Prioritizing sustainable practices for decarbonizing construction SMEs: an actionable roadmap for capability development in developing economies

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Abstract

Purpose – As the construction sector strives to meet global climate targets, small and medium-sized enterprises (SMEs) in developing economies represent a critical yet often overlooked frontier for decarbonization. Despite their significant role, construction SMEs face barriers such as limited financial capacity, weak technical capability and fragmented institutional support, which hinder the adoption of sustainable practices. This study aims to address this gap by identifying and prioritizing key sustainable entrepreneurship practices (SEPs) that can support decarbonization in construction SMEs, with a focus on Pakistan.

Design/methodology/approach – This study uses a hybrid methodology that integrates the decision-making trial and evaluation laboratory (DEMATEL), machine learning (ML) and interpretive structural modeling (ISM)-cross-impact matrix multiplication applied to classification (MICMAC). DEMATEL is used to identify causal relationships among SEPs, ML is used to validate the robustness of these relationships and ISM-MICMAC is applied to rank the SEPs based on their strategic influence. This integrated approach provides context-specific insights for decarbonization planning in construction SMEs.

Findings – The results identify artificial intelligence (AI)-driven process optimization (SEP19), building information modeling (BIM)-based sustainability integration (SEP17), energy-efficient building design

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(SEP16) and smart construction materials (SEP15) as key drivers of low-carbon transformation. These SEPs play a central role in improving operational efficiency, reducing carbon emissions and supporting long-term sustainability in the construction sector.

Originality/value – This study develops a context-specific decision-support framework for construction SMEs in a developing-economy setting, particularly Pakistan. By integrating DEMATEL, ML and ISM-MICMAC, it offers a structured approach for analyzing SEPs and provides actionable insights for SME owners, policymakers and other stakeholders seeking to advance decarbonization through strategically prioritized sustainability practices.

Keywords Sustainable entrepreneurship practices, Decarbonization, Construction SMEs, DEMATEL, Machine learning, ISM-MICMAC, Pakistan

Paper type Research paper

1. Introduction

The construction sector is a central driver of global economic development, contributing about 13% of global GDP and employing more than 7% of the global workforce (Institute, 2017). At the same time, it is among the most carbon-intensive industries, accounting for nearly 39% of global energy-related CO_2 emissions (Hussain and Hussain, 2023). As urbanization accelerates and infrastructure demand rises, decarbonizing construction has become essential for achieving global climate targets. This challenge extends beyond technology and involves large organizational and operational change in how construction activities are planned, governed and executed (Rashidian *et al.*, 2025).

Within this transition agenda, SEPs have emerged as a key pathway for reducing emissions at the firm level. SEPs include process innovation, digitalization, resource efficiency, energy-efficient design and organizational learning that embed sustainability into routine construction operations (Ma *et al.*, 2023). Evidence from advanced economies shows that construction-sector decarbonization is most effective when technological adoption is supported by organizational change and enabling policy environments (Hyvönen *et al.*, 2024; Khan and Khurshid, 2024). Related studies indicate that SEPs improve environmental performance and reduce emissions across the project lifecycle (Gu and Wang, 2022). Together, this literature positions SEPs as a viable operational lever for low-carbon transformation.

Despite this progress, a major implementation problem remains unresolved. Construction firms, particularly SMEs, lack clear guidance on which sustainability practices to adopt first, how to sequence them and how to align them with limited financial, technical and institutional resources. Existing research often lists best practices or evaluates performance outcomes but offers little decision-oriented support for prioritization. As a result, sustainability initiatives are frequently adopted as isolated actions rather than as parts of a coherent transition pathway. This leads to uncertainty and hesitation, where firms face difficulty deciding where to begin and how to scale low-carbon efforts.

The core issue is not simply whether SEPs are effective, but how they can be prioritized and implemented in a logical sequence under real-world constraints. Existing studies rarely explain how different SEPs depend on one another or which practices must be established first to support later adoption. As a result, SMEs may introduce advanced sustainability tools or technologies before developing the basic capabilities needed to use them effectively, such as digital infrastructure, workforce skills, data routines and organizational alignment. This weakens implementation and helps explain why many sustainability initiatives remain fragmented, short-lived or symbolic rather than embedded in everyday operations. What is therefore needed is a structured roadmap that identifies both the sequencing and enabling relationships among SEPs so that sustainability ambition can be translated into a feasible implementation pathway.

The urgency of this implementation gap is particularly evident among construction SMEs. Although SMEs dominate construction markets worldwide, decarbonization investments, technological innovation and sustainability support mechanisms remain concentrated in larger firms operating in advanced economies. Consequently, many SMEs struggle to develop the capabilities required for sustainability transitions, including technology adoption, data integration, workforce development and organizational coordination. These limitations make the prioritization and sequencing of SEPs especially important in resource-constrained environments.

These challenges are more pronounced in developing economies. In Pakistan, SMEs account for over 80% of construction activity and deliver most residential, commercial and infrastructure projects that shape the urban built environment (Ali and Mujahid, 2024). Although the construction sector contributes only about 5.86% to national GDP, it is responsible for more than 40% of national carbon emissions (Economics Advisor Wing's Finance Division, 2024; Kauffmann and Cusmano, 2022). Construction SMEs operate in informal and weakly regulated markets with limited access to green technologies, inconsistent financial incentives and fragile governance structures. Under such conditions, sustainability initiatives tend to be reactive and fragmented, resulting in limited long-term impact. This creates a structural sustainability dilemma: SMEs are essential for national decarbonization, yet they lack feasible pathways for implementing low-carbon change.

This study addresses this implementation gap by developing a structured decision-support framework to help construction SMEs prioritize and sequence SEPs under limited financial capacity, weak technical capability and fragmented institutional support.

The study addresses the following research questions:

RQ1. Which SEPs are most critical for enabling decarbonization in construction SMEs operating under limited financial capacity, weak technical capability and fragmented institutional support?

RQ2. How do interdependencies among SEPs shape feasible implementation pathways for sustainability transitions?

RQ3. Which SEPs act as foundational drivers that enable broader adoption of low-carbon technologies and practices?

RQ4. How can SEPs be strategically prioritized to support an effective, scalable and context-sensitive transition toward construction-sector decarbonization?

To answer these questions, the study maps causal relationships among SEPs, identifies high-impact leverage practices and organizes them into a staged and resource-efficient implementation roadmap. The focus is practical relevance rather than methodological novelty, providing SME owners, policymakers and industry stakeholders with tools to allocate limited resources and design targeted low-carbon interventions that can scale. By linking firm-level capability development with broader urban decarbonization goals, the study offers an actionable pathway for translating sustainability intent into operational outcomes in developing-economy construction sectors.

Beyond practical contributions, this study advances theory by conceptualizing SEPs as an interdependent system of organizational capabilities rather than discrete technical measures. This perspective extends sustainability transition and operations strategy literature by introducing a causal prioritization logic that explains how staged capability development supports low-carbon transformation in resource-constrained construction SMEs.

2. Literature review

2.1 Pakistan's construction industry, small and medium-sized enterprises and the need for sustainable entrepreneurship

The construction sector is a major contributor to Pakistan's economic growth, but it is also one of the country's important sources of carbon emissions. These emissions are largely associated with outdated construction methods, limited adoption of green technologies, inefficient resource use and continued dependence on nonrenewable energy sources (Economics Advisor Wing's Finance Division, 2024). Within this sector, SMEs play a decisive role because they account for more than 80% of construction firms in Pakistan (Shah and Syed, 2018). SMEs also contribute substantially to employment, local service delivery and project execution in residential, commercial and infrastructure development. Therefore, any meaningful decarbonization pathway for Pakistan's construction sector must consider the capabilities and constraints of SMEs.

Despite their importance, construction SMEs face several barriers that limit their ability to adopt sustainability-oriented practices. Weak regulatory enforcement, restricted access to finance, limited technical skills and fragmented institutional support constrain their transition toward low-carbon construction (Ali and Mujahid, 2024). Under these conditions, sustainability initiatives often remain informal, reactive and short-term. Sustainable entrepreneurship (SE) offers a practical pathway to address these limitations by embedding innovation, resource efficiency, collaboration and environmental responsibility into core business activities. Prior research suggests that SE can improve environmental performance while also strengthening SME competitiveness (Ghag and Sonar, 2024). However, this perspective remains underexamined in Pakistan's construction sector, where firms operate under resource scarcity and weak institutional conditions. This creates a need for context-specific research on how SE can support decarbonization in Pakistan's construction SMEs.

2.2 Sustainable entrepreneurship practices in construction small and medium-sized enterprises

SEPs integrate economic, environmental and social objectives to create long-term value. In construction, these practices include smart construction materials, 3D printing with sustainable materials, safety and welfare practices, energy-efficient building design, sustainable supply chain management, circular material use, modular construction, green procurement and digital technologies that improve resource use and project coordination (Oyejobi *et al.*, 2024; Ngo *et al.*, 2018; Tam and Tam, 2006; Boje *et al.*, 2020; Sharma, 2020). Recent studies increasingly adopt a systems-oriented view, showing that digitalization, lifecycle-based design, water conservation technologies, sustainable supply chain, process optimization and sustainability-oriented organizational routines that jointly improve construction sustainability performance (Shirazi *et al.*, 2024; Rahman *et al.*, 2019).

Evidence from developed economies indicates that SEPs can contribute to construction-sector decarbonization. Circular building materials, waste segregation, drone-based environmental monitoring, recycled aggregation and business model innovation can support carbon reduction across project lifecycles (Ren *et al.*, 2017; Silva *et al.*, 2017; Nußholz *et al.*, 2019; Ghisellini *et al.*, 2016). Firms that combine innovation-oriented and sustainability-oriented organizational structures also demonstrate stronger alignment between environmental and economic goals (Lans *et al.*, 2014). Similarly, prior studies show that green procurement, BIM-enabled coordination, renewable energy integration, modular and prefabricated construction techniques and energy-efficient design can reduce waste, improve operational performance and support low-carbon outcomes (Kamali and Hewage, 2016;

Kabir *et al.*, 2018; Azhar, 2011; Brandenburg *et al.*, 2014; Mariano-Hernández *et al.*, 2020; Mohammed, 2022).

However, research specifically addressing SEPs in construction SMEs remains limited. Construction SMEs tend to adopt selective practices such as waste reduction, energy-efficiency measures, circular material use, digital tools and basic supply-chain coordination when these practices are financially manageable and operationally feasible. For example, studies on construction SMEs show growing attention to circular economy adoption through resource-efficient practices, material recovery, AI integration for enhancing construction flow, AI-driven site monitoring and operational improvements, but adoption remains uneven and strongly dependent on firm-level readiness and external support (Pan and Zhang, 2021; Baduge *et al.*, 2022; Zuofa *et al.*, 2023). Similarly, sustainability integration in smaller firms is often shaped by managerial commitment and the ability to embed sustainability into day-to-day business activities rather than by stand-alone environmental initiatives (Witjes *et al.*, 2017).

Construction SMEs also face constraints that differ from those of larger firms. Their limited capital base, lower technical capacity and restricted access to innovation networks reduce their ability to implement multiple SEPs in an integrated manner (Walker and Preuss, 2008). This is especially visible in areas such as BIM-enabled process improvement, green procurement, lifecycle-oriented design and smart construction materials, where implementation depends on prior organizational capabilities, technical knowledge and coordination across actors. As a result, construction SMEs frequently adopt SEPs incrementally and unevenly, often in response to short-term pressures such as cost savings, compliance or client expectations rather than as part of a coordinated decarbonization strategy.

2.3 Cross-regional evidence and contextual limitations

Cross-regional evidence highlights both the potential and the limitations of transferring SEP models across contexts. Studies from Europe and East Asia show that practices such as BIM, energy-efficient design, circular material use and process optimization can improve environmental and operational performance (Hyvönen *et al.*, 2024). Similarly, sustainability-oriented entrepreneurship can help firms balance environmental and economic objectives across different institutional settings (Gu and Wang, 2022). These studies provide useful evidence on the value of SEPs, particularly in contexts where policy incentives, innovation ecosystems, financing mechanisms and technical support are relatively well developed.

However, many successful transitions reported in countries such as Denmark and The Netherlands are supported by strong institutional coordination, stable regulations and financial incentives (Witjes *et al.*, 2017; Tan *et al.*, 2015; Overgård *et al.*, 2022). These enabling conditions are often absent in developing economies. Unlike SMEs in developed economies, Pakistani construction SMEs frequently pursue sustainability actions under short-term survival pressures, limited financing, weak enforcement and low technical readiness. Therefore, while prior studies identify relevant practices, they provide limited explanation of how SMEs in developing economies should prioritize and sequence these practices to create feasible decarbonization pathways.

2.4 Research gaps

Despite growing interest in SE and SEPs, several gaps remain. First, many studies assume formal regulatory systems, access to finance and stable institutional support, conditions that do not reflect the operating reality of construction SMEs in developing economies such as

Pakistan. Structural informality, resource scarcity and weak institutional coordination remain underexamined.

Second, although prior research identifies sustainability enablers and barriers, limited attention has been paid to the interdependencies among SEPs. Existing studies often examine individual practices or barriers separately, but they rarely explain how different SEPs influence one another or which practices should be implemented first under constrained conditions.

Third, existing studies provide limited implementation-oriented guidance for construction SMEs. Studies on SME sustainability orientation and related barriers, such as Natividade *et al.* (2021) and Mendes *et al.* (2022) provide useful insights, but they do not offer a structured framework that helps construction SMEs prioritize and sequence practices for decarbonization.

Fourth, cross-regional evidence remains fragmented. While digitalization, energy-efficient design and circular practices are shown to be effective in developed economies, their applicability in developing contexts remains uncertain. Few studies distinguish between SEPs that are broadly transferable and those whose effectiveness depends on specific institutional and resource conditions.

These gaps justify the need for a structured, context-sensitive framework that enables construction SMEs in Pakistan to prioritize and sequence SEPs for decarbonization.

3. Methodology

This study adopts a four-stage methodology to identify, validate and prioritize SEPs relevant to decarbonization in construction SMEs in Pakistan. The methodology involves a systematic approach, including a literature review, causal analysis, validation and structural prioritization, as illustrated in Figure 1:

- Stage 1: An extensive review of the literature, complemented by preliminary expert input, was conducted to identify SEPs relevant to decarbonization in construction SMEs, with specific attention to their applicability in the Pakistani context.
- Stage 2: The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method examines cause–and–effect relationships among the identified practices and captures their interdependencies.
- Stage 3: An ML technique, including random forest (RF), was applied to validate and assess the robustness of the causal structure derived from DEMATEL.
- Stage 4: Finally, the Interpretive Structural Modeling (ISM) and MICMAC analysis were used to structure and prioritize the most influential SEPs based on their hierarchical position, driving power and dependence characteristics.

3.1 Stage 1: Identification of critical sustainable entrepreneurship practices through literature review

The initial search yielded 320 publications. These studies were screened using two inclusion criteria: first, the article had to be published in a peer-reviewed journal to ensure academic rigor; second, it had to address SE or sustainability-oriented practices within the construction sector with relevance to decarbonization. Based on these criteria, 53 studies were retained for detailed review.

From these 53 studies, an initial list of SEPs was compiled by extracting practices repeatedly discussed as relevant to sustainability improvement, resource efficiency, digitalization, emissions reduction and low-carbon construction management. To improve

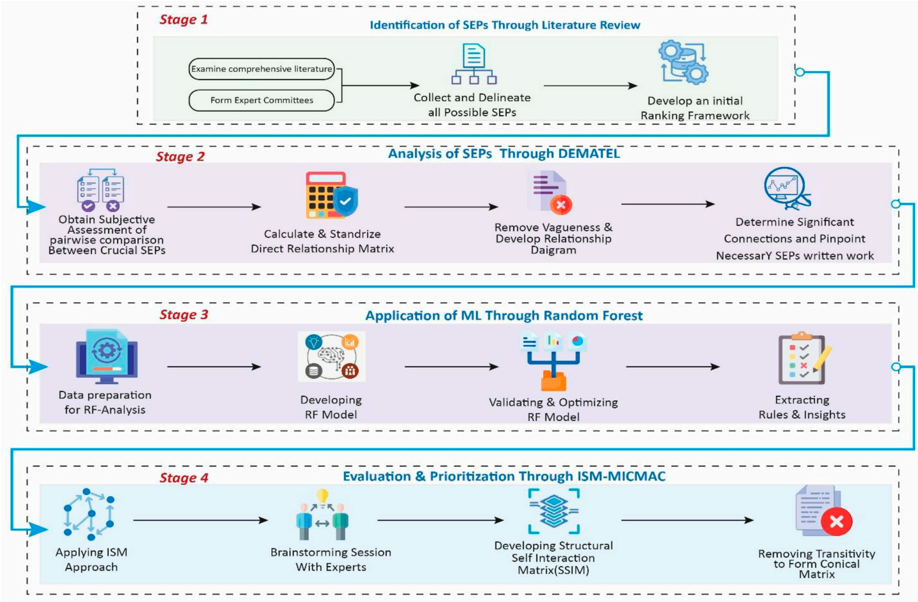


Figure 1. Step-by-step methodology framework
Source(s): Authors' own

contextual relevance, this preliminary list was reviewed by a preliminary screening panel consisting of three experts, including two senior construction professionals and one academic specializing in SE. The role of this panel was limited to reviewing the literature-derived practices and assessing their clarity, relevance and applicability to Pakistani construction SMEs. Based on their feedback, overlapping items were merged, ambiguous items were refined and practices considered unsuitable for the Pakistani SME context were removed.

This screening process resulted in a final set of 19 SEPs, which were subsequently evaluated through the DEMATEL, ML and ISM–MICMAC stages. A detailed description of these SEPs is provided in Table 1.

3.1.1 Expert engagement process. The study involved two separate expert groups with distinct roles. The first group was the preliminary screening panel of three experts described in Section 3.1. Their involvement was limited to reviewing and refining the literature-derived list of SEPs during the identification stage.

The second group was the main expert panel, which was established for the DEMATEL and ISM–MICMAC analysis. This panel was responsible for evaluating the interrelationships among the finalized SEPs and supporting the subsequent structural analysis.

Experts for the main panel were selected using three criteria. First, each participant was required to have at least eight years of professional or academic experience in fields directly related to construction, sustainability, environmental management, urban planning, architecture or sustainable entrepreneurship. Second, representativeness was ensured by including participants from multiple domains relevant to the study, including technical, managerial, consulting, policy-related and academic backgrounds, so that judgments were

Table 1. SEPs identified from earlier studies to achieve decarbonization

SEP#	Sustainable entrepreneurship practices	Reference
SEP1	Circular economy principles in project lifecycle	(Ghisellini *et al.*, 2016)
SEP2	Waste segregation and recycling on construction sites	(Tam and Tam, 2006)
SEP3	Recycled aggregate usage	(Silva *et al.*, 2017)
SEP4	Drone-Based environmental monitoring	(Ren *et al.*, 2017)
SEP5	3D Printing with Sustainable Materials	(Ngo *et al.*, 2018)
SEP6	Smart waste management systems	(Ali and Mujahid, 2024)
SEP7	Safety and welfare practices for construction workers	(Oyejobi *et al.*, 2024)
SEP8	Digital twins for resource optimization	(Boje *et al.*, 2020)
SEP9	On-Site renewable energy generation	(Kabir *et al.*, 2018)
SEP10	Water conservation technologies	(Rahman *et al.*, 2019)
SEP11	Sustainable supply chain management in construction	(Shirazi *et al.*, 2024)
SEP12	AI and IoT for energy optimization	(Bale *et al.*, 2024)
SEP13	Solar integration in building designs	(Peng *et al.*, 2020)
SEP14	Modular and prefabricated construction Techniques	(Kamali and Hewage, 2016)
SEP15	Use of smart construction materials	(Sharma, 2020)
SEP16	Energy-Efficient building design	(Ma *et al.*, 2023)
SEP17	BIM (building information modeling) for sustainability	(Mohammed, 2022)
SEP18	AI-Driven site monitoring	(Baduge *et al.*, 2022)
SEP19	AI for optimizing construction processes	(Pan and Zhang, 2021)

Source(s): Authors' own

not limited to a single professional perspective. Third, selected experts had to be willing to participate in multiple stages of the analysis, particularly DEMATEL and ISM–MICMAC. This selection approach is consistent with established practices in multi-criteria decision-making research (Kabra and Mukerjee, 2024).

In total, 35 experts were contacted through formal emails, telephone communication and personal outreach. Twelve experts agreed to participate after two rounds of follow-up. Due to geographical dispersion, expert discussions were conducted via Zoom, which enabled interactive exchange without requiring physical meetings (Iqbal *et al.*, 2025a). Before participation, all experts were informed about the objectives of the study, assured of confidentiality and asked to provide informed consent.

Of the 12 experts who participated in DEMATEL, 9 continued into the ISM–MICMAC stage. Although this number is modest, it is consistent with prior DEMATEL- and ISM-based studies, where similar expert panel sizes have been used to generate reliable causal and structural insights (Guo *et al.*, 2024; Dubey and Tanksale, 2022; Iqbal *et al.*, 2025c; Iqbal *et al.*, 2025b; Iqbal *et al.*, 2026b). This expert-driven process ensured that the matrices, model structure and interpretation remained grounded in practical feasibility and cross-disciplinary judgment. Additional expert details are presented in Table 2.

3.2 Stage 2: Decision-making trial and evaluation laboratory-Based evaluation of cause-effect relationships among sustainable entrepreneurship practices

The DEMATEL method was used to analyze cause–and–effect relationships among SEPs. DEMATEL is well-suited for systems characterized by strong interdependencies and limited quantitative data, conditions typical of construction SMEs, where decision-making often relies on expert judgment and experiential knowledge (Kabra and Mukerjee, 2024).

By using matrix-based computations, DEMATEL quantifies both the strength and direction of influence among system elements, enabling the distinction between driving

Table 2. Experts profile

Experts	Sex	Education	Profession	Experience (years)	Firm size
1	Male	Master	Sustainability consultant	12	Large
2	Male	Master	Construction manager	12	Medium
3	Male	PhD	Business analyst	10	Medium
4	Female	PhD	Project Coordinator	8	Medium
5	Male	M.Phil	Architect	20	Large
6	Male	Master	Environmental Consultant	18	Small
7	Male	Master	Urban planner	14	Small
8	Male	M.Phil	Construction engineer	9	Medium
9	Male	M.Phil	Sustainability consultant	16	Medium
10	Male	Master	Green building experts	19	Small
11	Male	PhD	Professor	10	Academic institution
12	Male	PhD	Senior research scientist	22	Academic institution

Source(s): Authors' own

(cause) and dependent (effect) factors (Zhang *et al.*, 2025; Gao and Zhou, 2025; Li *et al.*, 2025). In this study, DEMATEL supports the identification of key interdependencies among SEPs and provides a structured basis for their prioritization in decarbonization planning (Iqbal *et al.*, 2025a).

3.2.1 Phases in the decision-making trial and evaluation laboratory process. 3.2.1.1 Phase 1. Construction of the direct relation matrix. Experts evaluated the direct influence of each SEP (i) on every other SEP (j) using a five-point Likert scale, including (no influence 0, very low influence 1, low influence 2, high influence 3 and very strong influence 4).

The influence score is denoted by (aij). Individual expert judgments were aggregated using arithmetic means to construct the initial direct-relation matrix A, also referred to as the DRM, presented in Table 3:

$$A = \begin{bmatrix} 0 & a_{12} & \cdots & a_{1n} \\ a_{21} & 0 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 0 \end{bmatrix} \quad (1)$$

3.2.1.2 Phase 2: Normalization of the direct relation matrix. To ensure comparability of influence scores, the matrix A was normalized. The normalization coefficient k was calculated as follows:

$$\text{Where } k = \frac{1}{max_i \ \sum_{j=1}^{n} a_{ij}} \quad (2)$$

Although all influence scores were collected using a consistent Likert scale, normalization is required in the DEMATEL method to ensure that the maximum row sum of the DRM does not exceed one. This step guarantees the stability and convergence of the TRM calculation and allows both direct and indirect effects to be properly derived.

Table 3. Direct relation matrix DRM

SEP	SEP1	SEP2	SEP3	SEP4	SEP5	SEP6	SEP7	SEP8	SEP9	SEP10	SEP11	SEP12	SEP13	SEP14	SEP15	SEP16	SEP17	SEP18	SEP19
SEP1	0.000	0.047	0.036	0.055	0.047	0.039	0.043	0.037	0.060	0.040	0.049	0.060	0.054	0.037	0.046	0.047	0.037	0.050	0.046
SEP2	0.049	0.000	0.049	0.036	0.057	0.051	0.035	0.046	0.042	0.047	0.061	0.053	0.055	0.047	0.035	0.046	0.050	0.044	0.051
SEP3	0.036	0.049	0.000	0.047	0.037	0.061	0.049	0.055	0.055	0.039	0.055	0.050	0.047	0.060	0.033	0.046	0.051	0.060	0.042
SEP4	0.054	0.036	0.047	0.000	0.053	0.049	0.049	0.055	0.036	0.043	0.042	0.051	0.051	0.040	0.047	0.035	0.049	0.057	0.043
SEP5	0.047	0.057	0.037	0.053	0.000	0.043	0.061	0.046	0.061	0.046	0.062	0.049	0.060	0.057	0.040	0.061	0.055	0.040	0.053
SEP6	0.035	0.051	0.061	0.049	0.043	0.000	0.035	0.044	0.061	0.053	0.057	0.055	0.046	0.062	0.035	0.042	0.047	0.060	0.036
SEP7	0.043	0.035	0.049	0.047	0.061	0.035	0.000	0.062	0.050	0.053	0.042	0.062	0.043	0.044	0.046	0.055	0.054	0.043	0.057
SEP8	0.046	0.050	0.055	0.051	0.054	0.049	0.062	0.000	0.047	0.058	0.055	0.062	0.043	0.064	0.047	0.050	0.036	0.062	0.044
SEP9	0.061	0.037	0.051	0.044	0.057	0.061	0.054	0.047	0.000	0.051	0.055	0.057	0.055	0.046	0.061	0.049	0.050	0.061	0.047
SEP10	0.040	0.049	0.046	0.050	0.044	0.061	0.050	0.049	0.050	0.000	0.047	0.057	0.044	0.053	0.044	0.054	0.055	0.061	0.043
SEP11	0.055	0.062	0.051	0.037	0.064	0.060	0.043	0.062	0.055	0.047	0.000	0.058	0.055	0.064	0.039	0.062	0.051	0.062	0.047
SEP12	0.062	0.053	0.057	0.062	0.049	0.062	0.062	0.064	0.061	0.062	0.058	0.000	0.049	0.062	0.051	0.062	0.047	0.064	0.064
SEP13	0.060	0.062	0.055	0.054	0.055	0.037	0.050	0.047	0.062	0.036	0.062	0.049	0.000	0.062	0.051	0.061	0.044	0.062	0.044
SEP14	0.037	0.054	0.060	0.036	0.062	0.060	0.062	0.060	0.046	0.062	0.057	0.064	0.062	0.000	0.062	0.046	0.064	0.064	0.044
SEP15	0.053	0.033	0.033	0.050	0.046	0.033	0.055	0.047	0.055	0.055	0.047	0.062	0.062	0.062	0.000	0.055	0.055	0.061	0.058
SEP16	0.053	0.054	0.060	0.039	0.055	0.050	0.061	0.062	0.061	0.061	0.062	0.062	0.046	0.062	0.055	0.000	0.062	0.061	0.050
SEP17	0.035	0.060	0.062	0.054	0.053	0.054	0.058	0.037	0.057	0.062	0.049	0.064	0.064	0.064	0.062	0.062	0.000	0.036	0.057
SEP18	0.061	0.053	0.035	0.061	0.064	0.061	0.055	0.062	0.046	0.061	0.053	0.064	0.060	0.049	0.061	0.061	0.036	0.000	0.060
SEP19	0.061	0.053	0.057	0.054	0.057	0.051	0.054	0.051	0.062	0.054	0.036	0.058	0.051	0.064	0.061	0.058	0.057	0.060	0.000

Source(s): Authors' own

The normalized direct-relation matrix C was obtained as follows:

$$C = k \times A \tag{3}$$

The normalized matrix is reported in Table 4.

3.2.1.3 Phase 3: Derivation of the Total-Relation matrix (TRM). The TRM denoted by S, capturing both direct and indirect influences among SEPs was computed as follows:

$$S = C(1 - C)^{-1} \tag{4}$$

where I denotes the identity matrix. The resulting matrix is presented in Table 5.

3.2.1.4 Phase 4: Calculation of causal parameters. Row and column sums of a matrix $S = [S_{ij}]$ were calculated to derive causal parameters:

$$R_i = \sum_{j=1}^{n} s_{ij} \tag{5}$$

$$C_i = \sum_{j=1}^{n} s_{ji} \tag{6}$$

The values $R_i + C_i$ indicate the overall prominence of each SEP, while $R_i - C_i$ distinguish driving from dependent SEPs. These results are summarized in Table 6 and form the basis for causal diagram construction.

3.3 Stage 3: Application of machine learning for validating cause-effect relationships

To validate the DEMATEL-derived classifications, an RF model was applied. RF is an ensemble learning technique that combines multiple decision trees to improve prediction accuracy and robustness, particularly for expert-based data sets (Bhattacharjee *et al.*, 2023; Panigrahi *et al.*, 2024).

3.3.1 Phases in the machine learning process. 3.3.1.1 Phase 1: Data preparation. Nineteen SEPs were labeled as "cause" or "effect" based on DEMATEL results. Expert evaluations formed the feature matrix X, while cause–and–effect labels served as target variables.

Before applying the RF model, the data were pre-processed. The selected SEPs were used as input features, while the labels from the DEMATEL matrix (found in the last column, "Identity") served as the target variables. To mitigate bias, expert-level stratified cross-validation was applied using GroupKFold, ensuring that data from the same expert was excluded from both the training and testing sets. This approach reduced expert-specific patterns in the ratings. Additionally, feature scaling was applied using StandardScaler and categorical encoding was used for the target variable. After preprocessing, the data set was ready to train the RF model.

3.3.1.2 Phase 2: Model development. RF is a kind of ensemble learning, which constructs multiple decision trees and averages their results to make a prediction (Zhu *et al.*, 2025; Iqbal *et al.*, 2026a). This helps reduce overfitting by introducing randomness in feature selection and training the model on subsets of data. RF models were trained using stratified GroupKFold cross-validation to avoid expert-specific bias. Feature scaling and categorical encoding were applied before training.

Table 4. Normalize matrix NM

SEP	SEP1	SEP2	SEP3	SEP4	SEP5	SEP6	SEP7	SEP8	SEP9	SEP10	SEP11	SEP12	SEP13	SEP14	SEP15	SEP16	SEP17	SEP18	SEP19
SEP1	0.000	0.0472	0.0361	0.055	0.047	0.0388	0.0430	0.0374	0.059	0.040	0.0485	0.0596	0.0541	0.0374	0.045	0.047	0.037	0.049	0.045
SEP2	0.048	0.0000	0.0485	0.036	0.056	0.0513	0.0347	0.0458	0.041	0.047	0.0610	0.0527	0.0555	0.0472	0.034	0.045	0.049	0.044	0.051
SEP3	0.036	0.0485	0.0000	0.047	0.037	0.0610	0.0485	0.0555	0.055	0.038	0.0555	0.0499	0.0472	0.0596	0.033	0.045	0.051	0.059	0.041
SEP4	0.054	0.0361	0.0472	0.000	0.052	0.0485	0.0485	0.0555	0.036	0.043	0.0416	0.0513	0.0513	0.0402	0.047	0.034	0.048	0.056	0.043
SEP5	0.047	0.0569	0.0374	0.052	0.000	0.0430	0.0610	0.0458	0.061	0.045	0.0624	0.0485	0.0596	0.0569	0.040	0.061	0.055	0.040	0.052
SEP6	0.034	0.0513	0.0610	0.048	0.043	0.0000	0.0347	0.0444	0.061	0.052	0.0569	0.0555	0.0458	0.0624	0.034	0.041	0.047	0.059	0.036
SEP7	0.043	0.0347	0.0485	0.047	0.061	0.0347	0.0000	0.0624	0.049	0.052	0.0416	0.0624	0.0430	0.0444	0.045	0.055	0.054	0.043	0.056
SEP8	0.045	0.0499	0.0555	0.051	0.054	0.0485	0.0624	0.0000	0.047	0.058	0.0555	0.0624	0.0430	0.0638	0.047	0.049	0.036	0.062	0.044
SEP9	0.061	0.0374	0.0513	0.044	0.056	0.0610	0.0541	0.0472	0.000	0.051	0.0555	0.0569	0.0555	0.0458	0.061	0.048	0.049	0.061	0.047
SEP10	0.040	0.0485	0.0458	0.049	0.044	0.0610	0.0499	0.0485	0.049	0.000	0.0472	0.0569	0.0444	0.0527	0.044	0.054	0.055	0.061	0.043
SEP11	0.055	0.0624	0.0513	0.037	0.063	0.0596	0.0430	0.0624	0.055	0.047	0.0000	0.0583	0.0555	0.0638	0.038	0.062	0.051	0.062	0.047
SEP12	0.062	0.0527	0.0569	0.062	0.048	0.0624	0.0624	0.0638	0.061	0.062	0.0583	0.0000	0.0485	0.0624	0.051	0.062	0.047	0.063	0.063
SEP13	0.059	0.0624	0.0555	0.054	0.055	0.0374	0.0499	0.0472	0.062	0.036	0.0624	0.0485	0.0000	0.0624	0.051	0.061	0.044	0.062	0.044
SEP14	0.037	0.0541	0.0596	0.036	0.062	0.0596	0.0624	0.0596	0.045	0.062	0.0569	0.0638	0.0624	0.0000	0.062	0.045	0.063	0.063	0.044
SEP15	0.052	0.0333	0.0333	0.049	0.045	0.0333	0.0555	0.0472	0.055	0.055	0.0472	0.0624	0.0624	0.0624	0.000	0.055	0.055	0.061	0.058
SEP16	0.052	0.0541	0.0596	0.038	0.055	0.0499	0.0610	0.0624	0.061	0.061	0.0624	0.0624	0.0458	0.0624	0.055	0.000	0.062	0.061	0.049
SEP17	0.034	0.0596	0.0624	0.054	0.052	0.0541	0.0583	0.0374	0.056	0.062	0.0485	0.0638	0.0638	0.0638	0.062	0.062	0.000	0.036	0.056
SEP18	0.061	0.0527	0.0347	0.061	0.063	0.0610	0.0555	0.0624	0.045	0.061	0.0527	0.0638	0.0596	0.0485	0.061	0.061	0.036	0.000	0.059
SEP19	0.061	0.0527	0.0569	0.054	0.056	0.0513	0.0541	0.0513	0.062	0.054	0.0361	0.0583	0.0513	0.0638	0.061	0.058	0.056	0.059	0.000

Source(s): Authors' own

Table 5. Total relation matrix TRM

SEP	SEP1	SEP2	SEP3	SEP4	SEP5	SEP6	SEP7	SEP8	SEP9	SEP10	SEP11	SEP12	SEP13	SEP14	SEP15	SEP16	SEP17	SEP18	SEP19
SEP1	0.632	0.681	0.675	0.679	0.724	0.689	0.708	0.702	0.741	0.700	0.720	0.787	0.723	0.742	0.669	0.721	0.676	0.760	0.674
SEP2	0.694	0.654	0.704	0.677	0.751	0.718	0.718	0.727	0.743	0.724	0.750	0.800	0.742	0.770	0.675	0.738	0.705	0.774	0.696
SEP3	0.697	0.714	0.672	0.701	0.749	0.742	0.745	0.751	0.770	0.732	0.760	0.814	0.749	0.797	0.688	0.752	0.720	0.804	0.701
SEP4	0.685	0.674	0.687	0.629	0.732	0.700	0.716	0.720	0.722	0.706	0.716	0.783	0.723	0.748	0.672	0.712	0.688	0.769	0.674
SEP5	0.747	0.761	0.748	0.745	0.755	0.766	0.799	0.783	0.818	0.779	0.808	*0.859*	0.802	0.839	0.734	0.809	0.764	0.830	0.751
SEP6	0.695	0.715	0.728	0.701	0.752	0.684	0.732	0.740	0.774	0.743	0.760	0.818	0.747	0.798	0.688	0.747	0.715	0.803	0.695
SEP7	0.711	0.708	0.725	0.709	0.778	0.725	0.708	0.764	0.773	0.752	0.754	0.834	0.753	0.791	0.707	0.769	0.730	0.796	0.722
SEP8	0.752	0.761	0.770	0.751	0.813	0.778	0.807	0.747	0.812	0.798	0.808	*0.879*	0.794	0.852	0.746	0.805	0.753	*0.858*	0.750
SEP9	0.771	0.755	0.772	0.750	0.821	0.794	0.805	0.797	0.774	0.797	0.814	*0.880*	0.811	0.842	0.764	0.810	0.771	*0.863*	0.758
SEP10	0.719	0.731	0.733	0.722	0.774	0.760	0.766	0.763	0.785	0.713	0.771	0.841	0.765	0.811	0.716	0.779	0.742	0.825	0.720
SEP11	0.791	0.803	0.797	0.768	*0.854*	0.819	0.821	0.837	0.853	0.819	0.789	*0.910*	0.837	*0.886*	0.768	0.849	0.797	*0.892*	0.782
SEP12	0.848	0.845	0.854	0.841	*0.895*	0.874	*0.892*	*0.892*	*0.913*	*0.886*	*0.897*	*0.914*	0.885	*0.941*	0.830	*0.903*	0.845	*0.951*	0.848
SEP13	0.779	0.786	0.784	0.766	0.829	0.782	0.810	0.806	0.841	0.792	0.830	*0.882*	0.768	*0.866*	0.764	0.830	0.774	*0.873*	0.763
SEP14	0.792	0.813	0.823	0.785	*0.872*	0.837	*0.858*	0.853	0.864	0.852	*0.861*	*0.935*	*0.863*	0.846	0.807	0.853	0.827	0.913	0.798
SEP15	0.755	0.742	0.746	0.746	0.802	0.760	0.797	0.787	0.816	0.791	0.796	*0.874*	0.808	0.846	0.698	0.807	0.767	0.852	0.759
SEP16	0.817	0.824	0.834	0.798	*0.878*	0.840	*0.868*	*0.867*	*0.889*	*0.862*	*0.878*	*0.947*	*0.859*	*0.917*	0.812	0.821	0.837	*0.923*	0.814
SEP17	0.780	0.808	0.816	0.791	0.853	0.822	0.843	0.823	*0.863*	0.841	0.843	*0.924*	0.853	*0.895*	0.798	*0.857*	0.758	0.877	0.799
SEP18	0.811	0.808	0.796	0.804	*0.870*	0.834	0.847	0.852	*0.860*	0.847	0.853	*0.931*	*0.856*	*0.888*	0.803	*0.863*	0.798	0.849	0.808
SEP19	0.810	0.808	0.816	0.797	*0.863*	0.826	0.846	0.841	*0.874*	0.840	0.838	*0.926*	0.849	*0.901*	0.803	*0.860*	0.817	*0.905*	0.751

Source(s): Authors' own

Table 6. Sums of rows and columns

Serial #	Ri	Ci	R + C	R-C	Identity
SEP1	13.402	14.28415	27.68695	−0.88135	Effect
SEP2	13.760	14.39138	28.15175	−0.631	Effect
SEP3	14.056	14.4801	28.53687	−0.42332	Effect
SEP4	13.455	14.15843	27.61387	−0.703	Effect
SEP5	14.898	15.36594	30.2643	−0.46757	Effect
SEP6	14.034	14.74999	28.78441	−0.71557	Effect
SEP7	14.211	15.08593	29.29694	−0.87492	Effect
SEP8	15.031	15.05189	30.08324	−0.02054	Effect
SEP9	15.148	15.4842	30.63295	−0.33545	Effect
SEP10	14.435	14.97567	29.41155	−0.53979	Effect
SEP11	15.673	15.24724	30.92098	0.426493	Cause
SEP12	16.751	16.53895	33.29086	0.212957	Cause
SEP13	15.322	15.18529	30.5082	0.137622	Cause
SEP14	16.051	15.97459	32.02567	0.076495	Cause
SEP15	14.949	14.14269	29.09169	0.806312	Cause
SEP16	16.285	15.28503	31.57043	1.000371	Cause
SEP17	15.843	14.48382	30.32729	1.359653	Cause
SEP18	15.978	16.11606	32.09482	−0.13729	Effect
SEP19	15.970	14.26056	30.23102	1.7099	Cause

Source(s): Authors' own

3.3.1.3 Phase 3: Validation and optimization. To ensure that the model was reliable and widely applicable, different optimization methods were adopted:

- Stratified cross-validation

Model performance was evaluated using stratified cross-validation:

$$Accuracy_k = \frac{1}{k}\sum_{i=1}^{k}\left(\frac{number\ \ of\ \ correct\ \ predictions\ \ in\ \ fold\ \ i}{Total\ \ samples\ \ in\ \ fold\ \ i}\right) \quad (7)$$

- Hyperparameter Tuning

Hyperparameters were optimized via grid search, yielding the optimized prediction function:

$$\hat{y} = f\left(X, \theta^*\right) \quad (8)$$

where θ^* denotes the optimal hyperparameter set obtained via grid search.

- Feature importance and rule extraction

Feature importance scores and decision rules were analyzed to validate causal relationships and extract insights into SEP interdependencies.

3.4 Stage 4: Evaluation and prioritization of sustainable entrepreneurship practices using interpretive structural modeling-MICMAC

In this study, the ISM was used to structure causal SEPs into a hierarchical framework (Pourvaziri *et al.*, 2024). The ISM-MICMAC methodology stands out as it systematically visualizes and ranks influential factors, transforming complex models into well-defined conceptual structures that illustrate their interrelationships (Shaikh *et al.*, 2024). MICMAC analysis further classified SEPs based on driving and dependence power (Arantes and Ferreira, 2024; Sarvari *et al.*, 2024).

3.4.1 Phases in the interpretive structural modeling-MICMAC. 3.4.1.1 Phase 1: Establishing the structural self-interaction matrix (SSIM). SSIM embodies the pairwise relationships between SEPs Table 7 and is established from the critical viewpoint of the experts. The relationship that exists between two SEPs (i) and (j) of the system under consideration was the following:

V: SEP (i) will benefit from attaining SEP (j).

A: SEP (j) will benefit from attaining SEP (i).

X: SEP $(i \ and \ j)$ will benefit each other.

O: SEP $(i \ and \ j)$ are not beneficial for each other.

3.4.1.2 Phase 2: Converting SSIM into the reachability matrix (RM). Through SSIM, a binary matrix was developed to illustrate the directed relationships between the SEPs. This transformation converts the SSIM into a binary matrix, called the RM, by switching the $V, \ A, \ X, \ O$ symbols with 1 and 0 accordingly.

3.4.1.3 Phase 3: Level partition (LP). The Reachability Set $R(i)$and Antecedent Set $A(i)$ were derived for each SEP:

$R(i)$: all SEPs were reachable from i,

$A(i)$: all SEPs that impact i.

The intersection of $R(i)$ and $A(i)$ recognized the SEPs hierarchical levels. SEPs at the top level were removed in each iteration until all SEPs were allocated a level. Overall, LP was given in Table 8.

3.4.1.4 Phase 4: MICMAC analysis. The MICMAC analysis categorized SEPs according to their driving power (DP) and dependence power $(DepP)$:

$$DP_i = \sum_{j=1}^{n} RM_{final}[i][j] \tag{9}$$

$$DepP_i = \sum_{j=1}^{n} RM_{final}[j][i] \tag{10}$$

Table 7. Structural-self interaction matrix SSIM

Sr.	SEP11	SEP12	SEP13	SEP14	SEP15	SEP16	SEP17	SEP19
SEP11		V	V	V	V	A	V	V
SEP12			X	V	X	O	V	O
SEP13				V	X	A	V	O
SEP14					X	A	V	A
SEP15						A	V	O
SEP16							V	O
SEP17								A
SEP19								

Source(s): Authors' own

Table 8. Overall level partitions LPs

No.	Reachability set	Antecedent set	Intersection set	level
SEP11	1	1,6	1	IV
SEP12	2,3,4,5	1,2,3,4,5,6,8	2,3,4,5	II
SEP13	2,3,4,5	1,2,3,4,5,6,8	2,3,4,5	II
SEP14	2,3,4,5	1,2,3,4,5,6,8	2,3,4,5	II
SEP15	2,3,4,5	1,2,3,4,5,6,8	2,3,4,5	II
SEP16	6	6	6	V
SEP17	7	1,2,3,4,5,6,7,8	7	I
SEP19	8	1,6,8	8	III

Source(s): Authors' own

4. Results

4.1 Decision-making trial and evaluation laboratory results

This section presents the empirical results of the study, focusing on the identification, validation and structural prioritization of SEPs that drive decarbonization in construction SMEs. The results are organized based on the sequential analytical stages: DEMATEL, Machine Learning (ML) validation and ISM–MICMAC analysis.

Using the DEMATEL approach, an initial set of nineteen SEPs was identified, covering a broad range of practices related to energy efficiency, sustainability and technological innovation in construction. After expert consultation and contextual refinement, the practices were evaluated for their relevance and applicability to Pakistan's construction SMEs. As a result, eight SEPs demonstrating the strongest causal influence and contextual suitability were retained for further analysis in the ISM–MICMAC stage. This reduction reflects a focus on practices with the greatest strategic relevance for decarbonization in resource-constrained conditions.

(Figure 2, Panel A) illustrates the relative ordering of the identified SEPs according to their systemic influence. The recognized practices include AI-driven site monitoring (SEP18), modular and prefabricated construction techniques (SEP14), energy-efficient building design (SEP16), sustainable supply chain management in construction (SEP11), on-site renewable energy generation (SEP9), solar integration in building designs (SEP13), BIM for sustainability (SEP17), 3D printing with sustainable materials (SEP5) and digital twins for resource optimization (SEP8). The net causality values $(ri - ci)$ reported in the second-to-last column of Table 6 indicate the extent to which each SEP influences or is influenced by others. Eight SEPs exhibited positive net causality values and were therefore classified as causal SEPs, while the remaining practices were categorized as dependent. In descending order of influence, the causal SEPs were AI for optimizing construction processes (SEP19), BIM for sustainability (SEP17), energy-efficient building design (SEP16), use of smart construction materials (SEP15), sustainable supply chain management in construction (SEP11), AI and internet of things (IoT) for energy optimization (SEP12), solar integration in building designs (SEP13) and modular and prefabricated construction techniques (SEP14). Circular economy principles in the project lifecycle (SEP1) emerged as the most dependent SEP.

To further explore contextual relationships among SEPs, all practices were plotted on a causal diagram, with significance represented on the *x*-axis and net influence on the *y*-axis. A threshold value θ was calculated to identify statistically meaningful relationships within the TRM. Following the approach proposed by Iqbal *et al.* (2025a), the threshold was

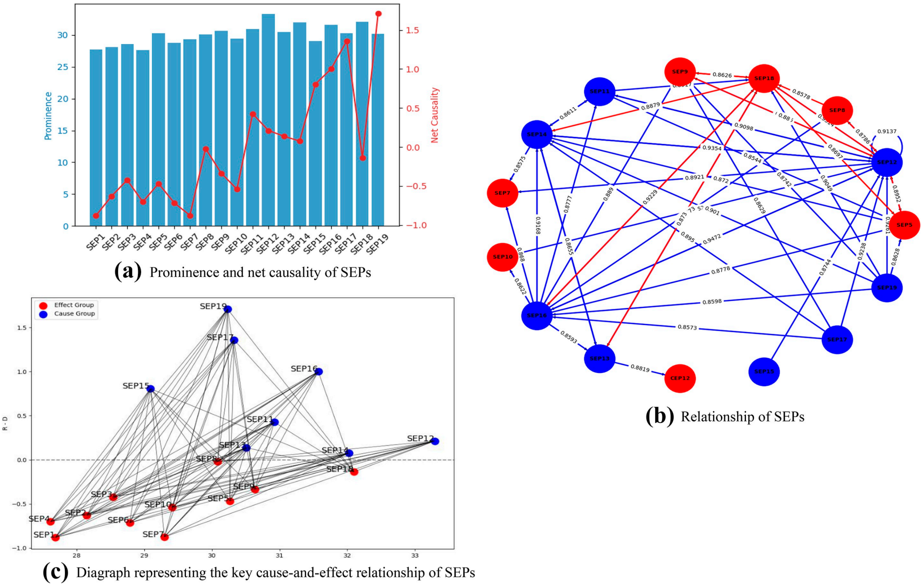


Figure 2. (a) Prominence and net causality of SEPs, (b) Relationship network of SEPs, (c) Cause-Effect relationship of SEPs
Source(s): Authors' own

determined by adding one standard deviation to the mean value of the TRM. The calculated mean and standard deviation were 0.790199 and 0.063922, respectively, resulting in a threshold value of $\theta = 0.854121$. Relationships exceeding this threshold were highlighted in bold in Table 5. (Figure 2, Panel B) presents the complete network of SEP relationships, where SEPs highlighted in blue represent causal practices, while those shown in red belong to the effect group.

(Figure 2 Panel C) displays the DEMATEL-based digraph, emphasizing the central role of AI for optimizing construction processes (SEP19). This practice influences multiple SEPs, such as BIM for sustainability (SEP17), energy-efficient design (SEP16), smart construction materials (SEP15) and others. The prominence of SEP19 underscores its potential to drive low-carbon transformation in construction SMEs.

4.2 Machine learning validation results

To validate the causal structure from DEMATEL, an RF model was used. The RF model achieved 96% classification accuracy, validating the cause-and-effect relationships among SEPs (Table 9). Precision, recall and F1 score further confirmed the model's robust performance. Figure 3 visualizes the RF decision tree, illustrating how SEPs are classified based on influential features like SEP11 and SEP12.

Feature importance analysis (Figure 4 Panel a) showed that SEP15, SEP3 and SEP14 were most influential in classifying SEPs, reinforcing their role in shaping the causal relationships. The confusion matrix (Figure 4 Panel b) confirmed the model's robustness, with 44 out of 46 samples correctly classified. The ROC curve (Figure 4 Panel c)

Table 9. Cause-and-effect classification report

Class	Precision	Recall	F1-score	Support
Cause	1	0.90	0.95	20
Effect	0.93	1.00	0.96	26
Accuracy			0.96	46
Macro average	0.96	0.95	0.96	46
Weighted average	0.96	0.96	0.96	46
Accuracy 0.96				

Source(s): Authors' own

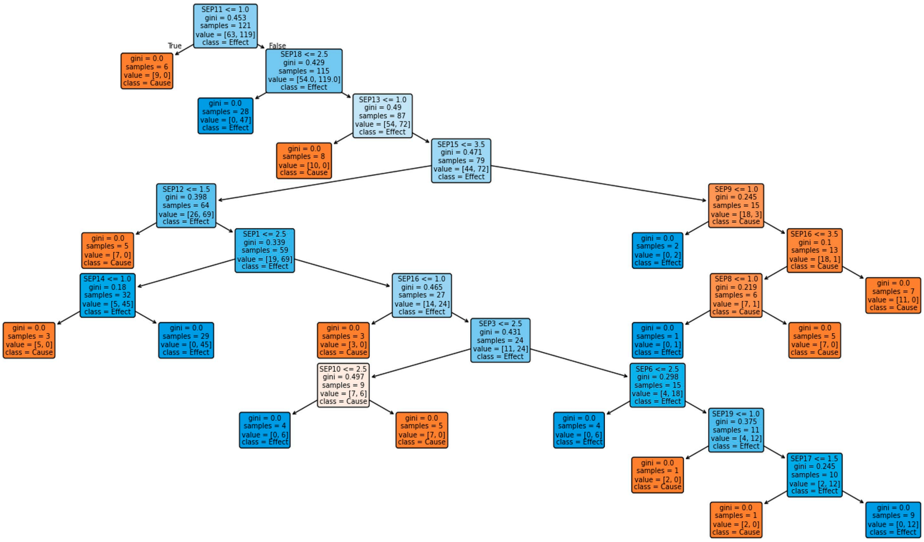
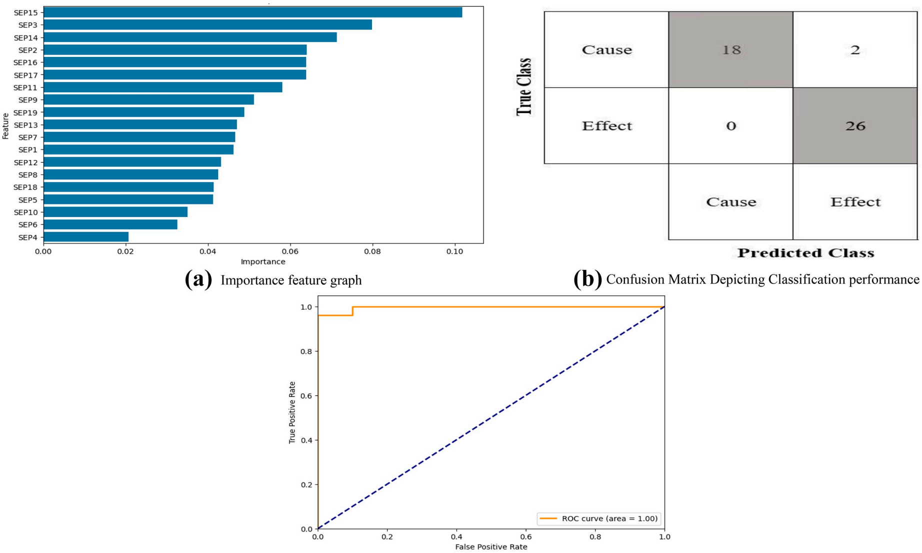


Figure 3. Random forest model visualization
Source(s): Authors' own

demonstrated excellent discriminatory power, with an area under the curve (AUC) value close to 1, indicating high classification performance.

4.3 Interpretive structural modeling-MICMAC results

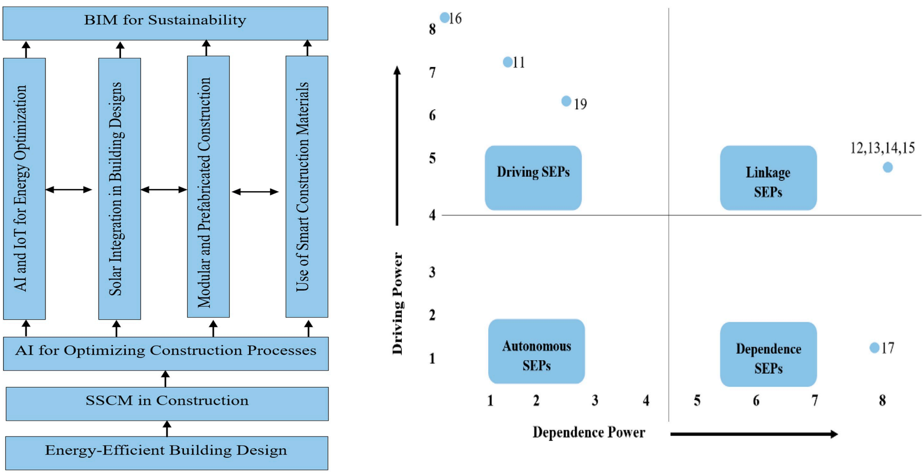
Following the DEMATEL and RF validation stages, the ISM–MICMAC method was used to analyze the hierarchical structure and mutual dependencies of the eight retained SEPs. (Figure 5 Panel a), illustrates the resulting ISM model, where Level 5 contains the most influential SEP: energy-efficient building design (SEP16) and SSCM in construction (SEP11) at level four. These practices are foundational for decarbonization. SEPs such as AI for optimizing construction processes (SEP19), AI and IoT for energy optimization (SEP12), solar integration in building design (SEP13), modular and prefabricated construction techniques (SEP14), use of smart construction materials (SEP15), occupy intermediate levels (Levels 3 and 2), enabling higher-level sustainability outcomes. SEP at Level 1, such as BIM for sustainability (SEP17), plays supportive roles.



(a) Importance feature graph **(b)** Confusion Matrix Depicting Classification performance

(c) ROC Curve

Figure 4. (a) Importance feature graph, (b) Confusion Matrix (c) ROC curve
Source(s): Authors' own



(a) ISM Model **(b)** MICMAC Analysis

Figure 5. ISM hierarchy and MICMAC analysis, (a) ISM model, (b) MICMAC analysis
Source(s): Authors' own

The MICMAC analysis (Figure 5 Panel b) classifies SEPs into four clusters based on driving and dependence power:

(1) *Driving cluster:* SEP16, SEP11, SEP19 (foundational drivers with strong influence and low dependence).

(2) *Linkage cluster:* SEP12, SEP13, SEP14, SEP15 (high driving and dependence power, indicating interdependencies).

(3) *Dependence cluster:* SEP17 (relies on the adoption of other SEPs for effectiveness).

(4) *Autonomous cluster:* No SEPs were classified here, emphasizing the interconnected nature of the SEPs.

The consistency between the DEMATEL and ISM–MICMAC results reinforces the robustness of the analysis and provides a comprehensive understanding of the strategic role of each SEP in decarbonization.

5. Discussion

5.1 Discussion of key findings

The findings of this study emphasize the central role of SEPs in supporting decarbonization within Pakistan's construction SMEs. These firm-level practices not only impact individual projects but also influence the material, energy and carbon profiles of the urban built environment. The analysis highlights that sustainability in this context is driven not by isolated actions but by interrelated practices that form staged low-carbon transition pathways across construction activities. The identified causal SEPs serve as foundational enablers, influencing multiple downstream practices and reinforcing system-wide sustainability outcomes at the built-environment level.

Among the causal SEPs, AI-based process optimization (SEP19), BIM for sustainability (SEP17), sustainable supply chain management (SEP11), AI and IoT for energy optimization (SEP12) and solar integration in building design (SEP13) emerge as the most influential. These practices, while operating at the firm and project levels, have direct implications for urban sustainability, enhancing building energy performance, reducing construction-related emissions and lowering resource intensity across urban development (Peng *et al.*, 2020).

AI for process optimization (SEP19) stands out as the most influential practice, improving productivity, reducing material waste and enhancing operational efficiency. When combined with BIM for sustainability (SEP17), AI enables informed design and construction decisions that support energy-efficient building outcomes across project lifecycles. At scale, these digitally enabled practices can reduce long-term energy demand and mitigate carbon lock-in within urban areas. This finding aligns with prior research by Azhar (2011), which underscores BIM's role in enhancing construction productivity and reducing emissions, while extending existing insights by showing how BIM and AI jointly foster sustainability in resource-constrained SMEs.

Sustainable supply chain management (SEP11) also plays a crucial role in decarbonization by influencing material sourcing, logistics and waste reduction. From an urban sustainability perspective, these practices impact material flows, embodied carbon and construction waste generation. The integration of supply chain sustainability with BIM-supported planning enhances transparency and efficiency, echoing Brandenburg *et al.* (2014), who emphasize the significance of green procurement in reducing material-related emissions.

The use of AI and IoT for energy optimization (SEP12) further highlights the importance of digital technologies in addressing the carbon intensity of construction. Continuous monitoring and automated energy management systems allow SMEs to identify inefficiencies and reduce energy consumption during both construction and building operation phases (Bale *et al.*, 2024). These practices contribute to lowering operational emissions in urban areas, which is particularly important in rapidly urbanizing developing economies.

Solar integration in building design (SEP13) reduces reliance on fossil fuels, supporting on-site renewable energy generation and promoting urban energy resilience. When combined with AI- and IoT-based energy management, solar integration optimizes energy use and further reduces carbon footprints. This finding reinforces evidence from Mariano-Hernández *et al.* (2020) which highlights renewable energy integration as key to achieving carbon neutrality, demonstrating its practical relevance for construction SMEs in Pakistan.

The RF validation analysis confirms the robustness of the identified causal relationships, with a classification accuracy of 96% (Table 9), reinforcing the applicability of the SEPs for policy design and broader implementation in decarbonization programs.

The ISM–MICMAC analysis provides further structural insights into the hierarchical relationships among SEPs. Energy-efficient building design (SEP16) emerges as the highest-level practice, reflecting its strategic importance as a long-term driver of sustainability. From a built-environment perspective, this suggests that foundational digital and organizational practices are prerequisites for achieving sustained improvements in building performance and urban carbon reduction.

Practices in the linkage cluster, such as AI for process optimization (SEP19) and AI and IoT for energy optimization (SEP12), display strong mutual interdependencies, indicating that their effectiveness depends on coordinated implementation rather than isolated adoption. The absence of autonomous SEPs emphasizes the systemic nature of sustainability transitions in construction SMEs, highlighting the need for integrated and sequenced approaches that align firm-level actions with broader urban decarbonization goals.

5.2 Theoretical implications

This study extends SE and decarbonization theory by foregrounding construction SMEs in developing economies characterized by resource constraints, weak regulatory enforcement and fragmented institutional support. Prior research has largely focused on large firms in developed countries, leaving the structural realities of SMEs in the Global South underexplored. By examining SEPs in Pakistan's construction sector, this study broadens SE theory to incorporate the organizational, financial and institutional dynamics shaping sustainability transitions in developing economies.

The findings contribute to theory by demonstrating the interdependent and cumulative nature of SEPs. Rather than operating as isolated interventions, SEPs function as foundational enablers that condition the feasibility and effectiveness of subsequent practices. This challenges linear and checklist-based models of sustainability adoption and supports a systems-oriented perspective in which sustainability emerges through the interaction of complementary organizational capabilities.

The study also advances sustainability transition theory by emphasizing the role of prioritization and sequencing in SME-dominated sectors. In developing economies, decarbonization does not follow comprehensive or simultaneous adoption of sustainability practices. Instead, it unfolds through incremental capability building driven by strategically influential practices. From an urban and sectoral perspective, this suggests that construction-sector decarbonization depends on the ordered diffusion of foundational practices across SMEs rather than on isolated flagship projects or advanced technologies alone.

5.3 Practical and policy implications

The findings offer actionable guidance for construction SMEs in developing economies seeking to move from fragmented sustainability efforts toward a coherent and feasible decarbonization pathway. Given persistent financial, technical and institutional constraints, SEPs are unlikely to be adopted simultaneously. The results highlight the importance of staged transitions, where foundational practices enable the gradual integration of advanced solutions.

5.3.1 Phase 1: Initiate (plan). At the entry stage, SMEs should prioritize SEPs with strong driving power and immediate operational benefits. Energy-efficient building design (SEP16) and sustainable supply chain management (SEP11) serve as effective starting points, as they reduce energy use and material waste with modest organizational adjustment. Policy support in the form of financial incentives, simplified regulations and short-term assistance is critical to lowering entry barriers and encouraging early engagement.

5.3.2 Phase 2: Analyze (plan). Once sustainability objectives are defined, SMEs should assess their readiness for adopting more advanced SEPs. This phase involves evaluating financial capacity, technical expertise and organizational preparedness for digital solutions. A structured readiness assessment helps identify capability gaps and implementation risks, informing subsequent pilot activities.

5.3.3 Phase 3 and 4: Configure (deliver). In the next stage, SMEs can begin integrating digitally enabled practices such as BIM for sustainability (SEP17) and AI-based process optimization (SEP19). These tools enhance planning accuracy, resource efficiency and project coordination. Incremental adoption through pilot applications allows SMEs to manage risk and evaluate feasibility. Policymakers can facilitate this stage through technical training, demonstration projects and partnerships with technology providers.

5.3.4 Phase 5: Validate (deliver). Following pilot implementation, SMEs should validate the performance of adopted SEPs under real operational conditions. This phase focuses on performance assessment, learning and refinement. Practices such as AI- and IoT-based energy optimization (SEP12) and solar integration in building design (SEP13) gain relevance as SMEs strengthen monitoring and data capabilities. Validation should be supported by performance metrics, monitoring systems and feedback mechanisms.

5.3.5 Phase 6: Deploy (adaptation). Once capabilities mature, SMEs can scale and integrate SEPs into routine operations. Deployment requires coordination among complementary practices to achieve system-level improvements. The integration of AI, IoT and renewable energy solutions can deliver substantial emission reductions and operational gains. Policy support should emphasize interoperability standards, public–private collaboration and shared digital or energy infrastructure.

5.3.6 Phase 7: Optimize (adaptation). In the final stage, sustainability practices should be institutionalized and scaled across projects. Advanced solutions, such as smart construction materials (SEP15) and standardized digital workflows, should be embedded into strategic planning and daily operations. Policymakers can reinforce this phase by integrating sustainability requirements into building codes, procurement frameworks and urban development strategies. Industry associations play a key role in facilitating benchmarking, knowledge exchange and collective learning among SMEs.

Figure 6 presents an illustrative roadmap that synthesizes this staged implementation logic, showing how construction SMEs can progress from basic sustainability practices to advanced, integrated solutions. The pathway is adaptable to firm size, project complexity and institutional conditions, offering transferable insights for other developing economies where SMEs shape the urban built environment.

6. Conclusion

This study examined how SEPs can support the decarbonization of construction SMEs in a developing-economy context, drawing on empirical evidence from Pakistan. The findings

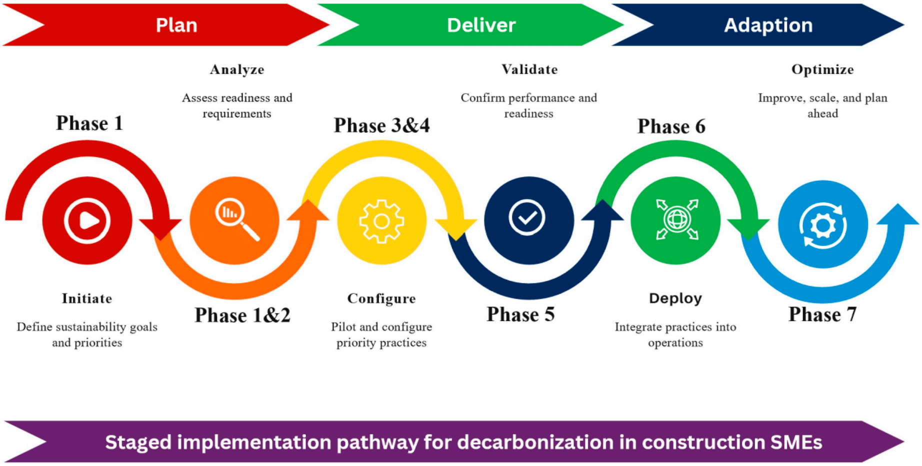


Figure 6. Illustrative staged roadmap for operationalizing priority SEPs in construction SMEs
Source(s): Authors' own

show that sustainability transitions in construction SMEs are driven not by isolated initiatives but by a set of interrelated and strategically influential practices. AI-enabled process optimization, BIM for sustainability, energy-efficient building design and smart construction materials emerge as key drivers of low-carbon transition, enhancing operational efficiency, resource utilization and environmental performance. As construction SMEs collectively deliver a substantial share of buildings and infrastructure, these firm-level practices generate cumulative effects that shape emissions trajectories and sustainability outcomes across the built environment.

The study further demonstrates that effective decarbonization depends on a sequenced and capability-oriented approach rather than the simultaneous adoption of multiple sustainability initiatives. Foundational practices, particularly energy-efficient design and process optimization, establish the conditions required for integrating advanced digital and material innovations. This sequencing logic highlights how gradual capability development at the firm level can support durable low-carbon outcomes, influence construction processes and shape long-term energy demand in urban systems.

While this study is grounded in the Pakistani context, the findings may hold analytical relevance for other developing economies that face similar institutional, financial and technological constraints. Rather than claiming direct generalizability, the results highlight the potential importance of aligning policy instruments, entrepreneurial practices and technological adoption with local capability conditions. They also suggest that phased interventions may help lower entry barriers for SMEs and support the gradual scaling of low-carbon practices. However, the applicability of this transition logic beyond Pakistan should be assessed through comparative studies in other national and regional settings.

This study has limitations that open avenues for future research. First, the analysis focuses on a single national context and future studies should examine the transferability of the proposed transition logic across different institutional and regional settings. Second, further research could incorporate social and economic dimensions of sustainable entrepreneurship, including workforce skills, organizational learning and stakeholder engagement. Longitudinal analyses may also help capture how sustainability practices evolve as firm capabilities mature. Finally, future studies could validate and extend the findings using alternative analytical approaches, such as structural equation modeling, to further examine relationships among SEPs and decarbonization outcomes.

Data availability

Data will be available upon reasonable request.

Declaration of generative AI

AI tools were used only for language editing and to improve grammatical clarity. All ideas, analysis and conclusions are the responsibility of the authors.

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