Journal of Open Innovation: Technology, Market, and Complexity 12 (2026) 100697

Contents lists available at ScienceDirect

Journal of Open Innovation: Technology, Market, and Complexity

journal homepage: www.sciencedirect.com/journal/journal-of-open-innovation-technology-market-and-complexity

Factors influencing circular economy business model adoption: Evidence from NCA and PLS-SEM

Noor Ul Hadi [a,*], M. Imran Khan [b]

[a] Department of Human Resource Management, College of Business Administration, Prince Mohammad Bin Fahd University, Al-Khobar, Saudi Arabia
[b] Department of Mechanical Engineering, College of Engineering, Prince Mohammad Bin Fahd University, Al-Khobar, Saudi Arabia

ARTICLE INFO

Keywords:
Circular economy business model adoption
Circular resources, circular collaboration and support
Necessary condition analysis
NCA

ABSTRACT

Several studies have examined the factors influencing circular economy business model adoption. However, understanding remains limited from the perspective of Necessary Condition Analysis, leaving a notable gap in circular economy research that explicitly applies Necessary Condition Analysis to uncover the hidden conditions necessary for the successful implementation of circular strategies in business organizations. Drawing on the Resource-Based View and Stakeholder Theory, this study combines Partial Least Squares Structural Equation Modeling (PLS-SEM) with Necessary Condition Analysis (NCA) to distinguish "should-have" associations from "must-have" thresholds. Using survey data from 209 marble manufacturing firms, we examine eight factors: circular human resource management, circular entrepreneurship, circular marketing, circular financing, circular manufacturing technologies, circular-oriented workplace culture, circular open innovation, and government support. The integrated results show that several internal capabilities and one institutional factor are both necessary and sufficient (circular human resource management, circular entrepreneurship, circular manufacturing technologies, circular-oriented culture, government support), circular open innovation is necessary-only, circular financing is sufficient-only, and circular marketing is neither in this context. NCA bottleneck thresholds provide actionable benchmarks indicating minimum levels each necessary condition must meet at different target levels of CEBM adoption. Methodologically, the study demonstrates how a dual-logic approach reveals hidden constraints that sufficiency models alone overlook. Theoretically, it reframes selected capabilities and institutional enablers as foundational preconditions rather than merely supportive resources. Practically, it offers a sequenced roadmap: meet the lowest unmet threshold first, then deploy sufficiency levers to scale circular outcomes supporting managers and policymakers seeking credible pathways toward a regenerative, circular economy.

1. Introduction

The global economy is currently facing unprecedented challenges, including climate change, resource depletion, waste accumulation, and biodiversity loss. These crises have placed significant pressure on governments, industries, and society to adopt more sustainable economic practices (Kirchherr et al., 2023; Geissdoerfer et al., 2023). In this context, the circular economy (CE) has emerged as a transformative paradigm, offering a viable pathway to decouple economic growth from resource exploitation and environmental degradation (Mukherjee et al., 2025; Pan et al., 2024; Abbate et al., 2023). Unlike the prevailing linear economic model of "take-make-dispose," which relies on extracting, processing, consuming, and discarding finite resources, the CE emphasizes closed-loop systems that prioritize reuse, recycling, remanufacturing, and resource efficiency (Prieto-Sandoval et al., 2019; Lieder and Rashid, 2016). This paradigm shift not only mitigates environmental harm but also fosters resilience and sustainability by reducing waste, lowering greenhouse gas emissions, and conserving dwindling natural resources (Velenturf and Purnell, 2021). The CE framework aligns with global sustainability objectives, including the UN SDGs, and offers businesses opportunities to reduce costs, mitigate risks associated with resource scarcity, and unlock new revenue streams through innovative business practices (De Angelis 2024; Brown et al., 2021). Central to the operationalization of CE are circular economy business models (CEBMs), which integrate circular principles into organizational strategies, redefining how value is created, delivered,

* Corresponding author.
E-mail addresses: n_hadi1@yahoo.com (N.U. Hadi), imran.hwu@gmail.com (M. Imran Khan).

https://doi.org/10.1016/j.joitmc.2025.100697
Received 6 October 2025; Received in revised form 19 November 2025; Accepted 2 December 2025
Available online 4 December 2025

and captured (Sgambaro et al., 2025; Hadi, 2024; Katou et al., 2023; Chowdhury et al., 2022; Aloini et al., 2020).

Despite their transformative potential, a critical limitation in the existing CEBM literature is its overwhelming reliance on symmetric, sufficiency-based statistical techniques such as regression and structural equation modeling. These methods typically operate on probabilistic sufficiency logic—that is, they assess whether the presence of a factor (X) makes the outcome (Y) more likely, on average, holding other variables constant. While valuable, this approach assumes that factors compensate for one another and tends to obscure non-compensatory conditions that may be absolutely required for the outcome to materialize. Such conditions are not merely helpful; they are structurally indispensable. In contrast, Necessary Condition Analysis (NCA) offers a different causal logic: it identifies factors that are deterministically necessary those without which the outcome cannot occur at all, regardless of the presence of other favorable factors (Dul, 2024, 2016a; Dul et al., 2023; Hauff et al., 2021). These "hidden conditions," as we refer to them, are often overlooked in traditional models. They represent bottlenecks that must reach minimum thresholds before progress toward circularity becomes possible. Their identification is particularly valuable in sustainability contexts where cascading failures may arise from missing foundational inputs. Accordingly, this study asks: which internal capabilities and external enablers are *necessary* in the non-compensatory "no X, no Y" sense for firms to adopt CEBMs, and how do these relate to *sufficiency*-based patterns estimated using PLS-SEM within a single, coherent design?

The use of NCA in this study is not based on its novelty alone. Rather, its adoption is motivated by a theoretical and methodological imperative. In the complex domain of circular economy transitions characterized by multiple actors, interdependent processes, and context-specific constraints understanding what is merely helpful versus what is fundamentally required is critical. Unlike fsQCA, which identifies combinations of conditions that are sufficient, and unlike PLS-SEM, which explains variance based on average effects, NCA isolates conditions that are non-substitutable. In doing so, it introduces a level of diagnostic specificity into CE research that other approaches cannot provide. As Dul, Hauff, and Bouncken (2023) argue, NCA is uniquely suited for domains where certain capabilities or supports must be in place for any outcome to occur, a situation commonly encountered in organizational transitions toward circularity. Methodologically, we implement this pairing by first validating the measurement model, then exporting latent composite scores, and finally conducting NCA to derive bottleneck thresholds using CE-FDH with permutation tests (e.g., Richter et al., 2023).

To further strengthen the conceptual foundation of this study, we embed the NCA approach within two well-established theoretical frameworks: the Resource-Based View (RBV) and Stakeholder Theory. According to RBV (Barney, 1991), firms derive sustained competitive advantage from internal resources that are valuable, rare, inimitable, and non-substitutable. In the context of CE, these resources may include entrepreneurial orientation, human capital aligned with circular principles, digital and manufacturing technologies, and an organizational culture of sustainability. Meanwhile, Stakeholder Theory (Freeman, 2010) underscores the central role of external actors governments, consumers, suppliers, and civil society in enabling or constraining organizational behavior. CE transitions are inherently relational; they require not only internal readiness but also supportive ecosystems. These theories jointly support the idea that certain internal capabilities and external supports are not simply contributing factors; they may be necessary conditions whose absence prevents circular outcomes altogether. The integration of RBV and Stakeholder Theory thus offers a theoretically grounded rationale for adopting NCA as an analytical tool in this study. A fuller, construct-by-construct justification is developed in the next section.

Empirically, the study focuses on the marble industry in Khyber Pakhtunkhwa, Pakistan - a resource-intensive and environmentally burdensome sector that presents a compelling context for investigating circular economy transitions. The industry is characterized by low formalization, high waste generation, and limited adoption of sustainable practices (Iqbal et al., 2022; La Scalia et al., 2022). Every cubic meter of processed marble generates hundreds of tons of waste in the form of rubble and slurry, posing significant ecological and health risks (Cobo-Ceacero et al., 2019). Yet, recycling this waste has shown potential for producing valuable inputs for other industries, including construction and ceramics (Demirel and Alyamac., 2018). This paradox (e.g., a sector with high environmental stakes and low CE maturity) makes the marble industry an ideal setting to uncover not just what supports CEBM adoption, but what must be in place to make such transitions feasible.

Within this setting, we examine eight key conditions hypothesized as necessary for the successful adoption of CEBMs. These include internal organizational factors such as circular human resource management, circular entrepreneurship, circular marketing practices, circular financing, circular manufacturing technologies, and a workplace culture oriented toward circularity. Additionally, we analyze external enablers including open circular innovation and government support. These eight conditions are carefully selected based on their prominence in CE research and their alignment with the RBV and Stakeholder Theory. Internal capabilities are framed as potentially VRIN resources critical for competitive advantage, while external supports are seen as enabling conditions shaped by stakeholder engagement, institutional environments, and policy frameworks.

The methodological contribution of this study lies in its dual application of NCA and PLS-SEM. While NCA is employed to detect non-compensatory constraints, PLS-SEM is used to test probabilistic sufficiency relationships. This two-pronged approach enables us to distinguish between "must-have" and "should-have" conditions between structural enablers and strategic amplifiers of circular adoption. By doing so, the study contributes not only to theory refinement but also to practice. It provides a roadmap for entrepreneurs, policymakers, and sustainability practitioners to prioritize interventions that unlock circular transitions. Ultimately, this study argues that identifying necessary conditions for circular economy business model adoption is not only methodologically robust but also theoretically coherent and practically urgent. In contexts like Pakistan's marble sector where institutional voids, resource constraints, and environmental degradation co-exist understanding what must be in place offers actionable clarity for organizations striving to move from linear inertia to circular transformation.

The remainder of the paper proceeds as follows: the next section elaborates the theoretical underpinnings and the a priori rationale for the eight conditions; subsequent sections outline the combined PLS-SEM → NCA workflow, present results, and discuss threshold-based implications, limitations, and conclusions.

2. Literature review

2.1. Theoretical background

Circular economy business model (CEBM) adoption requires an understanding of how internal firm capabilities and external enabling conditions interact to drive sustainable transformation. To frame this relationship, we draw on two foundational theoretical perspectives: the Resource-Based View (RBV) and Stakeholder Theory. Together, these frameworks provide a robust basis for identifying the necessary conditions for circular economy adoption and support the theoretical application of Necessary Condition Analysis (NCA) in this study. In particular, they help distinguish non-substitutable internal baselines from ecosystem feasibility requirements the kinds of conditions that function as thresholds rather than merely additive contributors.

The RBV posits that firms achieve sustainable competitive advantage through resources that are valuable, rare, inimitable, and non-substitutable (Barney, 1991). In the context of CEBM, several internal capabilities reflect these criteria and are hypothesized as foundational prerequisites for circular transformation (López & Ruiz 2022). These include circular human resource management (CHRM), circular entrepreneurship, circular marketing practices, access to circular financing, and the adoption of circular manufacturing technologies. Each of these resources contributes not merely as a facilitator but as a potential non-compensatory constraint their absence may create organizational bottlenecks that prevent circularity from materializing regardless of other positive factors. CHRM aligns skills and incentives with circular goals (Khan et al., 2024; Obeidat et al., 2023); circular entrepreneurship mobilizes opportunity recognition and proactive redesign (Diacono and Baldacchino, 2024; Konietzko et al., 2020); circular marketing reshapes demand toward loop-based value creation (Alrawabdeh, 2024; Mostaghel et al., 2023). Circular financing provides capital aligned with circular payback logics (Ozili, 2021), and circular manufacturing technologies enable reuse, remanufacturing, and resource efficiency (Kara et al., 2022). A circular-oriented workplace culture further serves as a socio-cognitive substrate that normalizes loop-closing routines and facilitates unlearning of legacy linear practices (Bertassini et al., 2021; Rizos et al., 2016). Under RBV, these internal assets function as indispensable baselines rather than optional enhancers.

Stakeholder Theory complements this internal perspective by emphasizing the relational and institutional environment in which firms operate. Circular transitions often require regulatory alignment, infrastructural support, and inter-organizational knowledge-sharing elements that extend beyond firm boundaries. Two constructs - government support and open circular innovation (COI) represent the most proximal and theoretically justified external enablers in this context. Government support reflects regulatory frameworks, incentives, and infrastructure that reduce uncertainty and coordination costs, enabling firms to adopt circular processes (Benito-Hernández et al., 2021; Dagiliene, et al., 2021). COI captures outward-facing collaboration and knowledge exchange (e.g., alliances, technology partnerships, co-development initiatives) that expand a firm's access to circular expertise and solutions (Hadi et al., 2025; Perotti et al., 2024). Although the number of external variables (two) is smaller than the internal set, this selection is deliberate and grounded in contextual relevance. In resource-constrained industrial settings such as marble manufacturing, government support and COI are consistently identified in prior CE research as the most immediate and actionable boundary conditions that determine whether internal capabilities can translate into circular outcomes. Other external actors (e.g., consumers, NGOs, global buyers) exert more distal or indirect influence and therefore fall outside the scope of firm-level necessity analysis. Thus, the focus on these two external factors reflects their salience as threshold conditions those without which circular transformation becomes infeasible regardless of internal strengths.

The integration of RBV and Stakeholder Theory thus offers a dual-lens explanation of the structural conditions necessary for CEBM adoption. RBV suggests that certain internal capabilities are non-substitutable, aligning with NCA's deterministic logic of "no X, no Y." Stakeholder Theory implies that specific external supports such as policy backing and collaborative ecosystems are essential for operationalizing circularity at scale. This theoretical alignment strengthens the rationale for applying NCA, which is explicitly concerned with identifying non-compensable preconditions rather than probabilistic contributors. Recent CE scholarship emphasizes that failing to identify structural bottlenecks can lead firms to misallocate effort toward impactful but insufficient conditions (Dul et al., 2023). Accordingly, we expect some conditions to act as feasibility-enabling thresholds, while others serve as amplifying drivers once these thresholds are met an expectation that sets the stage for combining necessity and sufficiency within a unified framework. To conclude, RBV explains why internal circular capabilities such as CHRM, entrepreneurship, and manufacturing innovation may constitute indispensable resources that anchor competitive advantage in a circular economy. Stakeholder Theory justifies the necessity of external supports specifically government backing and inter-organizational collaboration for enabling and scaling circular practices. Together, these perspectives provide a comprehensive theoretical foundation for empirically testing necessity logic in CEBM adoption, particularly in resource-constrained and policy-fragmented industrial contexts. The next section develops a construct-specific rationale for all eight conditions and articulates how they interrelate within this dual-theoretical lens.

2.2. Factors influencing circular economy business model adoption

2.2.1. Circular human resource management practices and CEBM

Circular human resource management is a crucial internal capability for organizations transitioning toward circular business models (Rubel and Rimi, 2024; Khan et al., 2024; Marrucci et al., 2021). CHRM is defined as the application of human resource practices such as recruitment, training, performance appraisal, and rewards to support circular objectives such as waste reduction, resource efficiency, and sustainability-oriented innovation (Obeidat et al., 2023; Jabbour et al., 2022; Renwick et al., 2016). Through targeted development of employee skills, competencies, and environmental awareness, CHRM aligns the workforce with circularity principles and embeds sustainability across the organizational culture and processes (Amrutha and Geetha, 2020; Jabbour and de de de Sousa Jabbour, 2016). The RBV positions human as a valuable, rare, and non-substitutable resource (Barney, 1991), particularly in knowledge-intensive or transformation-driven environments like the CE (Hadi, et al., 2025; Hadi, 2024). In this context, CHRM becomes not merely an enabling factor but a potentially indispensable one for fostering employee behaviors, capabilities, and mindsets that are compatible with circularity (Cvijović, 2023). Accordingly, CHRM is expected to provide a non-substitutable baseline that enables feasibility while also serving, on average, as a driver that strengthens the likelihood of adoption once that baseline is met.

The importance of CHRM extends beyond incremental environmental improvements. Without a workforce trained and incentivized to prioritize circular practices, organizations may experience resistance, misalignment, and implementation failure even when other technical or financial resources are available (Subramanian & Suresh, 2022; Dibia et al., 2020). This aligns with RBV's emphasis on the non-substitutability of core internal resources: circular transformation may be conceptually desirable, but it cannot be executed unless human resources are adequately developed and aligned with the transformation agenda (Barney, 1991; Teece, 2007). To further support this, one may consider the following necessity-based reasoning: Can an organization adopt a circular economy business model in the absence of CHRM? Even if technological infrastructure and external support exist, without skilled and environmentally committed personnel, the organization may struggle to operationalize CE principles, translating strategy into actionable routines (Amrutha and Geetha, 2020). There is no clear substitute for this alignment; external incentives or digital systems cannot replace internal behavioral commitment. Thus, CHRM functions as a bottleneck condition a constraint that blocks CEBM adoption when absent or underdeveloped, i.e., a "must-have" in the sense of necessity logic.

This interpretation finds indirect support in studies that, while using sufficiency-based methods, highlight the foundational role of CHRM in enabling green innovation, circular process redesign, and sustainability transitions. For example, Jabbour and de de de Sousa Jabbour (2016) describe CHRM as a "core element of environmental strategy," and Marrucci et al. (2021) emphasize the alignment of workforce skills with sustainability goals as essential for successful operations-level CE practices. In line with established guidance on combining NCA with PLS-SEM (Richter et al., 2023, 2020), we state the following hypotheses:

H1 (Sufficiency): Circular human resource management practices are positively associated with the adoption of circular economy business models.

N1 (Necessity): Circular human resource management practices are a necessary condition for the successful adoption of circular economy business *models.*

2.2.2. Circular entrepreneurship and circular economy business model adoption

Circular entrepreneurship plays a vital role in transforming linear value chains into sustainable and regenerative business models (Ferreira et al., 2024). It represents an entrepreneurial orientation that embeds circular principles into innovation, operations, and business design, thus supporting the transition from traditional production to closed-loop, low-waste systems (Diacono and Baldacchino, 2024; Cullen and De Angelis, 2021). Circular entrepreneurs demonstrate a high level of creativity, sustainability awareness, and a proactive stance toward value creation that decouples growth from resource use (Konietzko et al., 2020). As such, circular entrepreneurship reflects a firm's capacity to reimagine its role in the economy not merely optimizing within the current system, but disrupting and redesigning it toward sustainability (Dantas et al., 2022). In this sense, circular entrepreneurship is expected to function as a non-substitutable baseline for feasibility while, on average, also amplifying the likelihood of adoption once that baseline is met.

Within the RBV, this entrepreneurial mindset can be conceptualized as an intangible but strategic resource one that provides the cognitive and behavioral foundation for reconfiguring value propositions in alignment with CE principles (Barney, 1991). Entrepreneurs who embody circular values are likely to generate innovations that close resource loops, minimize ecological impact, and enable cross-sectoral collaboration (Diacono and Baldacchino, 2024). Importantly, these entrepreneurial capabilities cannot be easily imitated or replaced; they often reflect idiosyncratic experience, embedded environmental concern, and long-term strategic thinking, all of which are core tenets of VRIN-based resource advantage (Hadi et al., 2023). To understand why circular entrepreneurship may constitute a necessary condition for CEBM adoption, consider the following reasoning: In the absence of such orientation, organizations may lack the vision and risk-taking appetite required to pursue circular strategies that initially appear uncertain, less profitable, or disruptive. Unlike incremental changes to reduce waste or improve efficiency, circular business models demand a rethinking of product–service systems, supply chain partnerships, and value logic itself. These changes require an entrepreneurial drive that is not substitutable by external policies or internal technical upgrades alone (Linder et al., 2022). Even when government incentives or technological infrastructure are present, without the proactive mindset to reimagine business models in circular terms, firms may remain stuck in linear pathways due to institutional inertia or short-termism. Consistent with combined-use guidance, we articulate sufficiency expectations first and necessity expectations second to reflect the distinction between should have and must-have factors (Richter et al., 2020, 2023; see also Troiville et al., 2025).

Empirical literature, although largely grounded in sufficiency paradigms, offers indirect support for the necessity of circular entrepreneurship. Suchek et al. (2022) highlight that entrepreneurs are often the "catalysts of circular transformation" in sectors with weak institutional incentives. Similarly, Konietzko et al. (2020) suggest that circular innovation requires a "systemic agency" rooted in entrepreneurial identity and agency. Diacono and Baldacchino (2024) emphasize that circular entrepreneurs not only innovate differently but also think differently relying on life-cycle thinking and regenerative logic. These conceptualizations reflect characteristics that are deeply embedded and difficult to externally impose, further reinforcing the argument that circular entrepreneurship is not simply advantageous but essential for meaningful CEBM engagement.

H2 (Sufficiency): Circular entrepreneurship is positively associated with the adoption of circular economy business models.

N2 (Necessity): Circular entrepreneurship is a necessary condition for the successful adoption of circular economy business models.

2.2.3. Circular marketing practices and circular economy business model adoption

Circular marketing is increasingly recognized as a critical enabler for the adoption of circular business models (Lu et al., 2024; Alrawabdeh, 2024). It involves the alignment of marketing practices with circular economy values, including the promotion of sustainable consumption, customer engagement in closed-loop systems, and communication strategies that emphasize product life extension, reuse, and recycling (Mostaghel et al., 2023). Unlike traditional marketing, which often prioritizes short-term sales and consumption stimulation, circular marketing focuses on changing consumer mindsets, encouraging participation in circular solutions, and creating demand for sustainable offerings (Rejeb et al., 2022, p. 169). In this sense, circular marketing is expected to provide a demand-side baseline that enables feasibility while, on average, also amplifying adoption once that baseline is met.

From the RBV, marketing capabilities particularly those that align branding, communication, and market sensing with sustainability can be considered VRIN resources. They are difficult to imitate because they are embedded in a firm's reputation, customer knowledge, and internal learning systems (Barney, 1991). Marketing strategies that successfully communicate circular value propositions such as product-as-a-service models or take-back schemes play a pivotal role in enabling the behavioral shifts required for CE transitions (Mostaghel et al., 2023). These strategies not only differentiate the firm but also foster consumer trust and loyalty in a context where circular products may face market resistance due to perceived inconvenience, cost, or quality concerns (Alrawabdeh, 2024).

To justify the necessity of circular marketing for CEBM adoption, one can consider the following: Can firms adopt circular models effectively without reorienting their marketing logic? In the absence of circular marketing, consumers may remain unaware or unconvinced of the value embedded in circular offerings thereby resulting in low participation in take-back programs, hesitation toward reused products, or poor uptake of leasing models. Even with robust internal capabilities in technology or operations, without circular marketing the organization faces a demand-side bottleneck: value is created but not captured. Moreover, the educational role of marketing especially in emerging markets is irreplaceable, as it shapes consumer expectations and reduces the psychological distance from sustainability (Almashaleh et al., 2025; Vidal-Ayuso et al., 2023). No other organizational function provides an equivalent, scalable consumer-facing interface to normalize circular behaviors.

While the majority of empirical studies assess circular marketing's effect through sufficiency-based models, several scholars implicitly describe it as indispensable. Vassileva and Ivanov (2017) highlight that "without marketing strategies tailored to circular offerings, the CE cannot scale beyond niche applications." Alrawabdeh (2024) emphasizes that marketing must evolve into a tool for "mindset shift," which is required to bridge the gap between circular production and sustainable consumption. Similarly, Sumarsono et al. (2025) argue that marketing strategies must be reconfigured to reflect systems thinking and circular logic—thereby suggesting that this alignment is not optional but necessary for successful CEBM realization. Based on this reasoning, we posit: *H3 (Sufficiency): Circular marketing is positively associated with the adoption of circular economy business models.*

N3 (Necessity): Circular marketing is a necessary condition for the successful adoption of circular economy business models.

2.2.4. Circular financing

Circular financing refers to the availability and mobilization of financial resources tailored to support circular initiatives, including investments in remanufacturing technologies, reverse logistics, product-as-a-service systems, and resource-efficient infrastructure (Lin et al., 2024; Sepetis, 2022; Dewick et al., 2020; Goovaerts and Verbeek, 2018). Unlike conventional financing mechanisms that often favor short-term returns and linear production models, circular financing requires rethinking financial logic to accommodate longer payback periods, non-traditional assets, and life-cycle value creation. It enables firms to experiment with new business models, build sustainable capabilities, and absorb risks associated with early-stage circular investments (Zhou et al., 2020). Access to such finance is particularly critical in contexts like Pakistan's marble industry, where institutional support for sustainability remains limited and firms often lack the liquidity to invest in circular transformation (Ozili, 2021). From a resource-based perspective, financial capital is a foundational resource that underpins the acquisition and deployment of other valuable, rare, inimitable, and non-substitutable capabilities such as advanced manufacturing systems or skilled personnel. While financial resources are not rare in themselves, their alignment with circular objectives can become a differentiating asset, especially in environments where conventional funding streams are poorly adapted to circularity (Dewick et al., 2020). Firms that secure financing aligned with circular aims gain a strategic advantage in adopting and scaling circular economy practices that would otherwise remain economically unviable. Accordingly, circular financing is expected to provide an enabling baseline for feasibility and, on average, to further strengthen the likelihood of adoption once that baseline is met.

The necessity of circular financing can be reasoned as follows: Can a firm adopt and sustain a circular economy business model in the absence of financing mechanisms suited to circular principles? Even with entrepreneurial vision, skilled personnel, and government incentives, the lack of capital tailored to the specific needs of circular projects can paralyze implementation. For example, reverse logistics systems or remanufacturing units often require substantial upfront investment with delayed returns (Kumar et al., 2024). Traditional credit and capital structures may view such models as high-risk or incompatible with linear return metrics, creating a structural funding gap (Gonçalves et al., 2022). In this sense, circular financing acts as a bottleneck condition its absence constrains the deployment of all other enabling resources and capabilities. Where such financing is available at meaningful levels, firms can more readily convert technical readiness and organizational intent into implemented circular offerings.

Although most empirical studies treat circular financing as an enabling factor under sufficiency-based paradigms, several scholars offer implicit evidence of its necessity. Xiaofei (2022) and Zhou et al. (2020) identified financial barriers as the most frequently cited challenge in circular economy adoption among small and medium-sized enterprises, noting that "without access to suitable finance, many circular initiatives remain at the conceptual level." Goovaerts and Verbeek (2018) argue that the lack of tailored financial models is one of the "critical impediments" to circular progress, particularly in emerging economies. Other studies (e.g., Saarinen and Aarikka-Stenroos, 2023; Sepetis, 2022; Zhou et al., 2020) have similarly emphasized that scalable circular transitions cannot occur without financing mechanisms that accommodate systemic, long-term value creation. Based on this reasoning, we posit:

H4 (Sufficiency): Circular financing is positively associated with the adoption of circular economy business models.

N4 (Necessity): Circular financing is a necessary condition for the successful adoption of circular economy business models.

2.2.5. Circular manufacturing technology and circular economy business model adoption

Circular manufacturing technologies (CMTs) refer to the technological capabilities that enable firms to implement sustainable manufacturing practices, reduce resource intensity, and foster the reuse, remanufacturing, and recycling of products and materials (Lieder and Rashid, 2016). These technologies include modular production systems, additive manufacturing, automation for disassembly, energy-efficient machinery, and materials recovery technologies (Kara et al., 2022; Bürklin and Wynants, 2020; Walker et al., 2018). By supporting closed-loop systems, CMTs contribute to improved operational performance, environmental sustainability, and regulatory compliance. They help firms reduce their material footprint and transition toward low-waste, regenerative manufacturing strategies. Accordingly, these technologies are expected to provide a non-substitutable operational baseline for feasibility and, on average, to further strengthen adoption once that baseline is met.

Within the RBV, technological capabilities such as CMTs are considered core operational resources (Ren et al., 2023). When aligned with circular objectives, they offer sustained strategic advantage by facilitating the design and execution of processes that are difficult to replicate and costly to develop (Barney, 1991). The role of technology becomes even more critical in CE adoption, as technical feasibility often underpins the success of product–service systems, reverse logistics, and component reuse (Avenyo and Tregenna, 2022). To explore the necessity of CMTs, consider the following reasoning: Can a firm effectively adopt a circular business model without the enabling support of circular technologies? Even with the right mindset, financing, or regulatory support, the absence of core technologies for disassembly, tracking, reconditioning, or modular redesign would make it impossible to execute many CE strategies (Lieder and Rashid, 2016). For instance, product recovery cannot be operationalized without systems that allow for traceability and easy extraction of reusable components. In this regard, CMTs represent a non-substitutable infrastructure a bottleneck condition whose absence blocks the actual realization of circular practices, despite the presence of other favorable conditions. Where such technologies exist at meaningful levels, organizations can more readily convert strategic intent into implementable circular operations.

Although existing studies predominantly rely on sufficiency-based logics, they emphasize the centrality of technological readiness. Bhawna et al. (2024) highlight that firms with limited technical capacity face "serious implementation barriers" in shifting from linear to circular operations. Similarly, Alvarez-Risco et al., (2022) argue that technological innovation is "imperative" for enabling business model reconfiguration. Bhawna et al., (2024) further stress that without appropriate technologies, CE remains "a conceptual model with little practical value." These statements, while made within sufficiency frameworks, suggest a deeper necessity orientation that supports the use of NCA. Based on this reasoning, we posit: *H5 (Sufficiency): Circular manufacturing technologies are positively associated with the adoption of circular economy business models.*

N5 (Necessity): Circular manufacturing technologies are a necessary condition for the successful adoption of circular economy business models.

2.2.6. Circular-oriented workplace culture and circular economy business model adoption

Organizational culture plays a pivotal role in shaping employee behavior and aligning internal practices with sustainability-oriented objectives (Ali et al., 2024; Barros et al., 2021). A circular-oriented workplace culture refers to a set of shared values, norms, and assumptions that support resource efficiency, long-term thinking, innovation for reuse and recycling, and collective responsibility for environmental outcomes (Lacy et al., 2020). Such a culture motivates and guides employees to embrace circular practices and embed sustainability principles in daily routines, decision-making, and problem-solving processes (Dos Santos Ferreira et al., 2024). From a RBV view point, culture represents an intangible yet strategic asset that is embedded, socially complex, and difficult to replicate - qualities that make it a source of sustained competitive advantage (Barney,1991). A workplace culture aligned with circularity enables organizations to navigate complex change, overcome resistance to innovation, and internalize sustainability into all operational layers. It fosters an environment in which employees are not just instructed to comply with environmental regulations but are empowered to lead and innovate circular solutions organically (Hadi and Sheikh, 2024). Accordingly, a circular-oriented culture is expected to provide a non-substitutable baseline that enables feasibility and, on average, to further strengthen adoption once that baseline is met.

To assess the necessity of circular-oriented workplace culture, consider the following: Can a firm transition toward a circular business model in the absence of cultural alignment? Even with robust technology, financing, or human resource strategies, without a shared organizational mindset that values sustainability, such initiatives may falter due to resistance, superficial compliance, or misaligned behaviors. For example, initiatives in eco-design or waste segregation may be technically sound, but without cultural reinforcement, they may not be consistently adopted or sustained over time. Cultural values act as the interpretive lens through which employees understand and enact circular practices. Therefore, the absence of this cultural orientation presents a bottleneck that restricts circular transformation, even when other conditions appear favorable. No other organizational mechanism provides an equivalent, firm-wide social glue to normalize the routines and trade-offs required by circular business models.

Empirical and conceptual studies reinforce this perspective. Bertassini et al. (2021) underscore that a lack of cultural alignment is a "deep barrier" to circular adoption, often more significant than financial or technical limitations. Rizos et al. (2016) emphasize that circular culture serves as a "behavioral enabler," translating organizational intent into collective action. These studies, while generally framed around sufficiency logic, point to the criticality and by implication, the necessity of culture in embedding circular principles. Based on this reasoning, we posit:

H6 (Sufficiency): A circular-oriented workplace culture is positively associated with the adoption of circular economy business models.

N6 (Necessity): A circular-oriented workplace culture is a necessary condition for the successful adoption of circular economy business models.

2.2.7. Circular open innovation and circular economy business model adoption

Circular open innovation refers to a firm's capacity to collaborate across organizational boundaries in order to access and integrate external knowledge, capabilities, and technologies that support circular economy objectives (Hadi et al., 2025; Perotti et al., 2024; Yun et al., 2024a and 2024b; Pichlak and Szromek, 2022; Brown et al., 2021; Brown et al., 2019). It draws on the principles of open innovation such as co-creation, knowledge sharing, and inter-organizational learning while aligning them specifically with regenerative business strategies (Hadi, 2024, p. 3). Firms practicing circular open innovation actively engage with stakeholders including suppliers, customers, universities, start-ups, and even competitors to develop and scale circular solutions that cannot be achieved in isolation (Yun et al., 2025; Sergianni et al., 2024; Krmela et al., 2022; Yun and Liu, 2019). This construct is grounded in Stakeholder Theory, which emphasizes the interdependence of firms and their external environment. Stakeholders often provide the legitimacy, technical inputs, and institutional alignment needed to realize complex transitions such as circularity (Freeman, 2010). The ability to leverage external knowledge and coordinate collective action becomes critical when internal capabilities alone are insufficient to achieve systemic innovation (Jesus and Jugend, 2023). For example, product take-back systems or industrial symbiosis schemes require collaboration between actors that span the value chain something only possible through open innovation mechanisms (Chesbrough, 2006). In our study, circular open innovation is captured at the firm level as an outward-facing collaborative orientation, analytically distinct from government support as an institutional lever.

To establish the necessity of circular open innovation, we ask: Can an organization adopt circular business models in isolation, without collaborating with its ecosystem? While some internal efforts may be made, most circular strategies such as reverse logistics, product-life extension, or closed-loop recycling require stakeholder engagement. Without the infrastructure, data sharing, and coordination that open innovation fosters, these strategies are often unworkable (Cassetta et al., 2023; Yun et al., 2020a). The absence of collaboration channels presents a structural constraint that impedes the very operationalization of circular economy logic. Unlike internal R&D or investment which can, in theory, be scaled up collaborative capacity is irreplaceable in enabling the systemic change required for circularity. Empirical studies support this necessity perspective. Geissdoerfer et al. (2023) identify open innovation as "indispensable" for enabling industrial symbiosis, a core element of circular economy. Brown et al. (2019) suggest that the transition to circularity "relies on cross-sectoral innovation ecosystems," and Brown et al. (2021) argue that open innovation becomes particularly vital in complex, uncertain environments precisely the conditions under which circular transitions unfold. Although these studies primarily employ sufficiency-oriented language, their conceptual arguments clearly point to the non-substitutability of circular open innovation. Accordingly, circular open innovation is expected to provide an ecosystem-level baseline that enables feasibility and, on average, to further strengthen adoption once that baseline is met.

H7 (Sufficiency): Circular open innovation is positively associated with the adoption of circular economy business models.

N7 (Necessity): Circular open innovation is a necessary condition for the successful adoption of circular economy business models.

2.2.8. Government support and circular economy business model adoption

Government support is widely acknowledged as a critical external driver for circular economy implementation, particularly in developing and transition economies (Dagiliene, et al., 2021; Alkahtani et al., 2020). This support can take multiple forms, including financial subsidies, tax incentives, regulatory frameworks, technical guidance, and infrastructure development. Government involvement shapes the institutional environment by lowering the cost of adoption, reducing uncertainty, and fostering collaboration among actors (Benito-Hernández et al., 2021). In the context of the circular economy, where many business models require system-level transformation, government support not only facilitates compliance but actively enables value chain reconfiguration (Tleuken et al., 2022; World Economic Forum, 2020; Bolger & Doyon; Recycle.com, 2024). Within the lens of Stakeholder Theory, governments represent a central institutional stakeholder whose influence extends beyond regulation to agenda-setting and ecosystem orchestration (Freeman, 2010). In resource-constrained economies such as Pakistan where infrastructure gaps, policy ambiguity, and low consumer awareness challenge circular implementation government involvement becomes particularly vital. It can catalyze industrial change through policy signals, demonstration programs, or public–private partnerships that mobilize capabilities and reduce perceived risks (Ali et al., 2024). Accordingly, government support is expected to provide an ecosystem-level baseline that enables feasibility and, on average, to further strengthen adoption once that baseline is met.

To evaluate the necessity of government support, we ask: Can circular economy business models be adopted and scaled in the absence of coordinated institutional support? While firms may demonstrate initiative and possess internal capabilities, without enabling policies, financing mechanisms, and supportive regulations, circular strategies often remain fragmented or economically unfeasible (Xiang and Worthington, 2017). For instance, extended producer responsibility schemes, reverse logistics systems, and recycling standards require government orchestration. In this sense, the absence of government support becomes a systemic bottleneck one that cannot be overcome by isolated firm-level efforts or market-driven solutions alone. No internal mechanism offers a full substitute for coordinated policy, standards, and infrastructure when orchestrating reverse flows and cross-actor alignment.

This necessity logic is echoed in literature that identifies weak institutional support as a primary barrier to circular transitions. Su et al. (2013) describe the lack of government involvement as a "structural deficiency" in circular development, particularly in Asia. Ratner et al. (2025) and Alkahtani et al. (2020) stress that adoption "depends heavily on government intervention" to resolve coordination failures.

Zulu-Chisanga et al. (2021) argue that policy design is not a complement but a prerequisite for the functioning of circular systems. While these contributions are rooted in sufficiency modeling, they reflect necessity-oriented reasoning consistent with the logic examined here. Based on this reasoning, we posit:

H8 (Sufficiency): Government support is positively associated with the adoption of circular economy business models.

N8 (Necessity): Government support is a necessary condition for the successful adoption of circular economy business models.

3. Methodological approach

3.1. Research context and theoretical grounding

This study investigates the necessary and sufficient conditions for the adoption of circular economy business models in the context of the marble manufacturing sector in Khyber Pakhtunkhwa (KPK), Pakistan. The rationale for selecting this context stems from both empirical and theoretical considerations. The KPK marble industry, while rich in natural stone resources, faces persistent challenges including low resource efficiency, high levels of waste generation, informal operational structures, and limited environmental compliance (Hadi, 2024; Iqbal et al., 2022). These issues, while reflective of systemic constraints, simultaneously highlight the need for transformation and render the sector an appropriate setting for examining the foundational enablers of circular transition.

Importantly, the context's relative institutional weakness and technological lag make it suitable for identifying non-compensatory conditions that act as bottlenecks in enabling CEBM adoption. In such constrained environments, the presence or absence of key internal capabilities or external supports may make the difference between success and failure in circular initiatives. This analytical perspective justifies the use of Necessary Condition Analysis (Dul, 2024, 2016a; Dul et al., 2023, 2020; Richter and Hauff, 2022; Richter et al., 2020; Dul 2016b). To complement the necessity logic with variance-based evidence, we also employ partial least squares structural equation modeling (PLS-SEM) to estimate sufficiency-type associations, enabling an integrated view of "must-have" versus "should-have" conditions.

To complement the necessity logic, the study also adopts Partial Least Squares Structural Equation Modeling (PLS-SEM) to evaluate the sufficiency-based relationships between predictors and outcomes. PLS-SEM is particularly well-suited for predictive modeling in under-researched domains with limited theoretical consensus and moderate sample sizes (Hair et al., 2019). When used together, NCA and PLS-SEM enable a more holistic analytical approach, in which sufficiency relationships are interpreted through the lens of average effects ("if X then probably Y"), while necessity logic identifies constraints that follow a deterministic rule ("if not X then not Y") (Richter et al., 2020). This dual-method framing also accords with recent guidance on combined reporting and interpretation in integrated PLS-SEM–NCA studies (Richter et al., 2023; see also Troiville et al., 2025).

By leveraging both approaches, the study addresses a key methodological gap in circular economy research namely, the lack of integrated modeling that distinguishes between useful and indispensable predictors (De Angelis, 2022; Kirchherr et al., 2023). This dual-method design is particularly valuable in contexts such as KPK's marble sector, where the path to circularity is not linear or evenly supported by policy, infrastructure, or firm-level readiness. Thus, we believe that the empirical setting offers an opportunity to investigate how circular transitions unfold in structurally constrained environments and to distinguish between those organizational factors that are merely beneficial and those that are absolutely required. Overall, this integration serves the study's objective of identifying threshold conditions while also capturing variance-based patterns of adoption.

3.2. Data preparation and measurement design

To empirically examine the necessary and sufficient conditions for circular economy business model adoption, primary data were collected from 209 marble manufacturing firms operating in the KPK province of Pakistan. The unit of analysis is the firm, and respondents were firm owners or senior managers responsible for core operational and strategic decisions appropriate key informants for firm-level practices in this sector. Given the methodological requirements of both PLS-SEM and NCA, the chosen sample size meets the conditions for robust estimation in variance-based structural modeling and effect size–based necessity testing (Dul et al., 2023; Richter et al., 2020).

A structured questionnaire was used to collect data. The measurement instrument was developed using previously validated scales, adapted from prior research to fit the empirical context of circular economy adoption in resource-intensive and process-driven manufacturing environments. The questionnaire was structured into two sections. The first section covered general firm characteristics including size, ownership type, and operational structure. The second section measured the eight core constructs of interest: circular human resource management, circular entrepreneurship, circular marketing, circular financing, circular manufacturing technologies, circular-oriented workplace culture, circular open innovation, and government support, along with the outcome variable - CEBM adoption.

All construct items were measured using five-point Likert-type scales ranging from 1 ("strongly disagree") to 5 ("strongly agree"). The items were slightly reworded where necessary to ensure contextual relevance and conceptual clarity for firms operating in the marble sector. Prior to full-scale data collection, the questionnaire was reviewed by a panel of academic experts and industry professionals to validate content relevance and terminological clarity. A pilot study involving 20 firm representatives was then conducted to test the instrument's readability and response consistency. Based on this feedback, minor refinements were introduced to improve comprehension and reduce ambiguity. The final version of the instrument used in the main study is provided in Appendix A.

The data collection process was carried out in person by a team of trained field enumerators over a period of four weeks. A total of 273 firms were approached using a random sampling technique drawn from industry listings and local chambers. Of these, 221 completed surveys were returned, and after eliminating incomplete, patterned, or inconsistent responses, a final usable sample of 209 firms was retained for analysis. All responses were captured during a consistent time window to ensure contextual stability and minimize exogenous shocks. To address potential common method bias (CMB), both procedural and statistical remedies were applied. Procedurally, anonymity and confidentiality were assured, item ambiguity was minimized, and construct items were distributed across sections to reduce common-rater effects. Statistically, Harman's single-factor test indicated that the first unrotated factor explained 32 % of the total variance - well below the conventional 50 % threshold thereby suggesting that CMB is unlikely to be a major concern (Podsakoff et al., 2003). To further assess common method bias, we applied the marker-variable technique following the guidelines of Simmering et al. (2015), Lindell and Whitney (2001), and Malhotra et al. (2006). Based on the list provided in Simmering et al. (2015, p. 482), we selected Fashion Consciousness as a marker variable because it is conceptually unrelated to all organizational- and strategy-level constructs in this study. The items were adapted from Malhotra et al. (2006), such as *"When I must choose between the two, I usually dress for fashion, not for comfort."* As expected, the correlations between the marker variable and all substantive variables were small and non-significant, indicating conceptual independence and minimal method variance. Adjusting correlations using the marker variable did not alter the pattern or significance of the structural relationships, suggesting that common method bias is unlikely to threaten the validity of the findings.

All data were entered, screened, and analyzed using SmartPLS 4. Following established guidance, we first validated the PLS-SEM measurement model, exported unstandardized latent composite scores, and then conducted NCA within SmartPLS to estimate ceiling lines (CE-FDH/CR-FDH), necessity effect sizes (*d*), permutation-based *p*-values, and bottleneck thresholds (Richter et al., 2023, 2020). NCA results are reported in a bottleneck/improvement-potential format to facilitate interpretation of threshold requirements at substantively meaningful outcome levels. Using the integrated SmartPLS workflow ensures methodological coherence between measurement validation, score generation, and necessity testing as recommended in recent applications.

3.3. Measurement model assessment

The reliability and validity of the measurement model were evaluated using established criteria within the PLS-SEM framework. The assessment included tests of internal consistency reliability, convergent validity, and discriminant validity for all reflective constructs in the model (Hadi, 2022). Internal consistency reliability was assessed using both Cronbach's alpha and composite reliability (CR). As shown in Table 1, all constructs demonstrated Cronbach's alpha and CR values exceeding the threshold of 0.70, indicating satisfactory reliability (Hair et al., 2019; 2020). This confirms that the items for each construct consistently measure the same underlying concept.

Convergent validity was evaluated using the average variance extracted (AVE). All AVE values exceeded the minimum threshold of 0.50, which indicates that a substantial proportion of variance in each construct is explained by its indicators (Fornell & Larcker, 1981). Item loadings were also examined and found to be above 0.70 for the majority of indicators, further supporting indicator reliability. All outer loadings and cross-loadings were verified to confirm that indicators loaded highest on their intended constructs. The values are reported in Table 1, alongside the corresponding reliability coefficients.

Discriminant validity was assessed using the Heterotrait–Monotrait (HTMT) ratio of correlations, as this approach has been shown to be more robust than traditional methods in PLS-based models (Henseler et al., 2015). As shown in Table 2, all HTMT values fall well below the conservative threshold of 0.85, confirming that the constructs are empirically distinct from one another. This supports the construct validity of the measurement model and minimizes concerns regarding multicollinearity.

These results confirm that the measurement model meets established standards of internal consistency, convergent validity, and discriminant validity, providing a sound basis for the subsequent estimation of the structural model and integration with NCA.

Table 1
Construct reliability and validity.

Construct	Cronbach'sAlpha	Composite Reliability	AVE
CEBM	0.775	0.856	0.599
Circular HRM Practices	0.764	0.850	0.589
Circular Entrepreneurship	0.799	0.867	0.576
Circular Financing	0.921	0.942	0.805
Circular Manufacturing Technology	0.701	0.817	0.599
Circular Marketing Practices	0.713	0.787	0.524
Circular-Oriented Workplace Culture	0.724	0.793	0.501
Government Support	0.810	0.867	0.570
Open Circular Innovation	0.700	0.812	0.522

Source: Authors own compilation

3.4. PLS-SEM and necessary condition analysis

3.4.1. Structural model estimation

The structural model was estimated using Partial Least Squares Structural Equation Modeling (PLS-SEM) via SmartPLS version 4.1.0.9. The use of PLS-SEM is justified by the exploratory nature of the study, the complex model structure involving multiple latent variables, and the objective of prediction in an under-theorized empirical context (Hair et al., 2019). Before interpreting the structural paths, multicollinearity was assessed using variance inflation factor (VIF) values. All VIF values were below 3.3, suggesting that multicollinearity was not a concern among the predictor constructs.

The coefficient of determination (R^2) for the outcome variable circular economy business model adoption was 0.468, indicating that the model accounts for approximately 47 % of the variance in CEBM explained by the eight predictor constructs. This level of explained variance is commonly interpreted as substantial (Cohen, 1988). Predictive relevance was further evaluated using the Stone–Geisser Q^2 value obtained through the blindfolding procedure. The Q^2 statistic was positive, supporting that the model exhibits acceptable predictive relevance for the endogenous construct.

As shown in Table 3 and Fig. 1, six of the eight hypothesized relationships were statistically significant. Specifically, circular human resource management ($\beta = 0.172$, $t = 2.611$, $p = 0.009$), circular entrepreneurship ($\beta = 0.154$, $t = 2.013$, $p = 0.044$), circular financing ($\beta = 0.197$, $t = 3.124$, $p = 0.002$), circular manufacturing technologies ($\beta = 0.149$, $t = 2.466$, $p = 0.014$), circular-oriented workplace culture ($\beta = 0.161$, $t = 2.539$, $p = 0.012$), and government support ($\beta = 0.176$, $t = 2.231$, $p = 0.026$) showed statistically significant positive associations with CEBM adoption. These results are consistent with the logic of probabilistic sufficiency, where higher levels of a predictor are associated with higher levels of the outcome on average (Richter et al., 2020).

In contrast, circular marketing ($\beta = 0.069$, $t = 1.029$, $p = 0.304$) and circular open innovation ($\beta = 0.078$, $t = 1.178$, $p = 0.239$) did not show statistically significant associations in the structural model. While these factors may contribute in practice or interact with other conditions, they did not explain additional variance in CEBM adoption under sufficiency-based estimation. Their potential role as non-compensatory prerequisites is examined in the subsequent NCA analysis. Together, the structural model indicates that several internal organizational capabilities and external institutional supports are positively associated with the likelihood of CEBM adoption, providing a basis for the complementary application of NCA to assess whether these same constructs also operate as necessary enablers that must be present, rather than merely beneficial.

3.4.2. Robustness and predictive validity checks (PLS-SEM)

To further assess the credibility and predictive relevance of the structural model, a series of diagnostic procedures were conducted. These analyses aimed to address potential concerns related to endogeneity, model misspecification, and out-of-sample predictive validity each relevant for assessing the credibility of variance-based estimates in complex models (Hair et al., 2019; Richter et al., 2020). To test for potential endogeneity, the Gaussian Copula method was employed within SmartPLS. This nonparametric approach evaluates whether the residuals of the endogenous construct are statistically independent from its predictors. The resulting p-value of 0.324 suggests no statistical evidence of endogeneity under this diagnostic, reducing concern about simultaneity or omitted correlated predictors. Model specification integrity was further evaluated using the Ramsey Regression Equation Specification Error Test (RESET). The RESET procedure checks whether nonlinear combinations of fitted values can explain additional variance in the outcome, which would indicate a functional-form misspecification. The test returned a p-value of 0.417, which did not indicate detectable misspecification under this criterion.

The predictive performance of the model was assessed using the

Table 2
Assessment of Discriminant Validity via HTMT ratio - Matrix.

Construct Pair	CEBM	CHRM	CE	CF	CMT	CM	CWPC	GS	OCI
CEBM	-								
CHRM	0.489								
CE	0.461	0.369							
CF	0.341	0.220	0.050						
CMT	0.258	0.146	0.166	0.174					
CM	0.393	0.386	0.324	0.045	0.258				
CWPC	0.454	0.191	0.219	0.176	0.189	0.191			
GS	0.344	0.296	0.133	0.130	0.241	0.123	0.233		
OCI	0.438	0.314	0.191	0.133	0.173	0.291	0.352	0.360	-

Source: Authors own compilation
Note. CHRM = Circular Human Resource Management; CE = Circular Entrepreneurship; CM = Circular Marketing; CF = Circular Financing; CMT = Circular Manufacturing Technologies; CWPC = Circular-Oriented Culture; COI/OCI = Circular Open Innovation; GS = Government Support

Table 3
Path coefficients and p values.

Paths	Original sample	Standard deviation	tstatistics	pvalues
CHRM → CEBM	0.123	0.055	2.256	0.024
CE → CEBM	0.256	0.054	4.726	0.000
CF → CEBM	0.211	0.057	3.696	0.000
CMT → CEBM	0.126	0.049	2.575	0.010
CM → CEBM	0.133	0.050	2.669	0.008
CWPC → CEBM	0.230	0.066	3.481	0.001
GS → CEBM	0.241	0.047	5.118	0.000
COI → CEBM	0.127	0.055	2.336	0.020
VIFsSkewness and Kurtosis R^2Q^2	1.085–1.253–0.966–0.796 and −0.539 – 2.19147 %0.40			

Source: Authors own compilation.
Note. CHRM = Circular Human Resource Management; CE = Circular Entrepreneurship; CM = Circular Marketing; CF = Circular Financing; CMT = Circular Manufacturing Technologies; CWPC = Circular-Oriented Culture; COI/OCI = Circular Open Innovation; GS = Government Support

Cross-Validated Predictive Ability Test (CVPAT). The average prediction loss of the PLS-SEM model (0.217) was lower than that of the benchmark linear model (0.331), indicating comparatively stronger out-of-sample predictive performance under the CVPAT criterion. Taken together, these diagnostics support the robustness of the in-sample associations and provide evidence of useful predictive performance, while maintaining an association-based interpretation of the structural paths.

Additional diagnostic statistics confirm the robustness of the model. The SRMR value was 0.064, falling below the accepted threshold of 0.08 and indicating low residual discrepancy between model-implied and empirical relations. The Q^2 value for the CEBM construct was 0.349, which exceeds the zero benchmark and supports predictive relevance. Furthermore, the model's explanatory power remained substantial, with an R^2 of 0.468 for CEBM adoption. Finally, all predictor constructs demonstrated acceptable multicollinearity levels, with average VIF values of 2.31, remaining well below the maximum cutoff of 3.3. The collective results of these diagnostic checks are presented in Table 4, which summarizes the robustness, specification, and predictive accuracy of the structural model. Collectively, these diagnostics support the adequacy of the variance-based specification and provide an empirical basis for the subsequent application of Necessary Condition Analysis.

To maintain conceptual clarity and avoid mixing analytical perspectives, the interpretations of PLS-SEM and NCA are presented separately. PLS-SEM results are interpreted strictly under a non-causal, correlational sufficiency logic, examining whether increases in a predictor are *associated with* increases in the outcome. NCA, in contrast, follows deterministic necessity logic, identifying conditions that must reach minimum thresholds for the outcome to be *feasible at all*. Consistent with methodological guidance by Richter et al. (2020), (2023) and Dul et al. (2023), the two logics answer different questions probabilistic association versus non-compensatory constraint and are therefore reported independently, with integration provided only after both analyses.

3.5. Necessary condition analysis (NCA)

Following the structural model estimation using PLS-SEM, Necessary Condition Analysis was employed to identify which predictor constructs serve as non-compensable bottlenecks for the adoption of circular economy business models. While PLS-SEM reveals average effects based on probabilistic sufficiency logic suggesting that higher levels of a predictor increase the likelihood of an outcome NCA identifies conditions that must be present at minimum thresholds for the outcome to be attainable at all**.** This deterministic necessity relation is often summarized as "no X, no Y" (Dul et al., 2024; Dul et al., 2023; Richter et al., 2020). The analysis was conducted using SmartPLS 4.1.0.9, using unstandardized latent composite scores exported from the validated measurement model. The Ceiling Envelopment–Free Disposal Hull (CE-FDH) ceiling line was applied, consistent with recommendations for models involving ordinal Likert-scaled constructs and observed non-linear boundary patterns. This method estimates the minimum level of a condition required to enable varying degrees of the outcome CEBM adoption in the current study. Statistical significance of necessity effect sizes was evaluated with permutation tests (10,000 resamples), and bottleneck thresholds are reported in a bottleneck/improvement-potential format.

As shown in Table 5, six of the eight predictor constructs demonstrated necessity effect sizes (d ≥ 0.1), meeting the commonly used benchmark for practical relevance. These include circular human resource management (d = 0.270), circular entrepreneurship (d = 0.130), circular manufacturing technologies (d = 0.261), circular-oriented workplace culture (d = 0.207), government support (d = 0.142), and circular open innovation (d = 0.255). Each effect was statistically significant ($p < 0.05$, permutation), consistent with the "no X, no Y" necessity rule. In contrast, circular marketing (d = 0.090) and circular financing (d = 0.048) fell below the accepted threshold and are therefore not interpreted as necessary conditions in the deterministic sense. While these constructs may enhance outcomes under sufficiency-based logic, their absence did not consistently coincide with infeasible outcome levels in the current dataset.

The validity of the necessity logic rests on three criteria, all of which were satisfied in this analysis (Dul et al., 2023). First, each predictor was conceptually grounded in either the resource-based view or stakeholder theory, providing an a priori rationale for potential non-substitutability. Second, the condition–outcome scatterplots displayed clearly defined infeasibility zones in the upper-left quadrant, consistent with ceiling-line theory and visually indicating that higher outcome levels were not observed without sufficient levels of the condition (see Figure 4). Third, effect sizes exceeded d > 0.1 with significant permutation tests, affirming empirical relevance (see Fig. 2). These results support the interpretation that certain internal resources and

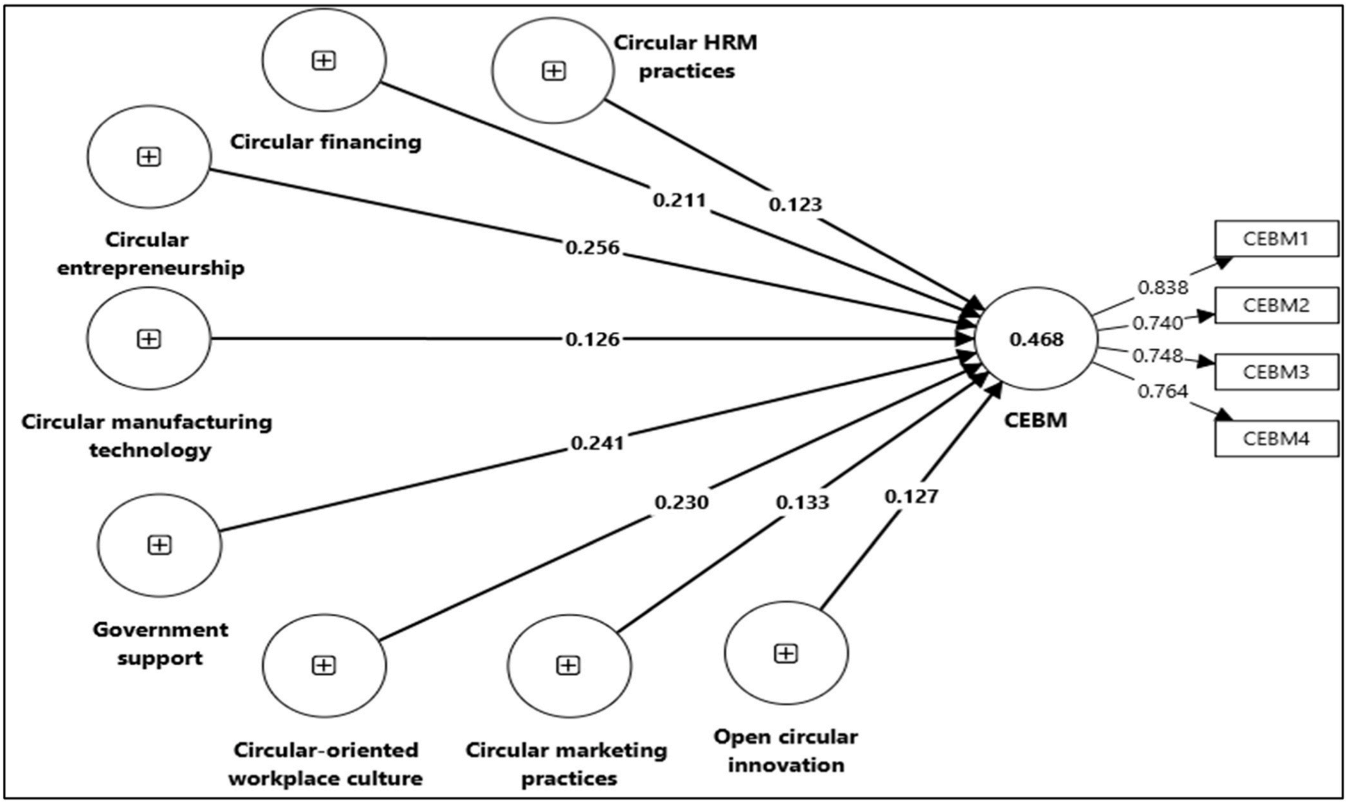

Fig. 1. Structural model. Source: Authors own compilation. Note. CHRM = Circular Human Resource Management; CE = Circular Entrepreneurship; CM = Circular Marketing; CF = Circular Financing; CMT = Circular Manufacturing Technologies; CWPC = Circular-Oriented Culture; COI/OCI = Circular Open Innovation; GS = Government Support.

Table 4
Robustness, Specification, and Predictive Validity Diagnostics for the Structural Model.

Metric	Value	Interpretation
Gaussian Copula p-value	0.324	*Non-significant* → No endogeneity detected
Ramsey RESET test result (p-value)	0.417	*No evidence of misspecification* → Model specification is valid
CVPAT Loss (PLS model)	0.217	*Lower than benchmark linear model (0.331)* → Strong predictive ability
SRMR (Standardized Root Mean Residual)	0.064	*< 0.08* → Model fit is acceptable
Q^2 (for CEBM)	0.349	*> 0* → Model shows predictive relevance for the endogenous construct
R^2 (for CEBM)	0.687	*Substantial explanatory power*
Average VIF across predictors	2.31	*< 3.3* → No multicollinearity detected

Source: authors own compilation: Note: All diagnostics were estimated using SmartPLS 4.1.0.9. CVPAT = Cross-Validated Predictive Ability Test; SRMR = Standardized Root Mean Square Residual; Q^2 = Stone–Geisser Predictive Relevance; R^2 = Coefficient of Determination; VIF = Variance Inflation Factor.

institutional enablers are not only advantageous but function as thresholds for meaningful circular transformation. Figs. 3 and 4 depict selected conditions with CE-FDH ceiling lines and infeasibility zones, illustrating the threshold pattern.

3.6. Bottleneck analysis

While NCA effect sizes indicate whether a condition is necessary, bottleneck analysis provides actionable thresholds by specifying how much of a necessary condition is required to attain a given level of the outcome. In this study, thresholds were estimated with the CE-FDH ceiling line in SmartPLS, which identifies the minimum value of each condition needed to make varying levels of circular economy business model (CEBM) adoption feasible. Table 6 reports thresholds across outcome levels from 10 % to 100 %. The results show a monotonic escalation in stringency as circular ambition increases. At the 50 % adoption level, relatively modest baselines enable progress: for example, circular human resource management (CHRM) ≥ 6.2 %, circular entrepreneurship ≥ 5.7 %, and circular-oriented workplace culture ≥ 4.3 %. These low thresholds represent foundational capabilities that support basic circular practices.

At higher targets the thresholds rise substantially. At 90 % adoption,

Table 5
NCA Effect size and p-values.

Effect	CHRM	CE	CMT	CM	CWPC	CF	GS	OCI
CE FDH	0.270	0.130	0.261	0.090	0.207	0.048	0.142	0.255
p values	*0.006*	*0.007*	*0.016*	*0.002*	*0.002*	*0.010*	*0.013*	*0.001*

Source: Authors own compilation
Note. CHRM = Circular Human Resource Management; CE = Circular Entrepreneurship; CM = Circular Marketing; CF = Circular Financing; CMT = Circular Manufacturing Technologies; CWPC = Circular-Oriented Culture; COI/OCI = Circular Open Innovation; GS = Government Support

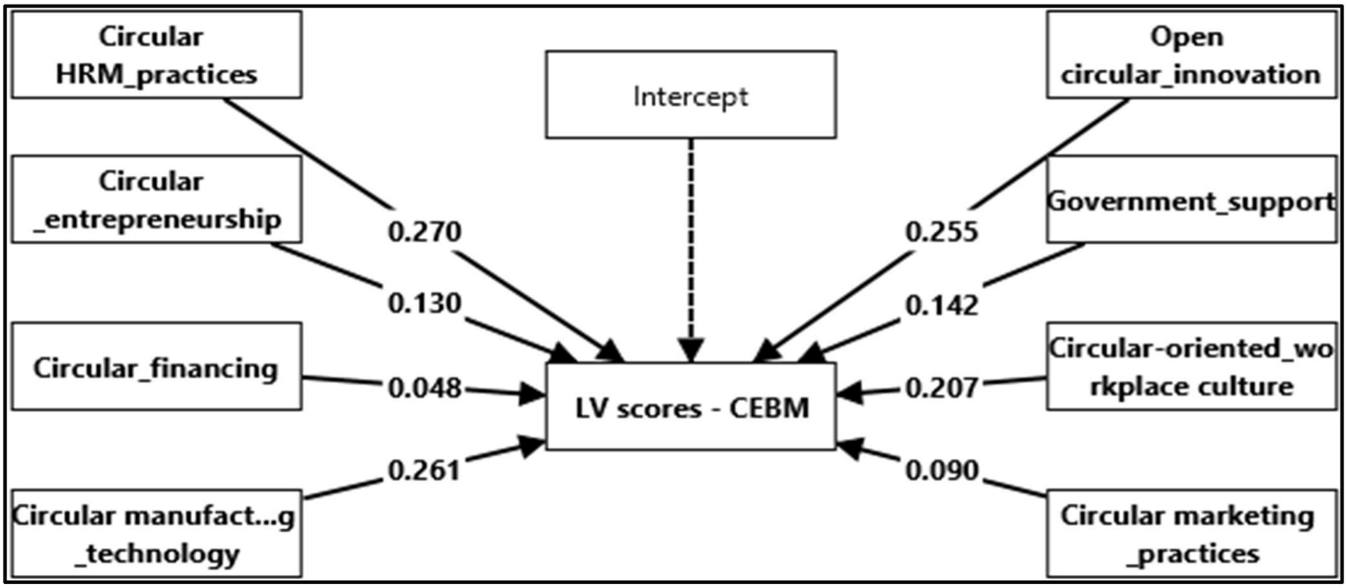

Fig. 2;. effect size of conditions.

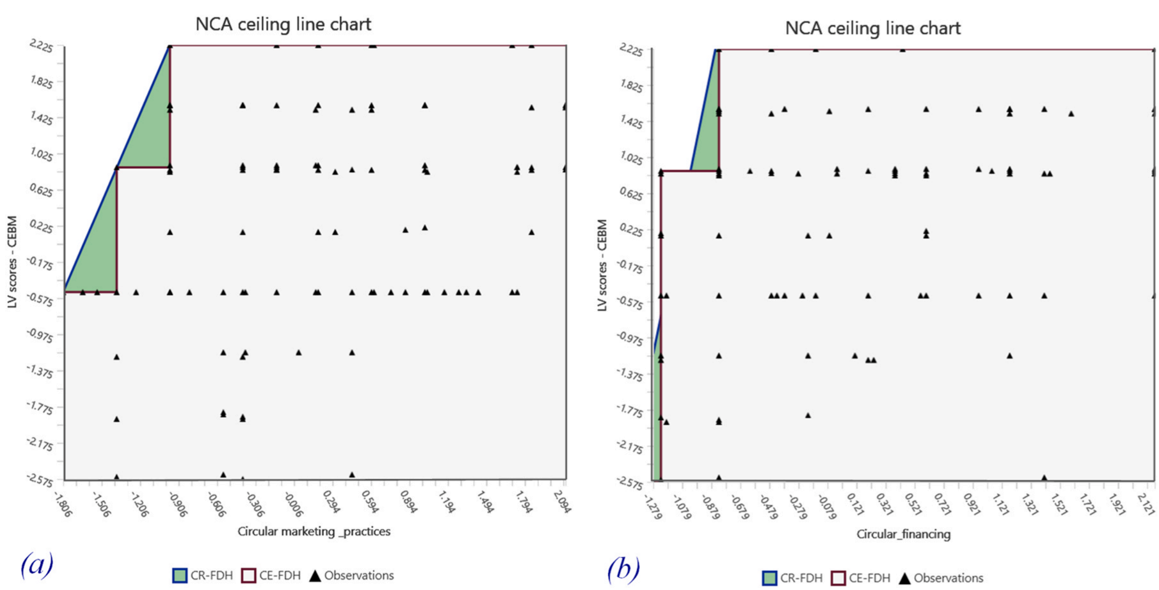

Fig. 3. Scatterplots illustrating the results of Necessary Condition Analysis (NCA) across key dimensions of circular economy practices: (a) Circular Marketing Practices, and (b) Circular Financing.

the cumulative burden intensifies: government support > 44 %, circular open innovation (OCI) ≥ 43.5 %, and the marketing, manufacturing, and workplace-culture dimensions all register marked step-ups. This pattern reflects a systemic requirement: near-total circular integration depends on both strong internal architecture and coordinated external alignment.

The interpretation follows non-compensatory logic. Unlike probabilistic models where shortfalls in one area might be offset elsewhere bottleneck thresholds indicate that feasibility is blocked if any one necessary condition falls below its minimum. For instance, at the 50 % adoption level, firms will not reach feasibility unless CHRM ≥ 6.2 %. These profiles offer concrete guidance: managers can use thresholds as diagnostic benchmarks for capability audits; policymakers can target institutional levers (e.g., regulatory incentives, capacity-building programs) to unblock sector-level progress. In sectors such as marble manufacturing, where formal HR systems, collaborative innovation practices, and financing models are still maturing, the thresholds provide an evidence-based roadmap for sequenced, feasible moves toward higher circularity.

3.7. Integration of sufficiency and necessity logic

To obtain a holistic understanding of the determinants of circular economy business model (CEBM) adoption, this study integrates findings from partial least squares structural equation modeling (PLS-SEM) and necessary condition analysis (NCA). Each method contributes a distinct logic: PLS-SEM indicates probabilistic sufficiency ("if X increases, Y is likely to increase on average"), whereas NCA indicates deterministic necessity ("if X is absent or below a threshold, Y cannot occur"). Table 7 synthesizes results by mapping each construct into four quadrants necessary & sufficient, necessary-only, sufficient-only, and neither and aligns these placements with the corresponding hypotheses.

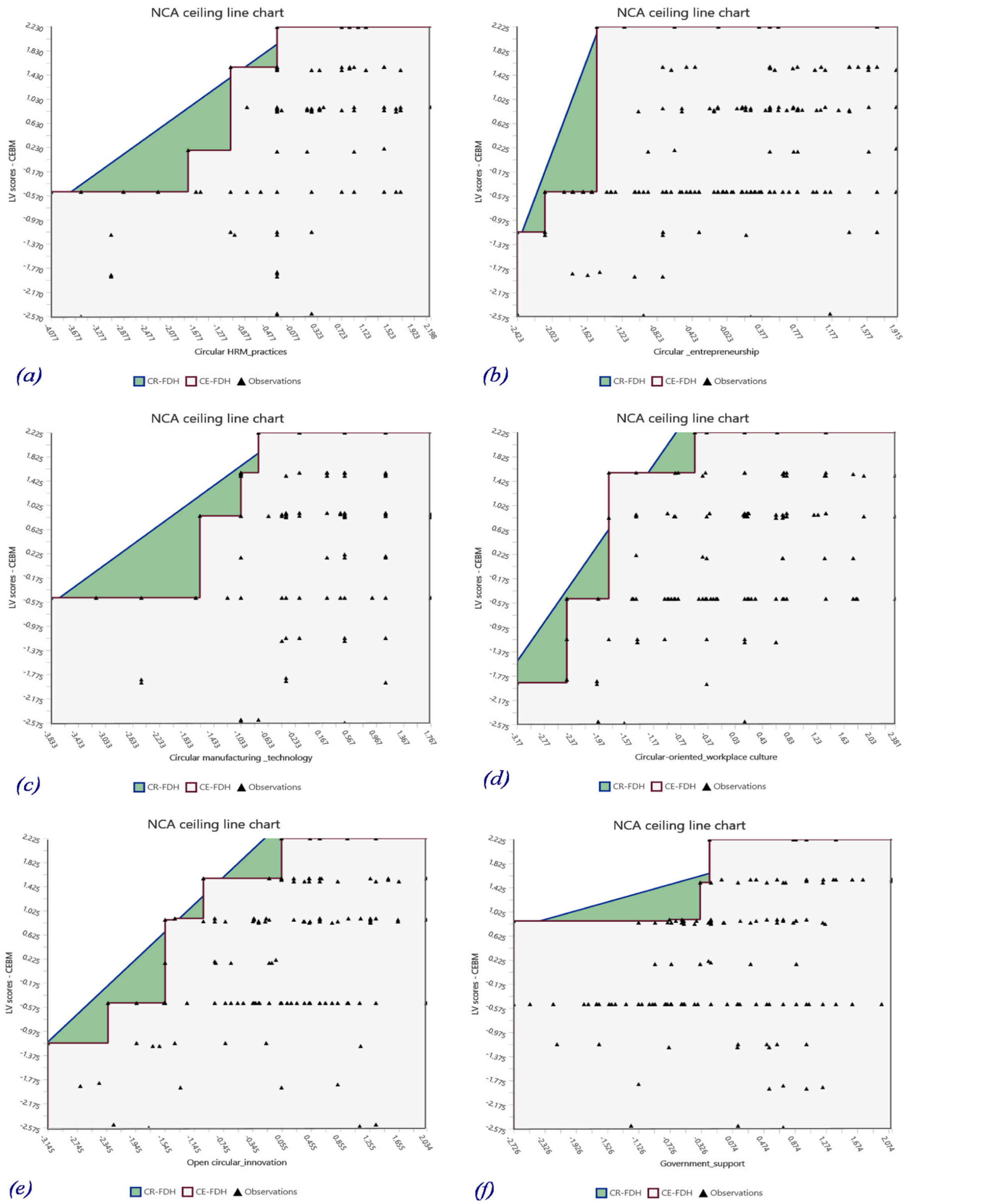

Fig. 4. Scatterplots illustrating the results of Necessary Condition Analysis (NCA) across key dimensions of circular economy practices: (a) Circular HRM Practices, (b) Circular Entrepreneurship, (c) Circular Manufacturing Technology, (d) Circular Oriented Workplace Culture, (e) Open Circular Innovation/Circular Open Innovation, and (f) Government Support.

As shown in Table 7, five constructs circular human resource management **(**supports N1 and H1**),** circular entrepreneurship **(**supports N2 and H2**),** circular manufacturing technologies **(**supports N5 and H5**),** circular-oriented workplace culture **(**supports N6 and H6), and government support **(**supports N8 and H8**)** are both necessary and sufficient in the present data: they show statistically significant associations in PLS-SEM and meet the NCA necessity benchmark (effect size $d \geq 0.10$ with significant permutation tests). This pattern indicates that these factors not only relate to higher CEBM adoption on average but also function as non-compensatory baselines that must be in place.

Circular open innovation (COI/OCI) appears as necessary but not sufficient supports N7; H7 not supported. Its absence blocks feasibility at

Table 6
Bottleneck Thresholds at varying levels of CEBM adoption (CE-FDH Ceiling Line Method).

CEBM Level	CHRM	CE	CMT	CM	CWPC	CF	GS	OCI
0 %	NN	NN	NN	NN	NN	NN	NN	NN
10 %	***NN***	***NN***	***0.478***	***NN***	***NN***	***NN***	***NN***	***NN***
20 %	NN	NN	0.478	NN	NN	0.478	NN	NN
30 %	NN	0.478	0.478	NN	NN	0.478	NN	1.435
40 %	NN	0.478	0.478	NN	NN	0.478	NN	1.435
50 %	***3.828***	***5.742***	***0.478***	***4.306***	***4.306***	***0.478***	***NN***	***6.220***
60 %	6.220	5.742	0.478	4.306	4.306	0.478	NN	6.220
70 %	6.220	5.742	0.478	4.306	4.306	0.478	NN	6.220
80 %	6.220	5.742	6.220	5.263	10.048	0.478	36.364	16.746
90 %	***36.364***	***5.742***	***6.220***	***20.574***	***10.048***	***27.751***	***44.019***	***43.541***
100 %	36.364	5.742	6.220	20.574	10.048	27.751	44.019	43.541

Source: Authors own compilation
Note. CHRM = Circular Human Resource Management; CE = Circular Entrepreneurship; CM = Circular Marketing; CF = Circular Financing; CMT = Circular Manufacturing Technologies; CWPC = Circular-Oriented Culture; COI/OCI = Circular Open Innovation; GS = Government Support

Table 7
Integration of Sufficiency and Necessity Findings.

Construct	Necessary? (d ≥ 0.1)	Sufficient? (PLS-SEM Sig.)	Category
Circular HRM (CHRM)	Yes (0.270)	Yes	Necessary & Sufficient
Circular Entrepreneurship (CE)	Yes (0.130)	Yes	Necessary & Sufficient
Circular Mfg. Tech (CMT)	Yes (0.261)	Yes	Necessary & Sufficient
Circular Workplace Culture (CWPC)	Yes (0.207)	Yes	Necessary & Sufficient
Government Support (GS)	Yes (0.142)	Yes	Necessary & Sufficient
Open Circular Innovation (COI/OCI)	Yes (0.255)	No	Necessary Only
Circular Marketing (CM)	No (0.090)	No	Neither
Circular Financing (CF)	No (0.048)	Yes	Sufficient Only

Source: Authors own compilation
Note. CHRM = Circular Human Resource Management; CE = Circular Entrepreneurship; CM = Circular Marketing; CF = Circular Financing; CMT = Circular Manufacturing Technologies; CWPC = Circular-Oriented Culture; COI/OCI = Circular Open Innovation; GS = Government Support

targeted outcome levels, yet its presence alone does not explain additional variance in PLS-SEM, suggesting an ecosystem enabler that requires complementary internal capabilities. Circular financing is sufficient but not necessary supports H4; N4 not supported. Higher levels are associated with higher adoption on average, but NCA thresholds are not met (effect size below 0.10), implying a performance amplifier rather than a universal prerequisite. Circular marketing is neither necessary nor sufficient neither N3 nor H3 supported in the present sample (PLS-SEM path not significant; NCA effect size below the 0.10 benchmark). This placement suggests a context-contingent role that may matter in tandem with other conditions or at specific stages, but it does not emerge as a standalone driver or baseline constraint here.

Overall, the integrated reading clarifies which constructs are “must-have” baselines (N-supported) versus “should-have” amplifiers (H-supported). These distinctions will be translated into theoretical implications (e.g., refining resource and stakeholder arguments around non-substitutability) and managerial guidance (e.g., sequencing investments to first meet necessity thresholds) in the implications section.

4. Discussion on findings

The findings provide contributions to understanding circular economy business model (CEBM) adoption in underdeveloped industrial settings such as the marble sector. By integrating necessary condition analysis (NCA) with PLS-SEM, the study surfaces both average-effect associations and non-compensatory constraints that must be in place for adoption to be feasible. The analysis highlights the interplay among circular human resource management (CHRM), circular entrepreneurship (CE), circular marketing (CM), circular financing (CF), circular manufacturing technologies (CMT), circular-oriented workplace culture (CWPC), circular open innovation (COI/OCI), and government support (GS). Overall, the dual-logic approach clarifies which factors act as “must-have” baselines (necessity) versus “should-have” amplifiers (sufficiency), adding empirical thresholds where applicable and sharpening theoretical claims about indispensability.

CHRM emerges as a foundational enabler of CEBM adoption. In line with resource-based arguments that position human capital as a strategic asset (Barney, 1991), the results indicate that CHRM is both necessary and sufficient. The bottleneck analysis shows that at the 50 % adoption level CHRM must reach at least 6.2 %**,** indicating a baseline below which adoption is infeasible. This reinforces prior work (Rubel and Rimi, 2024; Khan et al., 2024; Obeidat et al., 2023) by specifying minimum levels rather than only average associations. Practices such as circular job analysis, targeted training, and sustainability-aligned recruitment (Renwick et al., 2016) help embed circular routines across operations a profile consistent with both non-substitutability (necessity) and performance uplift (sufficiency)**.**

CE is likewise identified as indispensable. Consistent with the view of entrepreneurial orientation as a difficult-to-imitate intangible (Teece, 2007), the study finds CE to be both necessary and sufficient. The bottleneck table indicates a minimum of 5.7 % at the 50 % adoption level, suggesting that firms require a basic entrepreneurial stance opportunity recognition, experimentation, and proactive collaboration to unlock circular transitions (Diacono and Baldacchino, 2024; Linder et al., 2022; Suchek et al., 2022). In the marble industry, this is reflected in the repurposing of waste streams and in redesigning value propositions around circular logic. Circular marketing plays an important role in the broader CE literature (Lu et al., 2024; Alrawabdeh, 2024; Vidal-Ayuso et al., 2023; Mostaghel et al., 2023), particularly for shaping demand-side participation. In the present sample, however, circular marketing does not emerge as sufficient in PLS-SEM and does not meet the NCA necessity benchmark. This neither-necessary-nor-sufficient placement suggests a stage-contingent profile: where production/process changes dominate early transitions, market education may lag. The implication is that circular marketing likely gains salience after baseline bottlenecks are met, helping scale adoption rather than unlock feasibility.

CF is sufficient but not necessary in this study. While prior work underscores finance as a barrier in many settings (Saarinen and Aarikka-Stenroos, 2023; Sepetis, 2022; Zhou et al., 2020), NCA effect sizes here fall below the d ≥ 0.10 benchmark, indicating that the absence of CF does not consistently block adoption in the observed data. At the same time, PLS-SEM shows positive associations, consistent with CF acting as a performance amplifier once non-compensatory baselines (e.g., CHRM, CE, CMT, CWPC, GS) are in place especially relevant for capital-intensive upgrades in marble manufacturing. CMT is identified as both necessary and sufficient. This aligns with the view that modular design, remanufacturing, traceability, and recovery systems provide a technical backbone for circularity (Lieder and Rashid, 2016; Bhawna et al., 2024; Kara et al., 2022; Alvarez-Risco et al., 2022; Avenyo and Tregenna, 2022). In necessity terms, CMT functions as non-substitutable infrastructure: many CE practices are not feasible without minimal technological support. In sufficiency terms, incremental improvements in CMT are associated with higher adoption on average, reflecting the role of production technology in scaling circular operations and valorizing by-products.

CWPC also exhibits a both-necessary-and-sufficient profile. The bottleneck table indicates a 4.3 % minimum at the 50 % adoption level, pointing to culture as the social glue that normalizes circular routines and reduces implementation frictions (Lacy et al., 2020; Bertassini et al., 2021). From a resource-based view, cultural alignment is a socially complex, path-dependent asset that supports feasibility (necessity) and lifts average outcomes (sufficiency) through shared norms, leadership signaling, and participatory problem-solving. COI is necessary but not sufficient in the present data. This pattern is consistent with the idea that collaboration capacity sets ecosystem feasibility (Cassetta et al., 2023; Jesus and Jugend, 2023; Brown et al., 2021): reverse logistics, industrial symbiosis, and take-back schemes depend on multi-actor coordination. The bottleneck analysis shows rising thresholds at higher ambition levels (e.g., 43.5 % at 90 %), indicating that deeper circular integration requires stronger outward-facing collaboration. Its lack of a significant average association in PLS-SEM suggests that in nascent ecosystems, collaboration enables feasibility without yet yielding large variance-based gains, particularly when coordination costs are high or networks are thin. GS is both necessary and sufficient. As a central institutional stakeholder (Freeman, 2010), policy signals, standards, infrastructure, and incentives shift infeasibility regions and are also associated with higher adoption on average. In the bottleneck profile, GS requirements escalate with ambition (e.g., >44 % around 90 % adoption), highlighting the policy intensity needed for advanced circular integration in settings marked by infrastructure gaps and informality.

Together, the integration of necessity and sufficiency clarifies a sequence: first, meet the lowest unmet bottleneck among CHRM, CE, CMT, CWPC, OCI, and GS (necessity); then deploy amplifiers such as CF (and, context-permitting, CM) to raise performance. This threshold-then-amplify view aligns resource-based micro-foundations with stakeholder-driven feasibility, offering a structured path for firms and policymakers seeking to progress from basic feasibility to scaled circular adoption.

5. Theoretical and practical implications

5.1. Theoretical implications

This study makes several theoretical contributions to the circular economy business model (CEBM) literature by integrating probabilistic sufficiency (via PLS-SEM) with deterministic necessity logic (via NCA). First, it advances the resource-based view by showing that internal capabilities circular human resource management, circular entrepreneurship, circular manufacturing technologies, and circular-oriented workplace culture are not merely supportive but constitute non-compensatory bottlenecks**,** acting as structural preconditions rather than only sources of variance. This distinction clarifies the difference between "valuable" and indispensable resources in sustainability transitions. Second, extending stakeholder theory, the study demonstrates that government support and circular open innovation operate as system-level constraints that shape firm-level possibilities. The findings highlight a multi-layered interdependence between institutional environments and firm capabilities, reconceptualizing CE adoption as conditionally feasible dependent on alignment between internal readiness and external scaffolding. Methodologically, the study contributes by applying a necessity–sufficiency integration (dual-logic) perspective, moving beyond average effects to uncover minimum thresholds below which CEBM adoption becomes infeasible (Richter et al., 2020, 2023; Dul et al., 2023). Incorporating NCA provides empirical clarity on which conditions are essential versus complementary, offering a granular and context-sensitive understanding of CE adoption in resource-constrained environments.

5.2. Practical implications

From a practical standpoint, this study provides a diagnostic sequence that firms and policymakers can use to strengthen their readiness for circular transition, particularly in resource-constrained industrial settings. The core insight from the necessity results is that some conditions function as "baseline enablers" that must be reasonably developed before more advanced circular practices can take hold. In practical terms, this means that firms should first assess whether foundational capabilities such as circular-oriented HRM, entrepreneurial drive, manufacturing readiness, workplace culture, collaborative openness, and basic policy support are present at a meaningful level. If any of these areas is severely underdeveloped, efforts in other domains will deliver limited benefits because circular initiatives become structurally difficult to execute. Rather than focusing on precise numerical thresholds, managers can translate these insights into capability audits or readiness assessments. For example, firms may begin by examining whether employees possess the skills, training, and motivation needed to implement circular routines; whether entrepreneurial behaviors such as experimentation and opportunity recognition are encouraged; whether manufacturing processes are flexible enough to incorporate reuse or recovery options; whether the organizational culture supports long-term thinking; and whether the firm participates in knowledge-sharing networks or alliances that facilitate circular innovation. Even simple tools such as checklists, maturity scales, or internal workshops can reveal whether these foundational enablers are "present enough" to support circular initiatives.

Once these baseline enablers are strengthened, sufficiency-based levers become more effective. For instance, circular financing mechanisms can help firms scale or accelerate circular investments once the organization has built a minimal capability foundation. Similarly, circular marketing becomes more impactful after internal readiness is achieved and credible circular offerings exist. Policymakers can also use these insights to design interventions that target the most binding constraints such as workforce skills, manufacturing infrastructure, or network participation before promoting higher-order incentives. This sequencing approach helps avoid misallocation of resources and ensures that circular initiatives are implemented in an order that matches firms' structural readiness. Overall, the findings suggest that circular transformation in developing-country SMEs is best approached as a staged progression. Firms should first build enabling conditions, then deploy high-impact levers, and finally engage in market-shaping activities. This practical logic offers a realistic roadmap that managers, policymakers, and support agencies can adopt without requiring technical calculations, making the results actionable in real-world industrial environments.

5.3. Limitations and future research directions

While this study provides valuable insights into the necessary and sufficient conditions for circular economy business model adoption, several limitations offer promising opportunities for future research. First, the study is based on data from the marble manufacturing sector in Pakistan - a resource-intensive and institutionally constrained industry. Although this context is theoretically suitable for identifying bottlenecks, it may limit generalizability. Future studies should therefore conduct cross-context validation by testing necessity relationships and bottleneck thresholds across other industries such as textiles, construction, and electronics, as well as in different regional or institutional environments. Such comparative analyses would assess the transferability and contextual dependence of the thresholds identified here. Second, the study employed a cross-sectional design, which limits causal and temporal interpretation. Longitudinal or panel-based research could track how the interplay between necessary and sufficient conditions evolves as firms' circular capabilities mature revealing whether certain factors shift from being bottlenecks to becoming performance amplifiers over time.

Third, while the current analysis focused on theoretically grounded constructs, control variables such as firm size, ownership structure, and operational scale were not included. Future research should incorporate these to assess potential confounding effects. Moreover, multi-group analyses could be conducted to explore whether necessity and sufficiency patterns differ across organizational typologies (e.g., small vs. large firms or domestic vs. export-oriented enterprises). Fourth, this study relied on quantitative self-reported data from owners and managers, which, although appropriate for the research objective, could be complemented by qualitative inquiry in future work. Qualitative approaches such as interviews or case studies can enrich the interpretation of necessity thresholds by capturing managerial sense-making around circular bottlenecks and enabling mechanisms**.**

Fifth, future studies could apply advanced NCA-based extensions such as combinational Importance–Performance Matrix Analysis (cIPMA) or multi-level necessity modeling to map both intra-firm and inter-firm constraints along value chains. This would help in understanding systemic dependencies and leverage points for circular transformation across industrial ecosystems. Finally, future research should further examine the intersection of digital transformation and circularity, including the role of IoT, blockchain, and artificial intelligence. These digital enablers may either lower the thresholds required for CEBM adoption or introduce new forms of dependency, thus offering fertile ground for exploring their mediating or moderating influence on circular performance outcomes.

6. Conclusion

This study identifies internal and external conditions that are not only influential but, for several, structurally necessary for circular transformation. Using an integrated dual-logic design grounded in the resource-based view and stakeholder theory, we distinguish indispensable preconditions from performance amplifiers. Specifically, CHRM, CE, CMT, CWPC, and GS emerge as both necessary and sufficient; COI is necessary-only; CF is sufficient-only; and CM is neither in the present context. CEBM adoption thus depends on meeting minimum thresholds across key domains, challenging compensatory assumptions that strength in one area can offset deficits in another. Methodologically, the study shows how necessity logic complements sufficiency-based modeling to yield feasibility-aware insights, and theoretically it links micro-foundations (capabilities and culture) with ecosystem orchestration (policy and collaboration). While based on Pakistan's marble industry, the framework is adaptable to other resource-intensive sectors. Generalizability is bounded by the single-region, cross-sectional design; future work should assess sectoral and regional variation and track threshold dynamics over time. By highlighting non-compensable thresholds and their interplay with sufficiency-based levers, the study offers a roadmap for policymakers and practitioners seeking to sequence interventions from feasibility to scale in advancing business circularity.

CRediT authorship contribution statement

Noor Ul Hadi: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **M. Imran Khan:** Writing – review & editing, Visualization, Resources.

Ethical statement

The author(s) confirm that this manuscript adheres to the ethical standards of research and publication set forth by the *Journal of Open Innovation: Technology, Market, and Complexity*. This study was conducted in accordance with applicable institutional and national research-ethics guidelines. Participation was voluntary, informed consent was obtained from all respondents (adult owners/managers), and no personally identifiable information was collected. The survey posed minimal risk and used anonymized data throughout. Data are available from the corresponding author(s) upon reasonable request.

Funding

This research received no external funding.

Declaration of Generative AI and AI-assisted technologies in the writing process

During revisions, the authors used Grammarly (an AI-assisted proofreading tool) solely for grammar and abbreviations consistency checks. No AI tools were used to generate scientific content, conduct analyses, or draw conclusions. While such tools are useful for limited support tasks, they do not replace human expertise. After using Grammarly, the authors reviewed and edited all content and take full responsibility for the accuracy and integrity of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

I would like to express my sincere appreciation to the Editor-in-Chief, the Handling Editor, and the anonymous reviewers for their constructive and insightful feedback, which greatly strengthened this manuscript. I am also grateful to the data collection team for their dedicated support throughout the study. Most importantly, I extend my heartfelt thanks to Prince Mohammad Bin Fahd University (PMU) for providing the APC support that made this publication possible.

Appendix A

Measurement instruments

Constructs	Items description
Circular HRM practices	"HRM practices in marble manufacturing unit prioritize hiring individuals with skills and knowledge related to sustainability and circular economy principles" "Training programs in marble manufacturing unit focused on circular economy concepts and how they apply to marble industry" "Marble manufacturing unit supports employees in adopting circular practices by integrating them into performance evaluation and reward systems" "HRM practices at marble manufacturing unit emphasize the importance of long-term employment relationships and skill retention to support sustainable business models"
Circular marketing practices	"Marketing efforts at marble manufacturing unit educate customers about the benefits of circular economy practices" "Marble manufacturing unit collaborate with partners to co-create circular" "Marble manufacturing unit actively communicate their commitment to resource efficiency and sustainability through marketing channels" "Marketing strategies at marble manufacturing unit emphasize the environmental benefits of their products"
Circular Entrepreneurship	"Marble manufacturing unit actively develops innovative solutions to promote resource efficiency and waste reduction" "The pursuit of new business models based on circular economy principles is a core part of marble manufacturing unit strategy" "Marble manufacturing entrepreneur has a strong understanding of how to apply circular economy principles to marble manufacturing unit" "Marble manufacturing unit create new business opportunities centered around the reuse, recycling, and recovery of materials" "Marble manufacturing unit encourage entrepreneurial efforts aimed at reducing the environmental impact of marble manufacturing unit operations"
Circular financing	"Marble manufacturing unit allocates sufficient financial resources to circular economy initiatives" "Investments in circular economy practices at marble manufacturing unit are considered a key part of marble manufacturing unit financial strategy" "Marble manufacturing unit actively seek external funding opportunities (e.g., grants, loans) to support circular initiatives" Marble manufacturing unit budgeting process incorporates the long-term financial advantages of circular economy practices "Marble manufacturing unit regularly assess the financial outcomes of their circular economy initiatives"
Circular manufacturing technology	"Manufacturing technology at marble manufacturing unit has the ability to reuse, recycling, and recovery of materials" "Marble manufacturing technology produce minimal waste and by-products" "Marble manufacturing unit invest in innovative technologies that support closed-loop production systems" "Manufacturing technology use in marble manufacturing is adaptable to circular economy models, allowing for product take-back and material recovery"
Circular-oriented workplace culture	"Marble manufacturing unit fosters a culture of sustainability where circular economy practices are widely accepted and embraced" "Marble manufacturing unit values emphasize long-term sustainability, reducing environmental impact, and enhancing circularity" "Marble manufacturing unit culture prioritizes continuous improvement in sustainability practices across all functions" "Circular economy principles are integrated into marble manufacturing unit daily work environment and decision-making processes"
Government support	"There are clear government guidelines and regulations that help marble manufacturing transition to more circular practices" "Government policies actively promote the adoption of circular economy practices in marble manufacturing industry" "The government provides access to grants, funding, or tax benefits to support the development of circular product(s)" "Government regulations encourage the use of sustainable production methods and the reduction of waste in marble manufacturing industry" "Marble manufacturing benefits from financial incentives or subsidies provided by the government to support circular economy initiatives"
Circular economy business model adoption	"Marble manufacturing unit select raw material carefully" "Marble manufacturing unit can recycle wastes generated from operations" "Marble manufacturing unit has maintenance practices that enhances the life of facilities, machineries and equipment" "Marble manufacturing unit designs aiming at extending product life"
Circular open innovation	"Marble manufacturing unit establishes a high number of outside partners for the inflow of circular knowledge" "Marble manufacturing unit follows aggressive participation in circular technology-based alliances" "Marble manufacturing unit establishes a high number of outside partners for the outflow of circular knowledge" "Marble manufacturing unit shares circular knowledge with potential beneficiaries"
Marker variable (Fashion Consciousness)	"When I must choose between the two, I usually dress for fashion, not for comfort" "An important part of my life and activities is dressing smartly" "A person should try to dress in style"

Source: adapted from Hadi, (2024); Ozili, (2021); Goovaerts and Verbeek, 2018; Cullen and De Angelis, 2021; Dantas et al., 2022; Bürklin and Wynants, 2020; Dagiliene et al., 2021; Khan et al., 2024; Braik et al., (2024); Lacy et al., 2020; Malhotra et al., 2006).

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