability in the cement industry

Incorporating environmentally friendly practices in the cement industry requires more than technological upgrades; it demands a cultural transformation in which sustainability is integrated into every stage of production. Organisational culture plays a pivotal role in ensuring that employees and stakeholders align with environmental objectives, as awareness and engagement drive collective action (Gandhi *et al.*, 2017). This cultural shift is further reinforced when both developed and developing nations (Alinda, 2024) embed environmental performance metrics into operational standards, reflecting a global trend towards ecological responsibility (Amna Farrukh *et al.*, 2020). Nonetheless, embedding sustainability within organisational culture alone is not sufficient without the structural support of effective waste management systems and regulatory enforcement. A culture of environmental responsibility must be reinforced by infrastructure, policy, and accountability to achieve measurable impact. Waste minimisation emerges as a core environmental CSF, linking directly to both operational efficiency and circular economy goals. Advanced waste recycling technologies conserve resources, reduce landfill dependency, and improve economic performance through cost savings (Cherrafi *et al.*, 2016; Barbhuiya *et al.*, 2024). However, cultural commitment alone cannot achieve these results without supporting infrastructure, effective waste management systems and strong regulatory enforcement. The availability of appropriate disposal facilities and strict compliance mechanisms ensures that waste handling aligns with sustainability targets (Yadav *et al.*, 2021). Another critical CSF is raw material substitution, which directly reduces the depletion of natural resources and lowers the environmental footprint of cement manufacturing. Substituting clinker with supplementary cementitious materials such as fly ash, blast-furnace slag and calcined clay has proven effective in both emission reduction and resource conservation (Amrina and Vilsi, 2015; Khaiyum *et al.*, 2023). Coupled with strict emission control strategies, this approach ensures that material efficiency translates into measurable environmental outcomes.

While regulatory compliance and raw material substitution lay the groundwork for sustainability, they must be complemented by targeted emission control strategies. Identifying and operationalising emissions-related key performance indicators (KPI) is essential to translate policy adherence into tangible environmental outcomes. Emission reduction remains the most urgent priority for the cement industry, given its substantial contribution to global CO_2 levels. Emissions-related KPI, such as greenhouse gas (GHG) intensity per tonne of cement, provide measurable benchmarks for sustainability performance (Moktadir *et al.*, 2020). Among the innovative solutions, carbon capture and storage (CCS) has gained prominence as a long-term mitigation strategy. CCS captures CO_2 before it is released into the atmosphere, storing it underground or reusing it industrially, which significantly reduces the sector's climate impact. When integrated with other green technologies, CCS enhances the overall effectiveness of decarbonization pathways (Beguedou *et al.*, 2023). However, focusing solely on emissions control provides a partial view of environmental sustainability. A broader approach must also encompass resource efficiency and supply chain practices, particularly in water management and low-impact logistics. Cement manufacturing is water-intensive, and sustainable practices such as closed-loop recycling, wastewater treatment and efficient cooling systems can significantly reduce consumption and alleviate stress on freshwater resources (Belaïd, 2022). Additionally, adopting eco-friendly transportation and packaging methods further reduces the carbon footprint of cement products, aligning with global sustainability efforts. Greenhouse gas emissions are generated during the manufacturing process and throughout supply chain activities, including logistics and transportation (Amna Farrukh *et al.*, 2020). By addressing these environmental CSFs, the cement industry can create a robust foundation for sustainable growth while fulfilling its ecological responsibilities.

2.2 Social CSF for sustainability in the cement industry

The growing demand for green and sustainable products pushes industries, including the cement sector, to adopt more environmentally friendly practices. Meeting these market and consumer expectations fulfils social responsibilities and enhances the company's image as a "green" business, ultimately improving customer satisfaction. This dual benefit, fulfilling ethical obligations while strengthening market positioning, underscores the value of socially responsible operations. By proactively addressing the needs of customers and communities, organisations demonstrate a strong commitment to corporate social responsibility, thereby strengthening their public image. Such proactive measures can also mitigate potential reputational risks, which are increasingly significant in a socially conscious marketplace. However, social responsibility cannot be confined to customer-facing initiatives alone. Extending sustainability practices across the supply chain, particularly through strategic supplier partnerships, ensures deeper, system-wide environmental and reputational impact.

Establishing strong relationships with suppliers and prioritising sustainability is also vital for promoting environmental responsibility throughout the supply chain. Such partnerships can result in significant environmental benefits, such as reducing energy consumption and waste (Cherrafi *et al.*, 2016). Additionally, these collaborations enhance resilience within the supply chain, ensuring consistent performance even in the face of disruptions. Moreover, close collaboration with suppliers provides advantages like real-time information sharing, long-term contracts and supplier rationalisation, all of which contribute to a more resilient and sustainable supply chain. However, supplier collaboration alone cannot drive sustainability without strong internal leadership commitment. Embedding sustainability across the organisation requires top management to champion change and align strategic direction with environmental and operational goals.

Effective leadership and a strong commitment from top management are critical for embedding sustainability initiatives into the corporate strategy. Leaders play a pivotal role in allocating resources, educating team members on the importance of diverse skills and developing strategies to manage potential tensions within the team. Leadership's role extends beyond strategy; it sets the tone for a culture that values and integrates sustainability into every organisational process. A systemic approach to organisational change, including readiness for change, is also crucial for the successful implementation of sustainability initiatives. Still, leadership commitment must be reinforced through organisational capacity-building efforts. Training, communication, and knowledge sharing are essential enablers that translate strategic intent into daily sustainable practices across all levels.

Providing comprehensive training equips employees with the skills and knowledge needed to effectively implement sustainable practices, fostering a culture of continuous improvement.

Promoting clear communication across all levels of the organisation ensures that sustainability objectives are well understood and consistently implemented. Henríquez Machado *et al.* (2021) emphasised that critical success factors for sustainability include effective communication, education and training, knowledge transfer and knowledge management. These factors highlight the importance of bridging knowledge gaps to drive operational and strategic alignment (Dwikat *et al.*, 2025). Workplace safety and accident prevention are essential to maintaining a healthy, productive workforce, which is foundational to sustainable operations. Nonetheless, internal capacity-building must be complemented by external validation and accountability. Integrating health, safety, and recognised sustainability standards ensures that internal efforts align with global benchmarks and stakeholder expectations.

Prioritising occupational health and safety not only protects employee well-being but also supports a sustainable working environment (Barcia *et al.*, 2022). Collaborating with local and international sustainability-focused organisations and obtaining relevant certifications further solidifies an organisation's commitment to sustainability. Common indicators for evaluating sustainable manufacturing include metrics established by the World Business Council for Sustainable Development (WBCSD), along with standards such as International Organisation for Standardisation (ISO) 14,031, the Global Reporting Initiative (GRI) and the Organisation for Economic Co-operation and Development (OECD) (Amrina and Vilsi, 2015). These certifications not only validate sustainability efforts but also serve as benchmarks for continuous improvement.

2.3 Economical CSF for sustainability in the cement industry

Economic viability is a critical component of sustainability in the cement industry. While environmental and social considerations are paramount, economic sustainability ensures the industry's long-term survival and ability to invest in green technologies and practices (Habtemaryam *et al.*, 2025). Several economic CSFs contribute to the industry's sustainability. Cost reduction through optimised resource utilisation, waste minimisation, and energy efficiency is essential (Gandhi *et al.*, 2017). These cost-saving measures are not merely operational imperatives; they are strategic levers that enable reinvestment in innovation and sustainability. However, economic sustainability should not be viewed in isolation from environmental and social goals. Integrating cost-efficiency with regulatory compliance and innovation creates a synergistic pathway towards resilient and sustainable cement industry growth. Moreover, adopting lean and green practices simultaneously can yield significant economic benefits. Regulatory compliance is another crucial economic CSF. Adherence to environmental regulations not only avoids penalties but also fosters a level playing field, encouraging innovation and competitiveness (Cherrafi *et al.*, 2016). This alignment between compliance and competitiveness ensures that sustainability is not a burden but an enabler of growth. Using low-cost substitute raw materials can also reduce production costs while contributing to environmental sustainability (Amrina and Vilsi, 2015). Nevertheless, some sustainable strategies, like CCS and water management, require upfront investments that may challenge short-term economic goals. Balancing these costs with long-term benefits is key to unlocking the transformative potential of sustainability in the cement industry.

Emission reduction strategies, such as implementing CCS technologies, can incur initial investment costs but offer long-term economic advantages. Efficient water management is crucial for economic sustainability, as water scarcity can increase costs. Implementing water-saving technologies and practices not only reduces operational expenses but also enhances the industry's reputation for environmental responsibility (Belaïd, 2022). While emission reduction and resource management offer economic benefits, they must be integrated within a broader sustainability framework. Economic CSFs are intertwined with environmental and social aspects of sustainability. By focusing on cost reduction, regulatory compliance, resource optimisation and emission reduction, the cement industry can achieve long-term economic viability while contributing to a sustainable future. Recognising inventory costs as a key economic factor highlights the need for lean strategies that also support environmental objectives. This integrated approach builds on historical efforts in the cement industry to optimise resource use and manage energy expenses effectively.

Managing inventory costs efficiently is crucial for organisations' financial sustainability, as it aligns with economic and environmental goals. The lean manufacturing concept identifies inventory costs as a waste that should be minimised, contributing to both cost reduction and environmental benefits. This approach is particularly relevant in industries like cement, where energy costs and material efficiency are significant factors. Historically, the cement industry has leveraged alternative materials and fuels to mitigate rising energy costs, especially following the oil crisis of the 1970s (Supino *et al.*, 2015). While lean principles help minimise waste and costs, evaluating the financial impact of alternative materials is essential to ensure sustainable adoption.

Evaluating the financial implications of these alternatives is essential for balancing cost and sustainability, ensuring long-term economic viability. For instance, switching to renewable fuels and improving energy efficiency can reduce greenhouse gas emissions, aligning with global sustainability targets (Thwe *et al.*, 2021). Overcoming plant infrastructure constraints is vital to adopting sustainable practices, as local circumstances often dictate the feasibility of these initiatives (Sanjeev and Shrivastava, 2017). While addressing infrastructure and cost challenges is fundamental, leveraging innovation and continuous improvement tools is key to unlocking sustainability's full potential. Integrating these efforts strategically enables the cement industry to transform environmental initiatives into competitive and financial advantages. Effective management of energy costs and consumption not only lowers environmental impact but also enhances the financial viability of sustainable practices (Iglinski and Buczkowski, 2017). The cement industry, like many others, has seen extensive research efforts aimed at reducing energy consumption through alternative fuels and raw materials. Investing in research and development to foster innovative, sustainable manufacturing solutions is another key to long-term industry advancement. The return on investment (ROI) from transitioning to green manufacturing can justify the financial outlay, making strategic business decisions aligned with SDGs (Opoku, 2025). The use of LSS tools in this context can drive continuous improvement by enhancing process efficiency and reducing costs associated with product reuse, remanufacturing and material recovery (Henríquez Machado *et al.*, 2021). This not only promotes a circular economy but also optimises operational performance. Finally, leveraging sustainable manufacturing practices can open new market opportunities and support strategic expansion, positioning the UAE cement industry as a leader in sustainable practices. Environmental initiatives can enhance financial returns by attracting new customers, differentiating the brand in a competitive market, and reducing costs through waste reduction (Hartinia and Ciptomulyono, 2015). This showcases the broader potential of sustainability as a driver for growth and innovation. By systematically addressing these critical success factors, industry leaders and policymakers can develop targeted strategies to enhance sustainability adoption, positioning the UAE cement industry as a model for sustainable practices in the region. This comprehensive approach demonstrates that balancing environmental, social and economic priorities, as shown in Figure 2, is not just achievable but essential for meeting stakeholder demands and advancing industry performance.

The comprehensive review of existing literature clearly highlights critical insights and unresolved issues that form the foundation of this study. In particular, the gaps identified through prior research provide strong justification for undertaking this investigation. Accordingly, the research is being conducted to address the following facts:

(1) Fact 1: *A significant research gap lies in the limited application of MCDM techniques within the cement industry, particularly from an LSS or sustainability viewpoint.*

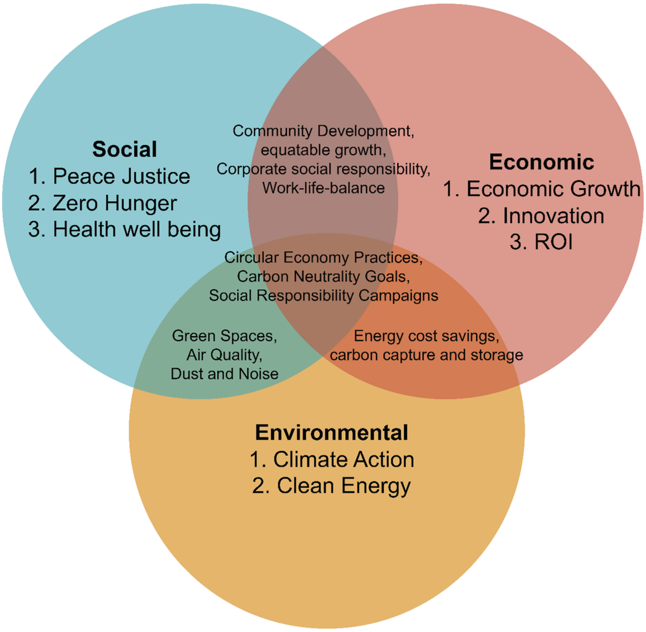

Figure 2. The three pillars of sustainability interconnected concepts. *Source: Authors' own work*

(2) Fact 2: *Regional studies that integrate all three sustainability pillars remain largely unexplored.*

(3) Fact 3: *To date, no research has adopted this novel approach of employing MCDM methods in this context.*

2.4 MCDM techniques in literature

The applications of MCDM techniques are numerous and span all known fields, such as engineering, business, healthcare and policy-making. Such techniques offer structured and precise ways to make complex choices easier. In the automotive industry, Dweiri *et al*. (2016) conducted a study where the AHP was employed to support the decision system when selecting the best suppliers for the factory. As indicated earlier, methods such as AHP and best worst method (BWM) are used for supplier selection and process optimisation due to their ability to include expert inputs and give weights to each criterion. AHP mainly targets decision problems by using hierarchical levels and compares criteria pairwise, making it ideal for problems that are structured and organised. On the other hand, BWM reduces the number of required comparisons and improves consistency in weighting. In a study conducted by Khokhar *et al*. (2020) in the field of supply chain management, it was identified that employment practices are the most significant criteria, while cultural values are the least important, using the BWM technique. Analytic network process (ANP) adds to AHP by considering interdependencies among criteria, which means that in complex industrial ecosystems, factors like cost and quality influence each other continuously. In the field of the construction industry, Shariati *et al*. (2017) conducted a study using ANP to identify and evaluate the critical factors of the application of nanotechnology in construction, focusing on the most critical ones.

In the sustainability and energy sectors, Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) and Elimination and Choice Expressing Reality (ELECTRE) are applied for evaluating renewable energy projects, ranking sustainability barriers and prioritising environmental policies. The practices for industrial steam boilers in a study conducted by Demirel *et al.* (2021) were identified using the PROMETHEE method. It was found that the most important energy efficiency practices were the reuse of condensate, maintenance and repair of steam traps, insulation of steam boilers and distribution systems. PROMETHEE provides a flexible outranking approach, which is effective to rank more than one alternative with conflicting objectives. ELECTRE is excellent in removing nonviable options in large-scale and complex decisions. For example, a study by Salvador *et al.* (2024) aimed at discovering the applications of ELECTRE in various industries shows that the tools have been used in more than 14 industries worldwide between 2018 and 2022. Moreover, Mehralian *et al.* (2016) used the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) in the pharmaceutical industry, where they identified the critical success factors for improving product quality without compromising cost or profit margins. TOPSIS ranks alternatives based on their closeness to the ideal solution and their distance from the worst-case scenario. This enables policymakers to select the most balanced option at hand. VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) is particularly beneficial to decision makers in sustainability studies, such as those where the goal is to achieve a balance between conflicting objectives. Research using the VIKOR method was conducted by Gokhan Torlak *et al.* (2021) in the Internet industry. They found that network and information quality, along with security/privacy, significantly positively impact customer trust. Additionally, network and information quality, as well as customer trust, significantly positively affect Internet users’ value perceptions.

DEMATEL is used in many fields, such as the aluminium industry, to identify and provide a clear visualisation of the cause/effect relationships between critical success factors (Santos *et al.*, 2025). This allows decision makers to address root causes of system down sides and areas for improvement. A study by Kashyapa *et al.* (2022), which used the DEMATEL model to investigate the impediments to incorporating a circular economy in the aluminium industry, clearly demonstrates the tool’s ability to solve complex scenarios.

MCDM tools are also used in maintenance planning systems. Tools like Multi-Objective Optimisation on the Basis of Ratio Analysis (MOORA) are known for their simplicity and ease of use in ranking alternatives for many projects. This tool has been utilised by Domínguez *et al.* (2018) to study decision-making in the industrial area, specifically in the maintenance of moulding machines. On the other hand, Weighted Aggregated Sum Product Assessment (WASPAS), which combines the strengths of weighted sum and weighted product models, has been used by researchers in many areas. For instance, in the cement industry, Singh and Modgil (2020) conducted a study where they evaluated and prioritised key supplier selection indicators and established the relationship between available alternatives and selected indicators. Multi-Attribute Utility Theory/Value Theory (MAUT/MAVT) is another MCDM tool used by Özdagoglu and Çirkin (2019) in the manufacturing industry, where the purchase decisions of electronic device alternatives are analysed in the industrial products and machinery sector.

The literature clearly outlines that these MCDM techniques provide powerful, organised and scientifically solid ways for solving problems with multiple dimensions. Using these tools enables decision makers to search and carefully select options without compromising any trade-off. Using these tools keeps objectives in sight and minimises difficulties related to uncertainty in various sectors and study areas.

2.5 Selection of sustainability CSF

The process of identifying the CSF essential for promoting sustainability within the industry was driven by the imperative need to improve both operational efficiency and strategic response to sustainability challenges. This foundational need catalysed a comprehensive investigation into the determinants of sustainable success. The primary objective was to explore, analyse and eventually define a set of key parameters that could be recognised as enablers of sustainability across environmental, social and economic dimensions. To initiate this process, an extensive literature review was undertaken, focusing on both foundational research and recent advancements in the field. This review served as a preliminary screening mechanism to extract a broad set of potential CSFs documented in academic and industry-specific sources. The analysis involved identifying relevant keywords and utilising peer-reviewed and verified databases to ensure the credibility and relevance of the extracted data. Following this, a structured survey was developed and disseminated to industry experts to assess the perceived relevance and significance of each identified factor. This expert validation phase was critical to refining the list by eliminating redundant, contextually irrelevant, or marginally impactful factors. To further strengthen the rigour of the selection process, a series of face-to-face interviews was conducted with a subset of experienced professionals and subject matter experts. These interviews facilitated deeper insights, allowing for a final round of qualitative validation and contextual calibration. As a result of this multi-stage filtering and validation process, a concise and targeted list of CSFs was developed. Specifically, as shown in Table 1, ten critical success factors were identified for each of the three pillars of sustainability: environmental, social and economic. These factors represent a well-designed and contextually grounded foundation for subsequent analysis and implementation efforts.

3. Methodology and research design

The methodological framework illustrated in Figure 3 follows a structured, multi-stage approach integrating literature analysis, expert validation and statistical modelling. First, an in-depth literature review of 100 Scopus-indexed journal articles in sustainability and engineering was conducted, leading to the identification of 30 preliminary CSF. The process begins to validate these CSF with data collection through surveys and interviews targeting key stakeholders, including industry experts, policymakers and environmental advocates.

The current study employs a mixed-method approach, utilising a variety of tools concurrently to construct the research methodology. Interviews serve as a complementary qualitative method, offering in-depth perspectives on contextual factors influencing sustainability adoption and benchmarking industry performance against international standards. In a study conducted in the machine learning field by Paleyes *et al.* (2022), surveys and interviews were used to examine the deployment of machine learning models in production systems, identifying the current number of issues and concerns. Our surveys are developed using a structured questionnaire to capture both quantitative and qualitative insights. A Likert scale is used, and it is considered one of the most fundamental and frequently used psychometric tools in educational and social sciences research (Joshi *et al.*, 2015). In a study conducted in the field of benchmarking operational capacity, conducted by Pescaroli *et al.* (2020), they used a Likert scale to derive a simple rating tool that can be used for benchmarking responses in questionnaires, like the ones used for assessing disaster risk reduction, gaps in operational capacity and organisational resilience. A 5-point Likert scale is employed in our study to assess the relative importance of various factors contributing to sustainability. At the same time, pairwise comparisons provide additional clarity on the significance of environmental indicators. To analyse the data systematically, the KMO test is performed to evaluate data adequacy for factor analysis, ensuring the dataset's suitability for further examination and Bartlett's test of Sphericity is used to assess the factorability of the data (Shrestha, 2021). Zhang *et al.* (2024) used KMO to establish an assessment framework for cultivating undergraduate applied talent, specifically emphasising data science competencies, in alignment with the development of China's regional economy. The validated CSF were then categorised into environmental, social, and economic pillars using EFA with Varimax rotation and factor loading complemented by ordinal grouping.

Table 1. Summary of literature reviewed to identify CSF for sustainable manufacturing

Main criteria	Sub-criteria (CSF)	CSF code	Authors and year	Aspects of sustainability		
				Economic	Social	Environmental
Environmental Based CSF	Environmentally friendly practices implemented	ENV1	Kumar *et al.* (2023), Yadav *et al.* (2021)	√	–	√
	Environmental awareness	ENV2	AlSanad (2018), Amna Farrukh *et al.* (2020)	–	√	√
	Waste recycling technology used	ENV3	Amna Farrukh *et al.* (2020), Swarnakar *et al.* (2020), Wang *et al.* (2021), Yadav *et al.* (2021)	√	√	√
	Availability of appropriate locations for waste disposal	ENV4	Kaswan and Rajeev (2021), Swarnakar *et al.* (2020)	–	√	√
	Local environmental regulations	ENV5	Cherrafi *et al.* (2016)/ Gandhi *et al.* (2017)	√	√	–
	Availability of substitute raw materials in the environment	ENV6	Amrina and Vilsi (2015), Singh *et al.* (2018)	√	–	√
	Harmful emissions generated	ENV7	Amrina and Vilsi (2015)/, Moktadir *et al.* (2020), Singh *et al.* (2018)		√	√
	Carbon capture and storage technology use	ENV8	Amna Farrukh *et al.* (2020)/ Gandhi *et al.* (2017)	√	√	
	Amount of water used	ENV9	Amrina and Vilsi (2015)/ Moktadir *et al.* (2020)	√	–	√
	Environmentally-friendly transportation	ENV10	Izumi *et al.* (2021)/Kumar *et al.* (2023a, b)/Belhadi *et al.* (2021)	–	√	√
Social Based CSF	Demand for Green/ Sustainable products	SOC1	AlSanad (2018)/Amna Farrukh *et al.* (2020)/ Kaswan and Rajeev (2021)/ Kumar *et al.* (2023a, b)/ Wang *et al.* (2021)	√	√	–
	Effective communication among workers	SOC2	Amna Farrukh *et al.* (2020)/ Kumar *et al.* (2023a, b)/ Venugopal and Saleeshya (2019)	–	√	√
	Organisational response to customer demands	SOC3	Amna Farrukh *et al.* (2020)/ Kaswan and Rajeev (2021)/ Kumar *et al.* (2023a, b)/ Swarnakar *et al.* (2020)	√	√	–
	Organisation's relationship with suppliers	SOC4	Cherrafi *et al.* (2016))/ Kumar *et al.* (2023a, b)/ Yadav *et al.* (2021)	√	√	–
	Quality of training provided to workers	SOC5	Amrina and Vilsi (2015)/ Amrina *et al.* (2016)/ Amna Farrukh *et al.* (2020)/ Kaswan and Rajeev (2021)/ Kumar *et al.* (2023a, b)/ Swarnakar *et al.* (2020)/ Wang *et al.* (2021)	–	√	–
	Level of involvement and support of top management	SOC6	Cherrafi *et al.* (2016)/Amna Farrukh *et al.* (2020)/ Kaswan and Rajeev (2021)/ Kumar *et al.* (2023a, b)/ Swarnakar *et al.* (2020)/ Yadav *et al.* (2021)	√	√	–
	Employees' adaptability to changes in work practices	SOC7	AlSanad (2018)/Wang *et al.* (2021)/Hanim *et al.* (2017)	–	√	–
	Workplace safety and accident prevention	SOC8	Amrina and Vilsi (2015)/ Moktadir *et al.* (2020)/ Singh *et al.* (2018)	–	√	–
	Availability of local and international sustainability-focused agencies	SOC9	AlSanad (2018)/Kaswan and Rajeev (2021)/Found *et al.* (2018)	–	√	√
	Level of occupational health and safety	SOC10	Amrina and Vilsi (2015)/ Amrina *et al.* (2016)/ Moktadir *et al.* (2020)/ Singh *et al.* (2018)	–	√	–

(*continued*)

Table 1. Continued

Main criteria	Sub-criteria (CSF)	CSF code	Authors and year	Aspects of sustainability		
				Economic	Social	Environmental
Economical Based CSF	Impact of inventory cost	ECO1	Amrina and Vilsi (2015)/Amrina *et al.* (2016)/Singh *et al.* (2018)	√	–	–
	The financial impact of using an alternate or substitute material is "cost and consumption."	ECO2	Amrina *et al.* (2016)/Jamwal *et al.* (2022)/Barcia *et al.* (2022)	√	–	√
	The plant's infrastructure constraints hinder sustainability adoption financially	ECO3	AlSanad (2018)/Amna Farrukh *et al.* (2020)/Kaswan and Rajeev (2021)	√	–	√
	LSS tools and methods are assigned to solve problems that arise	ECO4	Amna Farrukh *et al.* (2020)/Yadav *et al.* (2021)	√	–	√
	Energy cost and consumption level	ECO5	Amrina and Vilsi (2015)/Amrina *et al.* (2016)/Russo and Camanho (2015)	√	√	–
	Adequacy of R&D funding for sustainable manufacturing solutions	ECO6	Amna Farrukh *et al.* (2020)/Kumar *et al.* (2023a, b)/Sangwan *et al.* (2018)	√	√	–
	Using LSS tools to mitigate the cost of product reuse, remanufacturing and material recovery	ECO7	Gandhi *et al.* (2017)/Moktadir *et al.* (2020)/Mokhtar and Nasooti (2020)	√	√	–
	LSS tools and methods are used to create and utilise "finance and resources properly."	ECO8	Amna Farrukh *et al.* (2020)/Kaswan and Rajeev (2021)/Yadav *et al.* (2021)	√	–	√
	A degree of return on investment can be expected from transitioning to fully green manufacturing	ECO9	Kaswan and Rajeev (2021)/Moktadir *et al.* (2020)/Wang *et al.* (2021)	√	–	√
	Adopting sustainable manufacturing methods in new market opportunities and expansion	ECO10	Amna Farrukh *et al.* (2020)/Kaswan and Rajeev (2021)/Wang *et al.* (2021)/Yadav *et al.* (2021)	√	√	–

Source(s): Authors' work

Data consistency was tested using Cronbach's Alpha for reliability (Tavakol and Dennick, 2011), Corrected Item Minus Total Correlation (CIMTC), RII (Doloi *et al.*, 2012) and the Kruskal–Wallis test for hypothesis validation across stakeholder groups (McKight and Najab, 2010). Finally, FAHP (Saaty *et al.*, 2022; Kahraman *et al.*, 2003) was applied as a multi-criteria decision-making tool to address uncertainty and derive final rankings of CSF. In the area of landfill site selection, a study conducted in Turkey by Beskese *et al.* (2015) evaluated three possible landfill sites for the city of Istanbul through expert opinion and by facilitating FAHP and fuzzy TOPSIS.

4. Implementation

The methodology flowchart in Figure 3 outlines the steps and phases of the research. It provides a clear overview of the main steps conducted and a logical understanding of the research inputs and outcomes. The research began with an in-depth literature review of 100 articles from Scopus-indexed journals in sustainability and engineering. This review resulted in the identification and analysis of 30 CSF. These CSFs were validated through an expert survey analysis with a sample size of 24 (Al Fozaie and Hairunnizam, 2022), which revealed a high percentage that matched the literature, confirming their importance in positively contributing to sustainability in the cement industry.

To ensure the credibility and relevance of the data collected for verifying and validating the extracted CSF for sustainability in the cement industry, a set of expert selection criteria was

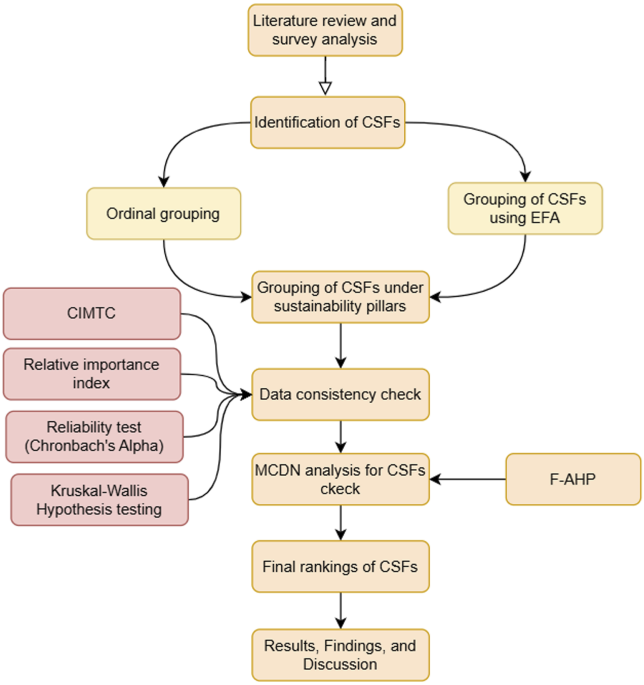

Figure 3. Proposed methodology for identification of CSF. *Source: Authors' own work*

established. Experts were chosen based on their professional experience, sector involvement, and familiarity with sustainability practices specific to cement manufacturing. Eligible participants typically possessed a minimum of seven years of experience in roles related to operations, environmental management, production, maintenance or strategic planning within the cement industry. Additionally, experts held mid-to-senior-level managerial or technical positions such as Sustainability Managers, Environmental Engineers, or Plant Directors, which enabled them to provide informed insights on both operational challenges and strategic priorities. Academic qualifications in relevant fields (e.g., engineering, environmental science, or industrial management) and professional certifications such as ISO 14001, LSS, or National Examination Board in Occupational Safety and Health (NEBOSH) further supported their expertise. Preference was given to individuals with direct experience in sustainability initiatives, including waste management, emissions reduction, water conservation, or energy efficiency projects. To ensure contextual relevance, participants were either based in or had significant professional experience within the UAE or the broader Gulf region. Experts meeting at least four of these criteria were considered qualified for inclusion in the questionnaire survey, ensuring that the validation process was grounded in informed, regionally relevant, and practically experienced perspectives.

The CSF was further categorised into three groups, i.e. environmental, social and economic, using Varimax rotation and factor loading, as well as through ordinal grouping. Their consistency was verified through exploratory factor analysis and Cronbach's alpha value. The data consistency and outcomes were also validated using CIMTC, RII and a p-test hypothesis testing using the Kruskal–Wallis method. After data collection, verification and grouping, FAHP, a multi-criteria decision-making technique, was used to rank and prioritise the 30 identified CSF.

4.1 Exploratory factor analysis

The KMO measure and EFA are commonly used in the preliminary stages of factor analysis to assess data adequacy and suitability for further analysis. In this study, the KMO measure is used to evaluate the adequacy of the sample data for conducting factor analysis. It assesses the proportion of variance in variables that underlying factors might cause. The KMO value ranges between 0 and 1, as shown in Table 2, with higher values indicating that the data is more suitable for factor analysis. Table 2 summarises the KMO values and their interpretation.

Initially, a set of variables, 30 CSF, believed to be interrelated and indicative of underlying constructs, was selected. Then, the correlations among these variables were used to identify the underlying factors through a correlation matrix. Next, the result was interpreted into three factors based on the pattern of loadings, which indicates the strength of the relationship between variables and factors. Iterative refinement and validation ensure the robustness and reliability of the extracted factors. One of EFA's primary benefits is its ability to simplify complex data, distilling it into essential dimensions without losing critical information. By uncovering these latent factors, we gain deeper insights into the phenomena under investigation, facilitating hypothesis testing, model development or decision-making processes. Moreover, EFA allows for creating more parsimonious models, reducing redundancy and enhancing the interpretability of results. EFA stands as a powerful tool in the researcher's arsenal, offering a systematic approach to uncovering the hidden structure within data. Its diverse applications, structured methodology and significance in advancing knowledge across various domains make it an indispensable asset in the pursuit of understanding complex phenomena.

Table 3 of KMO and Bartlett's test shows the results of the data adequacy check, confirmed by a KMO value of 0.7. A high KMO value suggests that factor analysis will likely yield distinct and reliable factors. In contrast, a low value suggests that the correlations between variables are too low to justify factor analysis. EFA is a statistical technique to identify the underlying relationships between measured variables. It is beneficial when there is no predefined hypothesis about the data structure.

EFA tries to explain the correlations among observed variables through a few unobserved variables called factors. Common methods include principal component analysis (PCA) and

Table 2. KMO value interpretation

KMO value	Adequacy level
Above 0.90	Excellent
0.80–0.89	Good
0.70–0.79	Adequate
0.60–0.69	Mediocre
0.50–0.59	Poor
Below 0.50	Unacceptable

Source(s): Authors' own work

Table 3. KMO and Bartlett's test

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO)		0.72
Bartlett's test of Sphericity	Approx. Chi-Square	1,443
	Df	435
	Significance according to Bartlett	0

Source(s): Authors' own work

principal axis factoring (PAF); in this study, the PCA method was implemented. Factor Loadings are coefficients that represent the relationship of each variable to the underlying factor. High loadings (commonly above 0.3 or 0.4) suggest a strong relationship. Factors are often rotated to make the structure more interpretable. Varimax rotation, as shown in Table 4, is a standard method that maximises the variance of squared loadings of a factor across variables, simplifying the interpretation. Various criteria can be used to determine the number of factors to retain, such as the eigenvalue "greater than 1" rule, scree plot analysis or parallel analysis. Before running an EFA, the KMO value must be checked to ensure the data is suitable for factor analysis. Once the data is confirmed to be adequate via the KMO statistic, EFA is performed to identify the underlying factor structure. The results of EFA help in understanding the dimensionality of the data and the relationships among variables. In this study, the data naturally fell under three categories, representing the three dimensions of sustainability in scope. EFA is a statistical technique employed to uncover the underlying structure of a set of variables. Its essence lies in reducing the complexity of data by identifying the latent factors that explain the patterns of correlations among observed variables. Each variable may seem distinct, but EFA helps unveil the hidden framework (factors) that connect them. By discerning these factors, researchers can grasp the essential dimensions influencing the phenomena under study. Through EFA, seemingly unrelated variables can be grouped, shedding light on the underlying constructs driving their interrelationships.

Table 4. Rotated component matrix

Rotated Component Matrix (Varimax)

CSF code	*Description*	*Component* *1*	*2*	*3*
ENV1	Environmentally friendly practices	0.51		
ENV2	Environmental awareness	0.69		
ENV4	Availability of waste disposal locations	0.57		
ENV5	Local environmental regulations	0.61		
ENV6	Availability of substitute raw materials	0.31		
ENV10	Environmentally-friendly transportation	0.45		
SOC1	Demand for Green/Sustainable products	0.55		
SOC2	Effective communication among workers	0.82		
SOC3	Response to customer demands	0.65		
SOC4	Organisation's relationship with suppliers	0.77		
SOC5	Quality of training provided to workers	0.71		
SOC6	Involvement and support of top management	0.6		
SOC7	Employees' adaptability to changes in work practices	0.63		
SOC8	Workplace safety and accident prevention	0.65		
ECO8	LSS tools and methods used to create and utilize "finance and resources"	0.45		
ENV3	Waste recycling technology used		0.37	
ENV7	Harmful emissions generated		0.65	
ENV8	Carbon capture and storage technology		0.71	
ENV9	Amount of water used		0.47	
SOC9	The degree of return on investment		0.73	
SOC10	Level of occupational health and safety		0.5	
ECO1	Impact of inventory cost		0.55	
ECO2	Cost and consumption of substitute fuels			0.43
ECO3	The plant's financial infrastructure constraints			0.64
ECO4	LSS tools and methods used to solve problems			0.53
ECO5	Energy cost and consumption level			0.7
ECO6	Adequacy of research and development funding			0.67
ECO7	LSS tools to mitigate the cost of product resource recovery			0.62
ECO9	The degree of return on investment			0.77
ECO10	Adopting sustainable manufacturing methods in new market opportunities			0.71

Source(s): Authors' own work

A PCA component plot, as shown in Figure 4, visually represents how the original data points are distributed in terms of the principal components. It helps to identify patterns, clusters or separations in the data based on the most important variance directions. The plot in Figure 4 forms three main groups, as illustrated by the arrangement of data points. On the other hand, Figure 5 shows the scree plot, which is a line graph that displays the eigenvalues of each principal component in descending order. It helps determine how many components should be retained by showing where the drop in the line is. Our graph shows three main curves. These plots are used to simplify complex datasets while preserving as much variance as possible.

4.2 Importance index analysis

Importance index analysis (IIA) dates back to the mid-20th century, when there was a growing need for systematic methodologies to evaluate the importance of various factors or variables in complex systems. Initially developed in fields such as engineering and operations research,

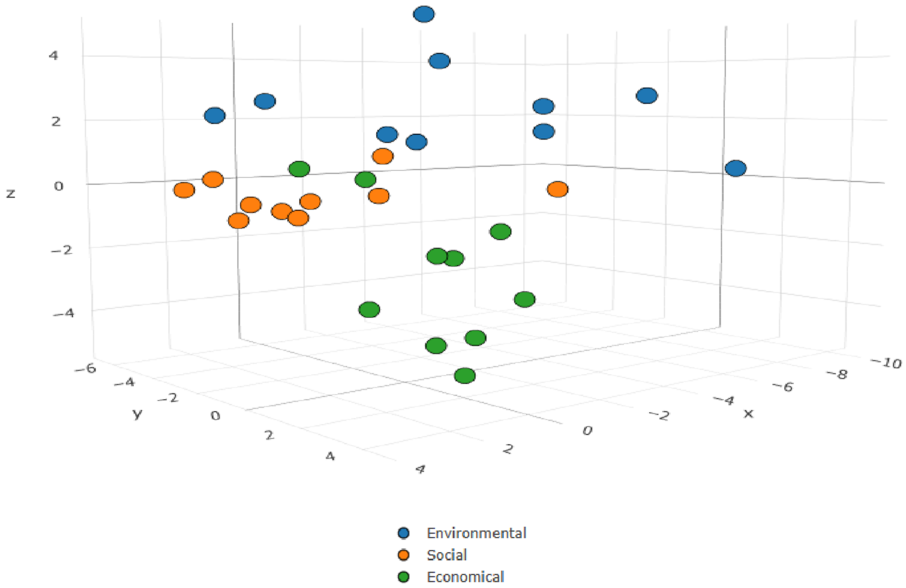

Figure 4. PCA component plot 3D

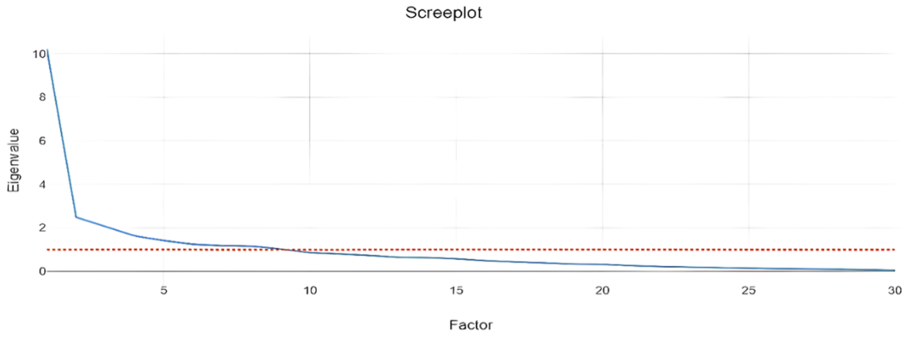

Figure 5. Scree plot line graph. *Source: Authors' own work*

IIA has since been applied in diverse domains, including project management, risk assessment, product development and strategic planning. The fundamental principle of IIA revolves around quantifying the relative importance or contribution of different factors towards achieving a desired outcome or objective. In this research, through literature review and industry experts' opinions, the factors or variables relevant to the decision or problem at hand were identified.

Next, data was collected to quantify the relationship between these factors and the desired outcome through surveys using a Satty scale. Once the data is gathered, IIA utilises mathematical algorithms to compute the importance index for each factor, as shown in Table 5. IIA values provide a numerical representation of the significance of each factor in achieving the desired outcome, which is sustainability. The interpretation of these indices guided us in prioritising these CSF, focusing efforts on the most influential factors. IIA offers a systematic approach to prioritising factors and resources in complex systems. Its rich history, diverse applications, structured methodology and numerous benefits underscore its significance in advancing decision-making processes across various domains.

4.3 Corrected item-total correlation

A Cronbach's Alpha value of 0.92, as shown in Table 6, suggests that the items in the set are highly consistent and reliable. Generally, a Cronbach's Alpha above 0.7 is considered

Table 5. Importance index values and rankings

CSF	Eq IMP	We IMP	Fa IMP	St IMP	Ab IMP	TOT	WI	IIA	Rank
ENV1	8	16	20	6	25	75	232	0.619	24
ENV2	10	17	11	13	24	75	240	0.640	23
ENV3	6	13	17	26	13	75	334	0.891	1
ENV4	4	19	18	14	20	75	278	0.741	11
ENV5	3	13	23	10	26	75	262	0.699	18
ENV6	7	13	17	16	22	75	274	0.731	13
ENV7	17	13	13	14	18	75	246	0.656	22
ENV8	13	12	20	13	17	75	266	0.709	17
ENV9	5	11	21	16	22	75	286	0.763	8
ENV10	6	14	18	13	24	75	262	0.699	18
SOC1	16	13	16	21	9	75	300	0.800	5
SOC2	5	16	17	14	23	75	268	0.715	16
SOC3	5	12	23	11	24	75	266	0.709	17
SOC4	4	17	20	12	22	75	270	0.720	15
SOC5	7	12	19	14	23	75	268	0.715	16
SOC6	8	15	17	14	21	75	266	0.709	17
SOC7	8	13	19	16	19	75	282	0.752	10
SOC8	8	18	17	10	22	75	248	0.661	21
SOC9	15	13	16	17	14	75	276	0.736	12
SOC10	7	15	11	23	19	75	296	0.789	6
ECO1	15	11	16	17	16	75	272	0.725	14
ECO2	12	18	13	19	13	75	286	0.763	8
ECO3	4	19	18	16	18	75	290	0.773	7
ECO4	7	13	22	21	12	75	324	0.864	2
ECO5	4	13	15	19	24	75	284	0.757	9
ECO6	10	6	24	20	15	75	312	0.832	3
ECO7	5	15	18	19	18	75	300	0.800	5
ECO8	3	22	13	21	16	75	306	0.816	4
ECO9	9	12	18	12	24	75	252	0.672	19
ECO10	7	15	13	14	26	75	250	0.667	20

Source(s): Authors' own work

Table 6. Reliability statistics

Cronbach’s alpha	Number of items
0.92	30

Source(s): Authors’ own work

acceptable, above 0.8 is considered good and above 0.9 is considered excellent. The obtained value of 0.92 falls into the excellent category, indicating that the items measure the underlying construct consistently. When interpreting the results of a Cronbach’s alpha analysis, we are interested in the CIMTC and Cronbach’s alpha when each item is omitted. Essentially, it is about assessing the scale’s internal consistency and how each item contributes to it. In our study, CIMTC calculation values revealed that the 30 CSF fall between strong and very strong correlation values.

4.4 Hypothesis testing

Hypothesis testing using the Kruskal–Wallis method is a statistical approach for comparing the distributions of multiple groups or samples. This method was developed by William Kruskal and Wilson Wallis in the mid-20th century as a non-parametric alternative to ANOVA. Since then, it has been widely accepted and applied in various fields, including medicine, social sciences and ecology. The main aim of hypothesis testing using the Kruskal–Wallis method is to determine whether there are statistically significant differences in the distribution of a continuous variable across our independent groups. In this study, data were collected from each group, ranked collectively, and then a test statistic was computed based on the ranks to measure the differences in the distributions of the groups. Moreover, the study utilized Chi-square distribution under the null hypothesis of no difference between groups. We determined whether the observed differences were statistically significant by comparing the calculated test statistic to the critical value from the chi-square distribution or computing the associated *p*-value. The Kruskal–Wallis method is helpful in scenarios where traditional parametric tests may not be appropriate, such as when the data is not normally distributed or the assumption of homogeneity of variances is violated. It is particularly valuable in fields like healthcare and environmental studies. The benefits of hypothesis testing using the Kruskal–Wallis method are significant. It provides a robust means of comparing multiple groups while mitigating the impact of non-normality and heteroscedasticity. Moreover, it offers researchers a versatile tool for hypothesis testing in situations where parametric assumptions cannot be met, ensuring the validity and accuracy of statistical analysis. The null hypothesis states that there is no difference between the three categories of the independent variable CSF in terms of the dependent variable Responses. The alternative hypothesis states that there is a difference between the three categories of the independent variable Group in terms of the dependent variable Responses.

A Kruskal–Wallis p-test value showed no significant difference between the independent variable categories with respect to the dependent variable, as illustrated in Table 7. Thus, with the available data, the null hypothesis was not rejected. A Chi-squared value of 0.63 suggests that there is not much difference between the groups. The larger the Chi-squared value, the more substantial the evidence for group differences. A lower Chi-squared value usually suggests that the differences between the groups are not as pronounced. Since we have three groups, the degree of freedom in this case is 2. Table 8 shows the CIMTIC, mean, standard deviation and importance index for each CSF.

4.5 Fuzzy analytic hierarchy process

To quantify and rank the magnitude of importance of CSF based on expert inputs, the FAHP methodology was employed. This advanced decision-making approach integrates subjective judgements and addresses the uncertainties inherent in sustainability assessments, making it

Table 7. Kruskal–Wallis hypothesis testing

Groups	n	Median	Mean rank
ENV	10	437	17.2
SOC	10	438	15.15
ECO	10	432	14.15
Total	30	435	

	χ^2	df	p
Response	0.63 Significance level 0.05	2	0.731

Source(s): Authors' own work

particularly suited for evaluating complex, multi-dimensional challenges such as sustainability in the cement industry. In this study, data were recorded on a 5-point scale, using a fuzzy scale of three to accommodate variability in expert opinions. A correlation matrix was generated, followed by a detailed analysis of the input data for each CSF concerning the three pillars of sustainability. The results provided a prioritised ranking of the CSF within each pillar. From the 45 comparisons made for each pillar, the Consistency Ratio (CR) was found to be 9.5% for the economic and social pillars and 9.9% for the environmental pillar, indicating reliable and consistent outcomes.

The FAHP builds upon the traditional AHP, introduced by Thomas L. Saaty in the 1970s, by incorporating fuzzy logic to address its limitations in handling uncertainty and vagueness in human judgment. Fuzzy logic, developed by Lotfi A. Zadeh in 1965, allows for partial truth values, enhancing the AHP framework. By merging these methodologies, FAHP emerged as a flexible and robust tool, particularly effective in scenarios where expert opinions are imprecise or contextually dependent, as in sustainability assessments.

The FAHP methodology begins with defining the decision problem and constructing a hierarchical structure to represent it visually and logically. This structure typically includes an overarching goal at the top, criteria (such as the three pillars of sustainability) at the intermediate level and sub-criteria (the CSF) at the bottom. Once the hierarchy is established, expert inputs are gathered to assess the relative importance of criteria and sub-criteria. Instead of assigning exact numerical values, judgements are expressed as triangular fuzzy numbers to capture uncertainty. These fuzzy comparisons are aggregated to produce fuzzy weights for each criterion, reflecting their relative importance.

A critical step in FAHP is defuzzification, which converts the fuzzy weights into crisp values. This process uses mathematical techniques such as the centroid method to provide a clear prioritisation of criteria. The defuzzified weights are then used to calculate the global weights for each CSF, reflecting their overall importance across all levels of the hierarchy. The consistency of judgements is assessed at this stage to ensure the validity of the results. A CR below 10% confirms acceptable consistency, as achieved in this study. Finally, the CSF are ranked based on their aggregated scores, with the highest-ranking factors identified as the most influential in achieving sustainability goals.

The FAHP offers significant benefits in its application to the cement industry. By providing a structured framework for evaluating and prioritising sustainability factors, it enables decision-makers to identify areas requiring the most attention and resources. Its integration of fuzzy logic ensures that subjective expert opinions, often influenced by ambiguity, are captured accurately, resulting in more reliable and adaptable outcomes. This methodology aligns decision-making with long-term strategic objectives, supporting the industry's efforts to enhance sustainability performance across economic, social and environmental dimensions.

Table 8. Critical success factors with CIMTC, mean, SD and importance index

Sr	Code	CSF	CIMTC	Mean	Standard deviation	IMP index
Environmental Critical Success Factors						
1	ENV1	Environmentally friendly practices	0.57	15	8	0.619
2	ENV2	Environmental awareness	0.68	15	5.700877	0.640
3	ENV3	Waste recycling technology used	0.61	15	7.314369	0.891
4	ENV4	Availability of waste disposal locations	0.53	15	6.557439	0.741
5	ENV5	Local environmental regulations	0.59	15	9.460444	0.699
6	ENV6	Availability of substitute raw materials	0.5	15	5.522681	0.731
7	ENV7	Harmful emissions generated	0.14	15	2.345208	0.656
8	ENV8	Carbon capture and storage technology	0.05	15	3.391165	0.709
9	ENV9	Amount of water used	0.53	15	7.106335	0.763
10	ENV10	Environmentally friendly transportation	0.61	15	6.63325	0.699
Social Critical Success Factors						
1	SOC1	Demand for Green/Sustainable products	0.49	15	4.415880	0.800
2	SOC2	Effective communication among workers	0.61	15	6.519202	0.715
3	SOC3	Response to customer demands	0.66	15	8.215838	0.709
4	SOC4	Organisation’s relationship with suppliers	0.6	15	7.211102	0.720
5	SOC5	Quality of training provided to workers	0.66	15	6.204836	0.715
6	SOC6	Involvement and support of top management	0.6	15	4.743416	0.709
7	SOC7	Employees’ adaptability to changes in work practices	0.56	15	4.636809	0.752
8	SOC8	Workplace safety and accident prevention	0.62	15	5.830951	0.661
9	SOC9	local and international sustainability-focused agencies	0.17	15	1.581138	0.736
10	SOC10	Level of occupational health and safety	0.62	15	6.324555	0.789
Economical Critical Success Factors						
1	ECO1	Impact of inventory cost	0.51	15	2.345208	0.725
2	ECO2	Cost and consumption of substitute fuels	0.55	15	3.24037	0.763
3	ECO3	The plant’s financial infrastructure constraints	0.55	15	6.244998	0.773
4	ECO4	LSS tools and methods are used to solve problems	0.39	15	6.363961	0.864
5	ECO5	Energy cost and consumption level	0.57	15	7.449832	0.757
6	ECO6	Adequacy of research and development funding	0.47	15	7.28011	0.832
7	ECO7	Using LSS tools to mitigate the cost of product reuse, remanufacturing and material recovery	0.54	15	5.787918	0.800
8	ECO8	LSS tools and methods used to create and utilise “finance and resources properly”	0.47	15	7.648529	0.816
9	ECO9	The degree of return on investment	0.43	15	6	0.672
10	ECO10	Adopting sustainable manufacturing methods in new market opportunities and expansion	0.67	15	6.892024	0.667

Source(s): Authors’ own work

The implementation of FAHP in this study underscores its effectiveness in delivering actionable insights for sustainability. The process allowed for a nuanced evaluation of CSF, highlighting their contributions to achieving sustainability within the cement industry. The prioritisation of factors based on total weights enables targeted interventions and informed policy-making. Ultimately, the FAHP methodology provides a rigorous, adaptable and reliable framework for navigating complex sustainability challenges.

5. Results and discussions

The results shown in Table 9 italicized the top CSFs identified for the sustainable development of the UAE cement industry, based on insights from literature reviews, survey data and

Table 9. FAHP output for 30 CSF

#	CSF code	Priority	Rank	(+)	(−)
Environmental CSF FAHP					
CR = 9.9%					
1	ENV1	0.0150	10	0.9%	0.9%
2	ENV2	0.0160	9	0.9%	0.9%
3	ENV3	0.3220	*1*	17.1%	17.1%
4	ENV4	0.1650	*3*	8.5%	8.5%
5	ENV5	0.0410	6	2.0%	2.0%
6	ENV6	0.0800	*4*	3.7%	3.7%
7	ENV7	0.0190	8	0.8%	0.8%
8	ENV8	0.0700	*5*	4.0%	4.0%
9	ENV9	0.2440	*2*	13.3%	13.3%
10	ENV10	0.0280	7	1.2%	1.2%
Social CSF FAHP					
CR = 9.5%					
1	SOC1	0.3070	*1*	27.1%	27.1%
2	SOC2	0.0350	7	1.3%	1.3%
3	SOC3	0.0240	8	1.1%	1.1%
4	SOC4	0.0500	*5*	2.3%	2.3%
5	SOC5	0.0390	6	1.8%	1.8%
6	SOC6	0.0210	9	1.2%	1.2%
7	SOC7	0.1580	*3*	6.2%	6.2%
8	SOC8	0.0130	10	0.9%	0.9%
9	SOC9	0.1160	*4*	4.4%	4.4%
10	SOC10	0.2360	*2*	13.4%	13.4%
Economical CSF FAHP					
CR = 9.5%					
1	ECO1	0.0200	8	1.0%	1.0%
2	ECO2	0.0520	6	2.8%	2.8%
3	ECO3	0.0770	*5*	3.7%	3.7%
4	ECO4	0.2370	*1*	9.7%	9.7%
5	ECO5	0.0360	7	2.0%	2.0%
6	ECO6	0.2110	*2*	9.8%	9.8%
7	ECO7	0.1530	*4*	8.1%	8.1%
8	ECO8	0.1860	*3*	9.4%	9.4%
9	ECO9	0.0140	9	0.8%	0.8%
10	ECO10	0.0140	9	0.8%	0.8%

Source(s): Authors’ own work

MCDM rankings. These CSFs are categorised into environmental, social and economic domains, reflecting the multidimensional nature of sustainability.

Adoption of Waste Recycling Technology (ENV3): Integrating advanced waste recycling technologies significantly reduces environmental impacts. These technologies enable companies to minimise ecological footprints, conserve natural resources and lower costs associated with waste disposal. Moreover, their adoption aligns with regulatory requirements and boosts corporate responsibility and public trust.

Availability of Waste Disposal Locations (ENV4): The strategic availability of appropriate waste disposal locations is pivotal for environmental compliance and risk mitigation. Properly managed disposal sites minimise pollution, protect ecosystems and ensure companies avoid legal and financial repercussions. This factor is especially crucial for industries like cement, which generate substantial waste.

Efficient Water Usage (ENV9): Managing water resources effectively is critical for environmental sustainability. By reducing water consumption, companies can conserve vital resources, cut operational costs and comply with stringent environmental regulations. Organisations that prioritise water efficiency are better equipped to address water scarcity challenges and escalating supply costs. Companies should adopt cutting-edge water recycling technologies and implement comprehensive water usage audits to track consumption and identify areas for improvement. Embracing rainwater harvesting and greywater recycling systems can further strengthen water sustainability efforts.

Demand for Green Products (SOC1): Growing consumer demand for green and sustainable products is reshaping market dynamics. Companies that respond to this shift by offering environmentally friendly products gain a competitive edge, enhance brand loyalty, and contribute positively to environmental well-being. Conversely, the absence of such demand can undermine the business case for green manufacturing, highlighting the interplay of market push and pull dynamics. Establishing consumer awareness campaigns to educate the public on the benefits of sustainable products can further drive demand. Industry collaborations to set benchmarks for sustainability certifications may also reinforce market trust.

Occupational Health and Safety (SOC10): Ensuring high standards of Occupational Health and Safety (OHS) is fundamental to social sustainability. A safe workplace not only protects employees but also boosts productivity, job satisfaction, and workforce morale. Prioritising OHS reduces absenteeism, turnover, and operational disruptions, creating a foundation for long-term organisational success. Companies must ensure regular OHS training, enhance reporting mechanisms for incidents and leverage technology such as wearables to monitor workplace conditions in real time.

Employees' Adaptability to Change (SOC7): Adapting to changing work practices is a critical social factor in sustainability. Successful implementation of sustainable practices often requires shifts in employee behaviour and processes. Organisations that invest in continuous training and skill development foster adaptability, enabling smoother transitions to new technologies and methodologies. Organisations should focus on building a culture of continuous learning through workshops, gamified training modules and mentorship programs.

Application of Problem-Solving Tools (ECO4): Utilising LSS tools to address operational challenges is essential for achieving economic sustainability. These tools help identify inefficiencies, streamline processes and improve quality, directly enhancing profitability and customer satisfaction while aligning with sustainability goals.

Investment in research and development for Sustainable Solutions (ECO6): Allocating adequate funding for these efforts drives innovation in sustainable manufacturing. Investments in research and development lead to the creation of advanced technologies, eco-friendly materials and efficient processes that reduce environmental impacts while maintaining competitiveness. Continuous research and development ensure that companies can adapt to evolving sustainability trends, offering a pathway to market leadership and stronger.

Efficient Resource Utilisation (ECO8): Maximising the use of resources through LSS tools is crucial for economic performance. By minimising waste and optimising resource allocation, organisations achieve cost savings and increased profitability, contributing to both economic and environmental objectives. Leveraging AI and IoT for real-time monitoring of resource consumption can lead to significant improvements in efficiency and waste reduction.

The findings underscore the interconnectedness of environmental, social and economic dimensions in fostering sustainability within the cement industry. By focusing on key areas such as waste recycling technologies, occupational health and safety, and resource optimisation, organisations can align with sustainability goals while remaining competitive in a rapidly evolving market. These findings also serve as a guide for policymakers and industry leaders, emphasising the need for strategic initiatives that balance sustainability with operational efficiency and economic viability. The italicized CSF represent actionable priorities that pave the way for a more sustainable and resilient future in the UAE cement industry.

The FAHP and RII analysis was conducted to prioritise the identified critical success factors based on their relative importance in promoting sustainability. Table 10 describes the

Table 10. Top CSF priority and importance index values

Rank	CSF code	CSF description	IIA weight (global)	FAHP priority (local)
TOP 3 Environmental				
1	ENV3	Waste recycling technology used	0.891	0.3220
2	ENV9	Amount of water used	0.763	0.2440
3	ENV4	Availability of appropriate locations for waste disposal	0.741	0.1650
TOP 3 Social				
1	SOC1	Demand for Green/Sustainable products	0.800	0.3070
2	SOC10	Level of occupational health and safety	0.789	0.2360
3	SOC7	Employees' adaptability to changes in work practices	0.752	0.1580
TOP 3 Economical				
1	ECO4	LSS tools and methods are assigned to solve problems that arise	0.864	0.2370
2	ECO6	Adequacy of research and development funding for sustainable manufacturing solutions	0.832	0.2110
3	ECO8	LSS tools and methods used to create finance and utilise resources	0.816	0.1860

Source(s): Authors' work

top 3 CSF obtained from the analysis, showing their relative importance globally across the 30 factors and their priority within the sustainability pillar locally.

5.1 Implications

The findings have important implications for many stakeholder groups and suggest an integrated, multipronged approach to sustainability in the UAE's cement sector. For researchers, the findings provide insight into the effectiveness of MCDM tools, which can be utilised for further investigation into other specific aspects of sustainability, offering a way for researchers to expand this field of study. There is a clear need to deepen empirical and applied work, exploring how waste recycling technologies and the availability of waste disposal sites affect cost, emissions and supply-chain logistics. Further investigating efficient water usage under UAE environmental constraints, and studying social dimensions like employees' adaptability to change, occupational health and safety, and demand for green products. Researchers should also focus on refining and combining LSS and MCDM tools to optimise resource utilisation and balance environmental, social and economic outcomes. Additionally, they should carry out longitudinal assessments of sustainability interventions to understand long-term effectiveness.

For practitioners, the findings imply that operational improvements using problem-solving tools are essential. Instituting real-time monitoring of water, fuel and waste, applying LSS-based diagnostics to identify process inefficiencies, integrating waste recycling into operations and ensuring access to adequate waste disposal locations. Workforce training becomes crucial for building adaptability to change and maintaining occupational health and safety when introducing new technologies or practices. In addition, product strategies should respond to growing consumer demand for green products, ensuring that sustainability claims are credible and tied to measurable improvements.

For the industry broadly, the findings can be used to summarise and provide the top-ranking sustainability CSFs across the three dimensions of sustainability, which are supported by literature and industry experts' opinions. Moreover, the implications include prioritising investment in research and development for sustainable solutions, developing alternative fuels, recycling friendly raw materials and water reuse systems. These actions not only support environmental goals but can also confer competitive advantage, reduce operational costs and mitigate regulatory or reputational risks. Industries will benefit from adopting circular economy models by making efficient resource utilisation central to their strategy, collaborating with academia, technology providers and waste management entities to pilot and scale promising innovations, and aligning operations with evolving market and regulatory expectations.

Governments and regulators are indicated to have a pivotal enabling role by setting and enforcing benchmarks for emissions, waste management, water usage, health and safety. Results show that the government and regulators can target the enabler factors, primarily focusing on mechanisms to promote sustainable development. Regulators can create regulatory incentives like tax reliefs, subsidies and preferential procurement to encourage the adoption of recycling technologies, efficient water systems and green processes. In addition, they can ensure that infrastructure and policies are in place for waste disposal and recycling locations. Moreover, they can support research, development and innovation through funding, grants or public–private partnerships. Additionally, they can foster skill building, capacity development and awareness to raise demand for green products and ensure the workforce and industry are ready for change.

6. Conclusion

The present work highlights the importance of integrating environmental, social and economic factors to achieve sustainable business practices. Environmentally, priorities include advanced waste recycling and water conservation, which support resource efficiency and regulatory compliance. Socially, rising demand for green products and the significance of occupational health and safety emphasise the need to align operations with evolving societal expectations. Employee adaptability is also vital for successfully implementing new sustainable practices. Economically, the use of LSS and investment in research and development are critical for innovation and resource optimisation. Companies should focus on adopting advanced recycling technologies and water-saving initiatives to reduce environmental impact. Proper waste disposal is also key to maintaining compliance and avoiding environmental risks. Socially, firms should respond to consumer preferences by developing green products and enhancing health and safety standards. Continuous employee training will ease transitions to sustainable operations. Economically, applying LSS tools and funding sustainable research and development will help companies stay competitive and ensure long-term growth.

6.1 Limitations and future scope of work

The primary limitation of this research is its focus on the UAE cement sector, which limits the generalizability of the findings. Results from a single regional context may not fully capture the diverse regulatory environments, cultural dynamics and market conditions present in other countries or industries. For example, policies on waste management, the availability of alternative fuels and consumer demand for sustainable products may vary significantly across regions, limiting the direct applicability of the outcomes. Another challenge is the risk of expert bias in qualitative and FAHP assessments. Since expert judgments form the foundation of pairwise comparisons and decision-making weights, the results may be influenced by individual backgrounds, professional experiences or cultural perspectives. Such bias can unintentionally skew priorities and rankings, reducing objectivity. Ensuring a diverse and sufficiently large expert panel, along with validation techniques, can help minimise this limitation. Moreover, while fuzzy logic is excellent at dealing with uncertainty and vague linguistic judgments, it carries its own limitations. The construction of membership functions and the interpretation of fuzzy scales are inherently subjective, which can lead to variability in outcomes if different researchers or experts define them differently. This subjectivity may reduce replicability and consistency across studies. Future research should consider refining fuzzy models, applying sensitivity analysis or integrating hybrid approaches with other decision-making techniques to strengthen reliability. Addressing these limitations in future work would improve the credibility and broader applicability of the findings.

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