Article

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Linking Structural Barriers and Circular Business Model Innovation in Small and Medium-Sized Enterprises: An Integrated Framework from a Timber Industrial Cluster

Jesús G. Rivas-Morales [1], Lilia Salas-Pérez[1,*], Sandra López-Chavarría [1], Artemisa B. A. Flores de Villa [1], Eyran R. Díaz-Gurrola [1], Víctor M. Moreno-Landeros [1], Emmanuel Contreras-Medina [1], María de J. Calleros-Rincón [1], Reyna R. Guillén-Enríquez [2] and Adlay Reyes-Betanzos [2]

[1] Universidad Autónoma de Coahuila, México
[2] Universidad Autónoma Agraria Antonio Narro, México
* Correspondence: lsalas@uadec.edu.mx

Abstract

The transition toward circular economy (CE) systems is essential for improving resource efficiency and sustainability performance in industrial production. However, small and medium-sized enterprises (SMEs) face structural barriers that limit the adoption of circular practices and business model innovation. This study examines the systemic drivers shaping circular transitions in timber-based SMEs within an industrial cluster in northern Mexico. The research integrates the Matrix of Cross-Impact Multiplications Applied to Classification (MICMAC) structural analysis with the Circular Business Model Canvas (CBMC) to examine influence–dependence relationships among key barriers and their implications for business model transformation. Empirical data were collected from 32 SMEs using structured surveys and expert consultation. Results identifies financial constraints, technological limitations, and weak collaboration networks as dominant systemic drivers. The CBMC assessment reveals an average implementation level of 45%, with high variability across firms (31%–99%), indicating fragmented and early-stage circular transition patterns. By linking structural diagnostics with business model components, the study identifies strategic leverage points and intervention pathways. The findings contribute to CE research by providing a systematic, replicable analytical framework and offering practical insights for policymakers and industry stakeholders seeking to accelerate circular bioeconomy transitions in SME-based industrial clusters.

Keywords: circular economy; circular business model innovation; SMEs; sustainability transition; systems approach; circular transition pathways; circular bioeconomy; MICMAC analysis

1. Introduction

The transition toward more sustainable production systems has become one of the most pressing challenges facing contemporary industrial economies. Increasing environmental pressures, resource scarcity, and climate change have intensified the need for alternative production models that decouple economic growth from environmental degradation. In this context, the circular economy (CE) has emerged as a strategic paradigm to improve resource efficiency through waste minimization, material recirculation, and product lifecycle extension [1–3]. By promoting closed-loop systems and regenerative resource flows, the CE offers a transformative alternative to the traditional linear "take–make–dispose" model, contributing to both environmental sustainability and long-term economic resilience [4].

Recent research has emphasized that CE transitions in small and medium-sized enterprises (SMEs) are not driven by isolated factors, but rather by complex interactions among financial, technological, organizational, and institutional constraints [5–7]. Empirical evidence indicates that these barriers function as highly interdependent systems, in which limitations in one dimension—such as access to finance—directly affect innovation capacity, technological adoption, and participation in collaborative networks [8]. This systemic perspective suggests that circular transitions should be understood as structural transformation processes rather than isolated operational challenges [6,9].

Furthermore, recent studies highlight that SMEs face significant difficulties in developing the key capabilities required for circular transformation, particularly in digitalization, technological upgrading, and knowledge integration [10,11]. These constraints are especially pronounced in emerging economies, where institutional weaknesses and underdeveloped innovation ecosystems further limit firms' ability to adopt circular practices [12]. As a result, firms often remain locked into linear production systems due to structural lock-in effects that constrain long-term investment in sustainable innovation [7,13].

Within this context, the circular bioeconomy has gained increasing attention as a strategic approach that integrates CE principles with the sustainable use of renewable biological resources [14]. Sectors such as the timber industry exhibit significant potential for a circular transition due to their capacity for material reuse, resource cascading, and long-term carbon storage [15]. These characteristics position such sectors as key contributors to climate change mitigation and sustainable industrial development.

SMEs play a central role in enabling these transitions, as they constitute the backbone of industrial clusters and regional production systems. However, despite their potential, SMEs face substantial structural constraints that limit the adoption of circular practices, including financial limitations, technological capability gaps, restricted access to knowledge networks, and insufficient institutional support [5,8,11].

Another critical dimension of CE implementation is the circular business model canvas (CBMC). This involves redesigning the mechanisms for value creation, delivery, and capture to retain the value of materials and products within the economic system for as long as possible [3]. Nevertheless, recent empirical evidence suggests that SMEs tend to adopt CE practices incrementally, prioritizing operational efficiency improvements over more fundamental transformations of their business model structures [9,10].

Despite the growing body of literature on CE and CBMC, several important research gaps remain. First, existing studies often analyze barriers in isolation, failing to adequately capture the systemic interactions among them in complex production systems [6,7]. Second, research on circular business models has largely focused on conceptual frameworks for value creation, with limited attention to the structural constraints organizations face during implementation [3,9]. Third, empirical evidence linking structural barriers to business model configuration remains scarce, particularly in SME-based industrial clusters operating in emerging economies [12].

Addressing these gaps requires analytical approaches that integrate system-level diagnostics with firm-level strategic analysis. Structural analysis methods, such as MICMAC (Matrix of Cross-Impact Multiplications Applied to Classification), provide valuable tools for identifying influence–dependence relationships among variables within complex socio-economic systems [16]. However, their integration with business model innovation frameworks remains limited. In response, this study develops an integrated analytical framework that links structural barrier analysis (MICMAC) with the Circular Business Model Canvas (CBMC), enabling a systematic connection between system-level constraints and firm-level strategic configurations.

This study contributes to the literature in three main ways. First, it provides a systemic understanding of CE transitions in SME-based industrial clusters by identifying key structural drivers. Second, it demonstrates how these structural barriers affect the alignment of circular business model components. Third, it proposes a replicable methodological framework that integrates structural system analysis with strategic management tools to study sustainability transitions.

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Based on the identified research gaps and the systemic perspective adopted in this study, the following hypotheses are proposed: H1. Financial and technological barriers are primary drivers influencing the adoption of CE practices in SME-based industrial clusters, H2. Structural barriers to CE adoption exhibit strong systemic interdependence rather than functioning as isolated constraints, H3. Structural barriers significantly influence the alignment of SMEs with circular business model components, and H4. The integration of MICMAC and CBMC provides a robust framework for identifying strategic leverage points in CE transitions.

2. Materials and Methods

2.1. Research Design

This study adopted a sequential mixed-methods research design to analyze the structural barriers influencing the transition toward circular economy (CE) practices in timber-based small and medium-sized enterprises (SMEs) and their relationship with circular business model innovation. Mixed-methods approaches are particularly appropriate for examining complex socio-economic systems in which qualitative insights and quantitative analytical techniques must be integrated to capture systemic interactions among organizational variables [17].

The study followed a five-phase analytical process commonly applied in sustainability transition research. First, structural barriers affecting CE adoption were identified through a structured literature review and expert consultation. Second, a survey instrument was developed to measure the perceived relevance of these barriers among firms within the industrial cluster. Third, quantitative data were analyzed using correlation analysis and Matrix of Cross-Impact Multiplications Applied to Classification (MICMAC) structural analysis to identify systemic influence relationships among the barrier variables. Fourth, the implementation level of circular business model components was evaluated using the circular business model canvas (CBMC) framework [18]. Finally, the outputs of the structural analysis and the business model assessment were integrated to identify strategic leverage points supporting circular bioeconomy transition processes within SME-based industrial clusters. The overall research design and analytical framework of the study are illustrated in Figure 1.

The diagram illustrates the five-phase research process, including barrier identification, data collection via SME surveys, MICMAC structural analysis, CBMC assessment, and the integration of results to identify strategic leverage points for the CE transition. This methodological design enables triangulation among theoretical constructs, empirical data, and structural system modeling, thereby ensuring analytical robustness and replicability of the research process.

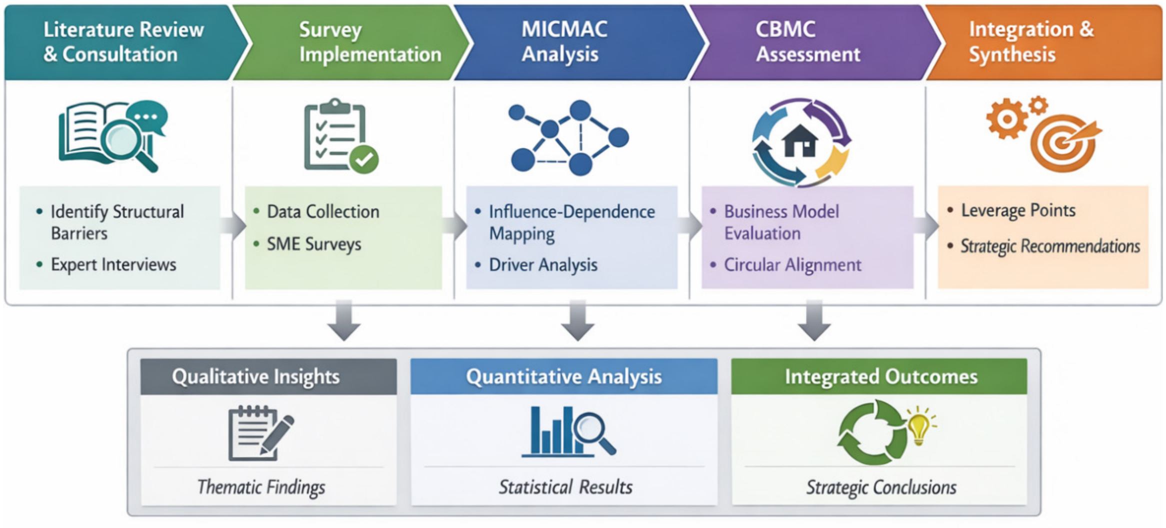

Figure 1. Research design and analytical framework of the sequential mixed-methods approach.

2.2. Study Area and Sample

The empirical research was conducted in Torreón, Coahuila, Mexico, located within the industrial region known as La Comarca Lagunera (25°33′46″ N; 103°23′45″ W). The geographical location of the study area within Mexico, specifically the state of Coahuila, is illustrated in Figure 2.

Figure 2. Geographic location of the study area: México, Coahuila, and Torreón.

This region represents an important manufacturing hub in northern Mexico with a significant concentration of timber furniture SMEs integrated into regional production networks.

The target population consisted of 32 timber furniture SMEs formally registered within the local industrial cluster. Given the manageable population size, a census approach was adopted in which all firms were invited to participate in the study. Participation was obtained from all 32 firms, resulting in 100% population coverage.

Although the sample size is limited to 32 firms, the use of a census approach ensures full population coverage, which significantly enhances internal validity. From a statistical perspective, the sample size exceeds the minimum threshold commonly recommended for correlation-based exploratory analyses (n > 30), thereby providing sufficient power to detect medium-to-strong relationships in the dataset.

This strategy minimizes sampling error and strengthens the internal validity of the analysis. Although the absolute number of firms is relatively small, the dataset represents the entire population of formally registered SMEs within the cluster, ensuring complete sectoral representation. Consequently, the results should be interpreted as cluster-specific empirical evidence rather than generalized patterns for the broader timber industry.

2.3. Identification of CE Barriers

Structural barriers to CE adoption were identified through a structured literature review conducted using the databases Web of Science, Scopus, and ScienceDirect. A total of 142 peer-reviewed publications, published between 2016 and 2025, addressing barriers to CE adoption in manufacturing and SME contexts were analyzed.

The selection criteria included peer-reviewed journal articles, relevance to CE implementation in manufacturing industries, conceptual clarity in barrier classification, and citation relevance within the sustainability literature. From this review, 65 initial barrier variables were identified and classified into seven analytical dimensions: legislative, economic, market, financial, information and network management, technological, and cultural and organizational. The distribution of the identified barriers across analytical dimensions is presented in Table 1.

Table 1. Classification of CE barriers by analytical dimension.

Dimension	Number of Variables
Legislative	6
Economic	7
Market	7
Financial	5
Information & Network Management	6
Technological	6
Cultural & Organizational	8

To ensure contextual relevance, a focus group comprising nine experts (SME managers, industry specialists, and academic researchers) was convened. Through thematic convergence and saturation analysis, the variables were refined and reduced to 45 operational indicators representing the most relevant barriers affecting circular transition processes in the sector. The complete list of CE barriers and operational indicators used in this study is provided in the Supplementary Materials (Table S1).

Each indicator was measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), enabling quantitative evaluation of barrier perceptions among participating firms.

2.4. Instrument Validation

The reliability and internal consistency of the survey instrument were evaluated using Cronbach's alpha coefficient. The results indicated $\alpha = 0.966$ for the complete instrument and $\alpha = 0.938$ for the aggregated barrier dimensions. Both values exceed the commonly recommended threshold of 0.70 for exploratory and confirmatory research, indicating high internal consistency and measurement reliability [19,20]. In addition, inter-item correlation matrices were examined to verify conceptual coherence among indicators within each barrier dimension.

2.5. Data Collection

Primary data were collected through structured online questionnaires distributed using Google Forms. Participation was voluntary, and respondents were informed of the research objectives before completing the questionnaire.

Several procedures were implemented to reduce potential response bias. First, anonymity and confidentiality of responses were guaranteed. Second, follow-up communications were conducted to clarify ambiguous responses when necessary. Third, all questionnaires were verified for completeness before inclusion in the dataset.

The data collection process lasted three months.

2.6. Statistical Analysis

Prior to correlation analysis, the distribution of the variables was evaluated using the Shapiro–Wilk normality test. Although Likert-scale data are ordinal by nature, several methodological studies indicate that aggregated Likert-scale constructs can be treated as approximately continuous variables when multiple items are combined into composite indicators and the sample size exceeds 30 observations. Under these conditions, the use of parametric techniques, such as Pearson's correlation coefficient, is considered statistically robust and widely accepted in social science and management research [21].

Pearson's correlation coefficient (r) was calculated to determine the strength and direction of relationships among the barrier variables. Statistical significance levels were defined as $p < 0.05$

(statistically significant) and $p < 0.01$ (highly significant). Correlation coefficients were interpreted according to the following scale: 0.00–0.39 (weak), 0.40–0.59 (moderate), 0.60–0.79 (strong), and ≥0.80 (very strong). Only strong and very strong correlations ($r \geq 0.60$) were retained for structural analysis. All statistical analyses were conducted using IBM SPSS Statistics version 26.

Although MICMAC is traditionally based on expert judgment, this study incorporates correlation analysis as a complementary filtering mechanism to enhance the robustness of variable selection. By retaining only statistically significant and strong relationships ($r \geq 0.60$), the analysis reduces subjectivity in constructing the cross-impact matrix and strengthens the empirical grounding of the structural model. This hybrid approach has been increasingly adopted in recent sustainability and systems research to improve the reliability of structural analysis in complex socio-economic systems. This procedure enhances empirical consistency without altering the theoretical foundations of MICMAC, which remain grounded in expert-based structural interpretation.

2.7. MICMAC Structural Analysis

To identify systemic relationships among the barrier variables, the MICMAC structural analysis method was applied. MICMAC is widely used in sustainability and innovation research to identify key drivers within complex socio-technical systems [16]. The method enables the identification of structural relationships among interdependent variables and facilitates their classification by driving power and dependence.

To ensure methodological rigor, the cross-impact matrix was constructed through a structured expert elicitation process using a standardized influence scale (0 = no influence; 1 = weak; 2 = moderate; 3 = strong). Experts independently evaluated pairwise relationships among variables, and consensus was achieved through iterative validation rounds. This procedure enhances the reliability of the MICMAC classification by minimizing individual bias and ensuring consistency in assessing influence–dependence relationships [16].

The expert panel for the structural analysis comprised nine specialists with an average of 14 years of professional experience in the timber industry, sustainability management, and CE practices. Experts were selected according to three criteria: (1) direct experience in SME management; (2) knowledge of CE principles; and (3) involvement in industry or academic sustainability initiatives.

The MICMAC procedure involved the following steps:

1. Construction of a square cross-impact matrix using the selected barrier variables.
2. Calculation of driving power through the summation of row values.
3. Calculation of dependence power through the summation of column values.
4. Classification of variables into four structural categories: autonomous variables, dependent variables, independent (driving) variables, and linkage variables.

This classification enables the identification of strategic leverage variables that exert the greatest influence on system behavior. MICMAC calculations were performed using Microsoft Excel 365 following standard structural analysis procedures.

2.8. Circular Business Model Assessment

The second analytical phase assessed the degree of alignment of 11 firms with the CBMC framework. This framework provides a structured representation of how firms create, deliver, and capture value within CE systems [18].

An adapted CBMC framework was applied to assess the implementation level of circular business model components among participating firms. Each CBMC component was evaluated using structured indicators measured on a three-level implementation scale: 2 = fully implemented, 1 = partially implemented, and 0 = not implemented.

The alignment level for each firm was calculated using the following equation:

$$A = \left(\frac{OS}{MPS}\right) * 100$$

where:

A = alignment percentage
OS = observed score
MPS = maximum possible score

To facilitate interpretation, results were categorized using a traffic-light visualization system: green (high implementation), yellow (moderate implementation), and red (low implementation).

To enhance the robustness of the CBMC assessment, the scoring criteria were validated through expert consultation and pilot testing with selected firms prior to full-scale implementation. The use of a three-level ordinal scale allows for consistent evaluation across firms while maintaining interpretability and comparability of results in SME contexts, where data granularity is often limited.

To ensure analytical consistency, the CBMC assessment was designed as an exploratory, yet structured evaluation framework tailored to SME contexts. Given the limited availability of standardized quantitative metrics for implementing circular business models in SMEs, a simplified ordinal scale (0–2) was adopted to balance interpretability and comparability across firms.

The subsample of 11 firms was selected based on data completeness and willingness to provide detailed operational information. While this reduces statistical generalizability, it enhances the depth and reliability of the assessment. Therefore, the CBMC results should be interpreted as indicative of structural alignment patterns rather than as statistically representative estimates.

This approach is consistent with prior research emphasizing the need for flexible, context-sensitive measurement tools for circular business model analysis, particularly in SME environments with data constraints.

2.9. Integration of Structural and Business Model Analyses

The integration between MICMAC results and CBMC components was conducted using a structured mapping logic. Specifically, high-driving and linkage variables identified through MICMAC analysis were systematically associated with CBMC components based on their functional roles in value creation, delivery, and capture.

This mapping followed two analytical criteria: (i) functional influence, referring to the extent to which a structural barrier affects a specific business model component; and (ii) systemic relevance, referring to the position of the variable within the influence–dependence structure.

This procedure enables a consistent linkage between structural system dynamics and business model configuration, reducing interpretive bias and strengthening the analytical robustness of the integration framework.

The final analytical stage integrated the results obtained from the MICMAC structural analysis and the Circular Business Model Canvas assessment. This integration involved linking high-driving and linkage barriers identified through MICMAC with CBMC components exhibiting low implementation levels.

Through this cross-analysis, 23 strategic intervention areas were identified to address systemic barriers and strengthen innovation in circular business models within timber furniture SMEs.

The integration followed a systems-based interpretive approach commonly applied in sustainability transition and strategic management research [22,23].

2.10. Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to confidentiality agreements with participating firms, individual survey responses cannot be publicly disclosed. However, anonymized aggregated data used for the statistical and structural analyses can be provided for academic research purposes.

No generative artificial intelligence tools were used in the design of the study, data collection, analysis, or interpretation of results. AI-based tools were used only for minor language editing.

3. Results

3.1. Structural Barriers Affecting Circular Economy (CE) Adoption

The analysis identified a set of structural barriers that significantly influence the adoption of CE practices among timber-based small and medium-sized enterprises (SMEs). The results indicate that circular transition processes are primarily constrained by a limited number of systemic barriers with strong structural influence.

Based on the literature review and expert consultation described in Section 2, six key barriers were identified as the most relevant for the sector:

- Financial constraints;
- Technological limitations;
- Limited access to specialized knowledge;
- Regulatory uncertainty;
- Weak collaboration networks;
- Insufficient market incentives for circular products.

These barriers reflect the structural characteristics of resource-based SMEs, which typically operate with limited financial resources, restricted technological capabilities, and weak integration into collaborative innovation networks. Such limitations restrict the implementation of circular practices, including product life extension, material recovery, eco-design strategies, and resource recirculation mechanisms.

3.2. Correlation Structure of Barrier Dimensions

Pearson correlation analysis revealed statistically significant relationships among several barrier dimensions ($p < 0.01$). The strongest correlations were observed between financial barriers and information-network management barriers ($r = 0.867$), financial and technological barriers ($r = 0.844$), and market and financial barriers ($r = 0.798$).

These results suggest that financial constraints strongly influence firms’ technological capacity and their ability to develop collaborative innovation networks. Limited access to financial resources restricts investment in digital infrastructure, circular innovation initiatives, and collaborative platforms necessary for circular value chain development.

Additional moderate-to-strong correlations were identified between economic and market barriers ($r = 0.795$) and legislative and cultural barriers ($r = 0.796$). These relationships indicate that barriers to CE adoption operate as an interconnected system rather than as isolated constraints.

Only correlations equal to or greater than 0.60 were retained for the subsequent structural modeling process. Prior to the structural analysis, item-level Pearson correlations were examined within each barrier dimension to assess internal consistency and the strength of relationships among indicators. The results revealed predominantly moderate-to-high correlations among items, supporting the internal coherence of the barrier constructs. The economic barrier exhibited the highest number of strong correlations, followed by technological and market barriers, indicating a high degree of interdependence among their respective indicators. These findings reinforce the validity of aggregating items into composite dimensions for subsequent structural analysis. The complete item-level correlation matrices for each barrier dimension are provided in the Supplementary Materials (Table S2). The complete Pearson correlation matrix is presented in Table 2.

Table 2. Pearson correlation matrix of structural barrier dimensions.

Dimension	LB	EB	MB	FB	GRIB	TB	CB
LB (Legislative)	1.000	0.691	0.705**	0.652**	0.603**	0.469**	0.796**

Dimension	LB	EB	MB	FB	GRIB	TB	CB
EB (Economic)		1.000	0.795**	0.743**	0.682**	0.623**	0.664**
MB (Market)			1.000	0.798**	0.711**	0.667**	0.646**
FB (Financial)				1.000	0.867**	0.844**	0.694**
GRIB (Information & Network Management)					1.000	0.807**	0.626**
TB (Technological)						1.000	0.461**
CB (Cultural & Organizational)							1.000

Note: LB = Legislative barriers; EB = Economic barriers; MB = Market barriers; FB = Financial barriers; GRIB = Information and network management barriers; TB = Technological barriers; CB = Cultural and organizational barriers. Correlation is significant at the 0.01 level (two-tailed).

The correlation matrix reveals a high degree of interdependence among barrier dimensions, supporting the systemic nature of constraints on CE adoption.

3.3. Structural Classification of Barriers Using Matrix of Cross-Impact Multiplications Applied to Classification (MICMAC)

To support the structural classification of variables, a preliminary analysis of driving and dependence power was conducted at the item level based on correlation values. The results allowed the identification of items with high influence and dependence within each barrier dimension, providing an additional layer of validation for the structural modeling process. Items such as I1EB, I2EB, I2MB, I3FB, I4GRIB, and I3TB exhibited high driving and dependence power, indicating their relevance as key linkage variables within the system. The detailed item-level driving dependence results are presented in the Supplementary Materials (Table S3).

The MICMAC structural analysis enabled the classification of barrier variables according to their levels of driving power and dependence within the circular transition system.

The resulting influence–dependence map is presented in Figure 3.

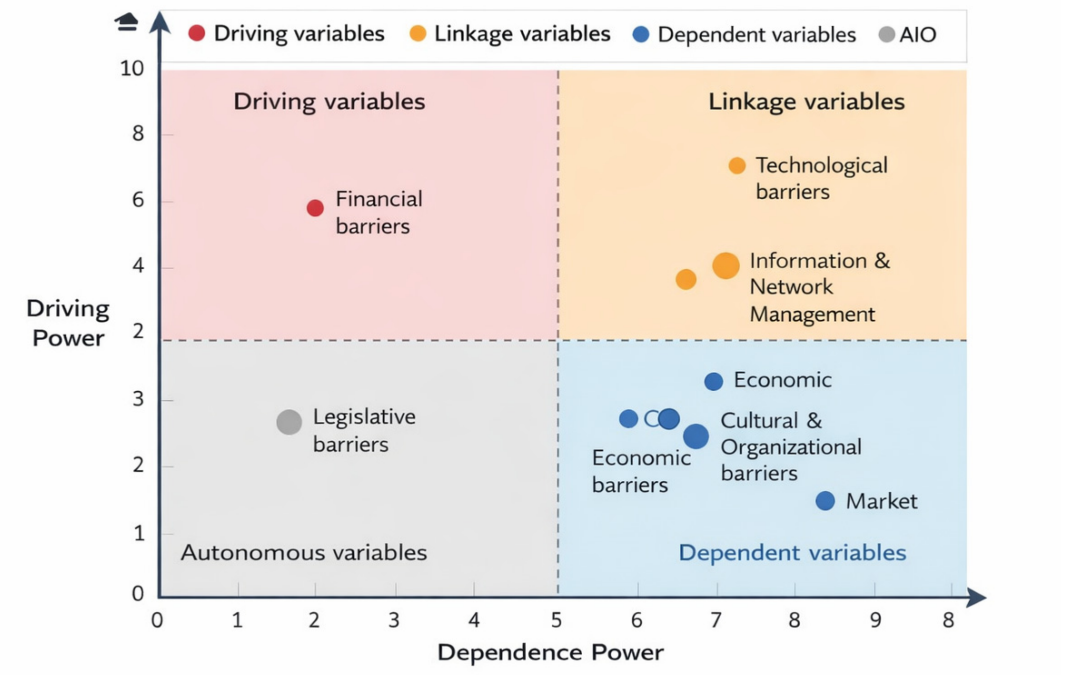

Figure 3. MICMAC influence–dependence map of CE barrier variables.

The figure classifies barrier variables according to their driving and dependence power into four categories: driving, linkage, dependent, and autonomous variables. The intersection lines represent the average values of driving and dependence power.

The structural classification identified three main categories of variables:

Driving Variables

These variables exert a strong influence and exhibit relatively low dependence within the system.

- Financial constraints
- Technological limitations

These drivers exert a strong influence over other system variables. Addressing these barriers could therefore generate cascading improvements across multiple dimensions of CE adoption.

Linkage Variables

Linkage variables exhibit both high influence and high dependence, acting as mediating elements within the system.

- Limited access to specialized knowledge
- Weak collaborative networks

These variables link structural drivers to operational constraints that affect SMEs circular innovation capacity.

Dependent Variables

Dependent variables exhibit high dependence but relatively low driving power.

- Market demand for circular products
- Regulatory incentives

These barriers are largely influenced by upstream structural drivers but have limited capacity to influence the system independently.

3.4. Mapping Structural Barriers to Circular Business Model Components (CBMC)

Following the conceptual framework presented in Section 2, the structural barriers identified through MICMAC analysis were mapped to the components of the CBMC.

Structural barriers were treated as independent variables influencing SMEs’ capacity to implement circular business model innovations.

The analysis revealed several key relationships:

- High-driving barriers, particularly financial and technological limitations, strongly affect value creation activities, resource management practices, and cost structures.
- Linkage barriers, including limited knowledge access and weak collaborative networks, constrain firms’ ability to establish strategic partnerships and participate in collaborative circular value chains.
- Dependent barriers primarily affect downstream business model components such as customer segments and market development for circular products.

These results provide empirical support for the systemic interaction between structural constraints and business model configuration within circular transition processes.

3.5. Alignment of SMEs with Circular Business Model Components

The evaluation of circular business model implementation using the CBMC framework revealed heterogeneous levels of adoption among firms within the cluster. The detailed traffic light assessment results for each firm and CBMC component are provided in the Supplementary Materials (Table S4).

Overall alignment results indicate that 45% of firms achieved more than 50% alignment with CBMC components, while 55% remained below this threshold. These findings suggest that most firms are currently in early or intermediate stages of circular transition.

Figure 4 presents the alignment levels of each firm with the CBMC. The results show a wide variation in implementation levels, with alignment values ranging from 31% to 99%. Firms with higher alignment scores demonstrate more advanced adoption of circular practices, while those with lower scores remain at early stages of transition.

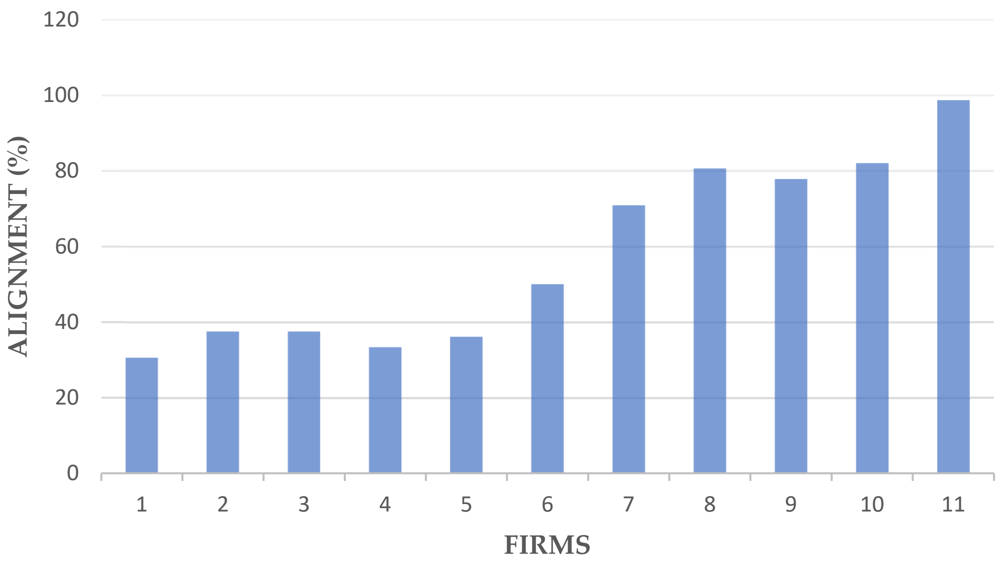

Figure 4. Alignment of SMEs with CBMC components, showing variation in implementation levels across firms within the cluster.

Figure 5 provides a block-level analysis of the CBMC structure and performance. Figure 5a illustrates the relative participation of each block within the CBMC, showing a greater emphasis on collaborative and circular activities such as resource recovery, remanufacturing, and circular product design. In contrast, the cost structure block exhibits a lower relative participation, suggesting that economic considerations may be underrepresented.

Figure 5b presents the alignment levels across CBMC components. Five blocks exhibit performance levels above 50%: Results (83%), Context (77%), Cost Structure (73%), Revenue Streams (68%), and Reverse System (57%). In contrast, the lowest levels of alignment are observed in Key Partnerships (41%) and Value Proposition (25%), indicating critical gaps in implementing circular business models.

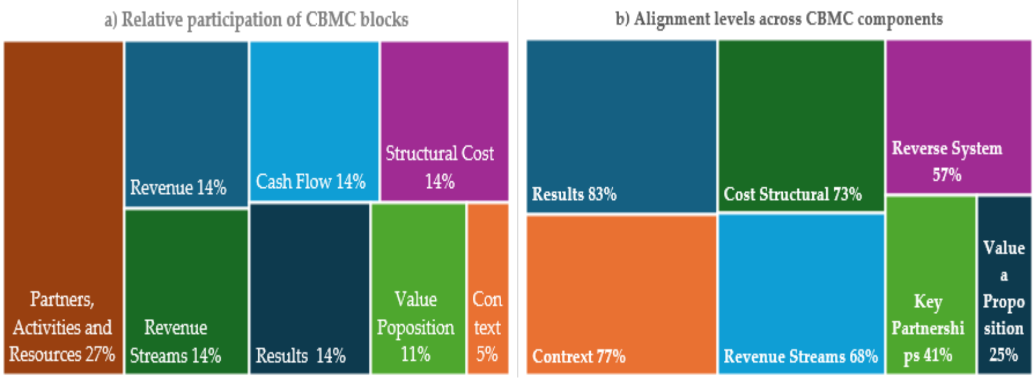

Figure 5. (a) Relative participation of CBMC blocks based on the proportion of items assigned to each component; (b) Alignment levels of firms across CBMC components.

Furthermore, Figure 6 illustrates the relationship between firm size and CBMC alignment. The regression analysis indicates a positive association between the number of employees and the level of circular business model implementation, suggesting that larger firms may have greater access to financial resources, technological capabilities, and organizational structures that facilitate circular innovation.

Conversely, smaller firms may face structural constraints that limit their capacity to adopt circular practices, reinforcing the importance of financial, technological, and organizational barriers identified in the structural analysis.

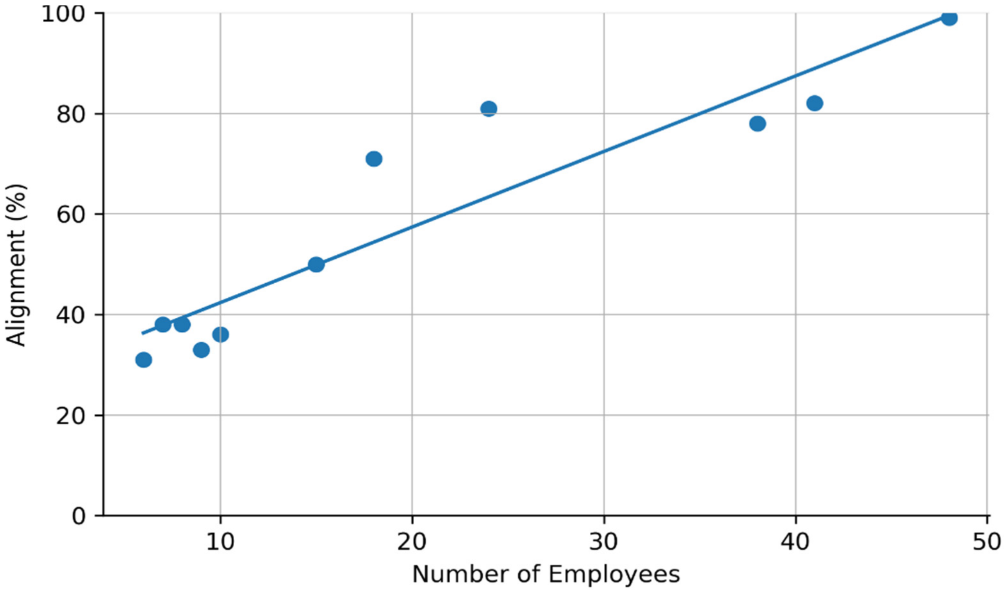

Figure 6. Relationship between firm size and CBMC alignment.

3.6. Integration of Structural and Business Model Findings

The integration of MICMAC and CBMC results revealed clear systemic alignment patterns between structural barriers and levels of business model implementation. Figure 7 illustrates the relationship between high-driving structural barriers and the lowest-performing CBMC components.

The cross-analysis identified three key relationships. First, driving and linkage barriers—particularly financial, technological, and information-network limitations—are strongly associated with the weakest CBMC components, namely Value Proposition and Key Partnerships. Second, financial and technological constraints limit firms' capacity to redesign value propositions, including adopting product-service systems and modular product architectures. Third, weak network management reduces the feasibility of collaborative recovery systems and closed-loop material flows.

The integration framework highlights that the items I1BE, I2BE, I2BM, I3BF, I4BGRI, and I3BT represent key leverage variables within the system, as they directly influence the development of critical CBMC components. These variables constitute priority intervention points for enabling circular business model innovation in SME clusters.

Overall, the findings confirm the systemic nature of circular transition challenges and emphasize that effective strategies must focus on high-driving structural barriers to enable coordinated transformation across business model components.

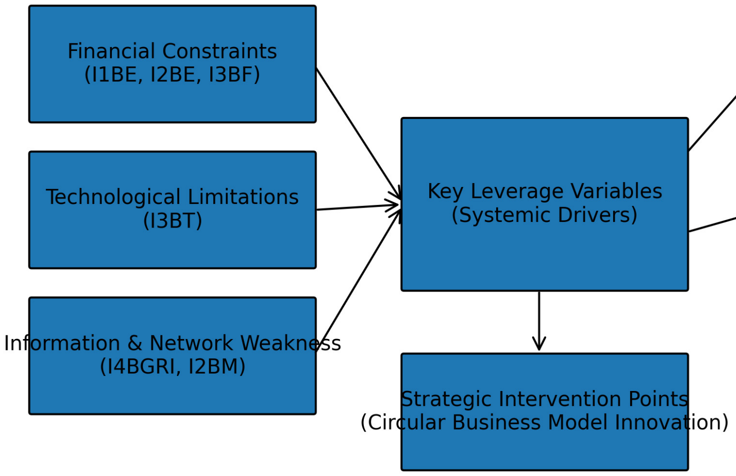

Figure 7. Conceptual integration framework linking high-driving structural barriers identified through MICMAC analysis with low-performing CBMC components.

The figure highlights key leverage variables and strategic intervention points for circular business model innovation.

3.7. Strategic Implications for Circular Transition

Based on the integrated analysis of MICMAC structural drivers and CBMC components, a set of strategic interventions was identified to address the main systemic barriers and accelerate innovation in circular business models within timber-based SMEs. Table 3 summarizes the key intervention areas by linking CBMC blocks with the most influential structural barriers and corresponding strategic actions. These interventions represent high-leverage points within the system, as they target driving and linkage variables identified in the structural analysis. The complete set of strategies is provided in the Supplementary Materials (Table S5).

Table 3. Strategic interventions for circular transition in timber SME clusters.

CBMC Block	Barrier Addressed	Strategic Action
Value Proposition	Technological (I3TB)	Modular product design and lifecycle planning
	Economic (I2EB)	Product-service systems and customer retention strategies
Key Partnerships	Financial (I3FB)	Government-supported financing programs
	Technological (I3TB)	Closed-loop collaboration networks
Key Activities	Economic (I1EB)	Process optimization and innovation training
	Information (I4GRIB)	Development of circular performance indicators
Resource Management	Market (I2MB)	Material recovery and reuse systems

To provide a systemic and integrative perspective, Figure 8 presents a conceptual framework that connects high-driving structural barriers with circular business model components and strategic intervention pathways. The framework illustrates how coordinated actions across CBMC dimensions can generate cascading effects that facilitate the transition toward circular production systems.

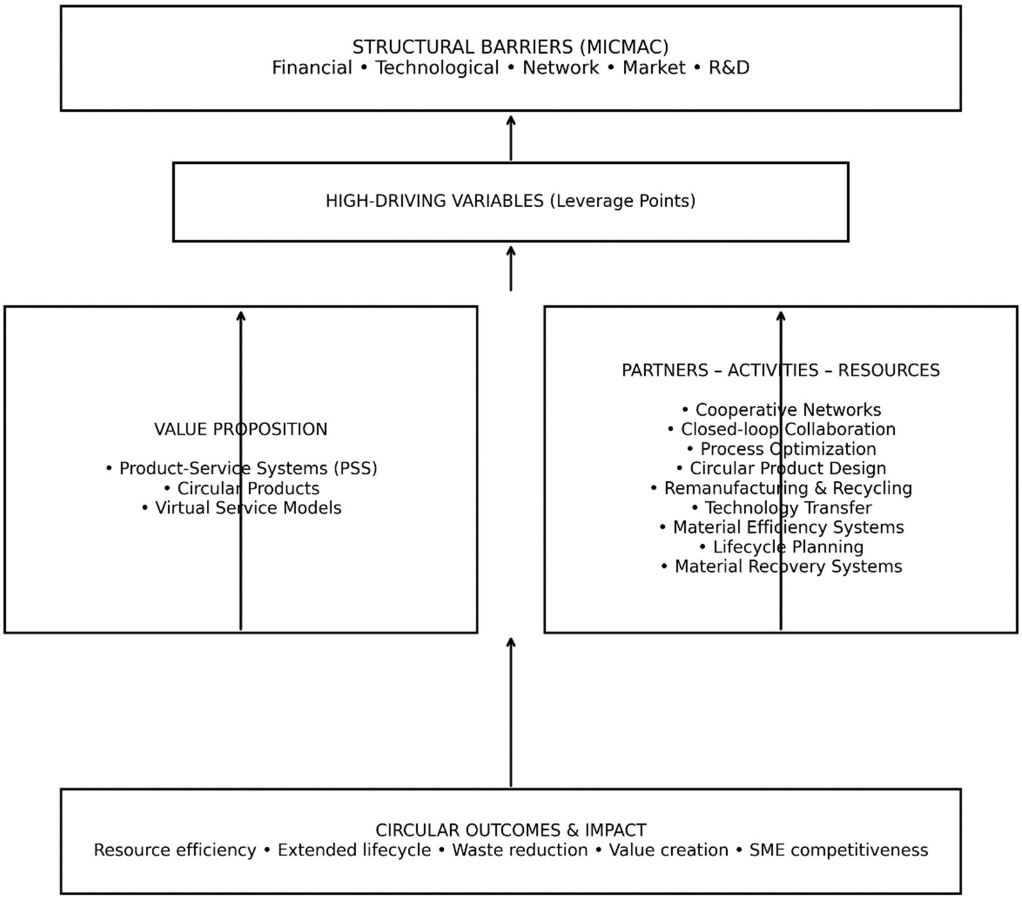

Figure 8. Integrated framework linking high-driving structural barriers (MICMAC) with circular business model innovation (CBMC) and strategic intervention pathways in timber-based SMEs.

The proposed interventions are organized into four main strategic domains: (i) product modularity and lifecycle planning, (ii) development of collaborative recovery systems, (iii) investment in circular innovation capabilities, and (iv) strengthening of sectoral support and knowledge networks. These domains reflect the structural interdependencies identified in the MICMAC analysis and their direct influence on business model configuration.

From a systems perspective, interventions targeting high-driving variables—particularly financial, technological, and network-related barriers—are expected to produce the greatest impact. For instance, enhancing access to financial resources enables investments in eco-design, digitalization, and process innovation, which in turn strengthen firms' capacity to implement circular value propositions. Similarly, improving technological capabilities facilitates modular design, material recovery, and lifecycle extension strategies.

The development of collaborative networks plays a critical role in enabling circular production systems. As illustrated in Figure 8, linkage variables such as limited access to knowledge and weak inter-firm collaboration constrain the implementation of closed-loop value chains. Addressing these barriers through cooperative platforms, industrial symbiosis, and knowledge-sharing mechanisms can significantly enhance circular innovation capacity at the cluster level.

In addition, market-related barriers, such as the lack of functional markets for recycled materials, highlight the need for institutional and infrastructural support. The establishment of material banks, collection centers, and reverse logistics systems can facilitate resource circulation and improve the economic viability of circular practices.

Overall, the integration of structural and business model analyses demonstrates that effective circular transition strategies must adopt a systemic approach. Rather than addressing isolated

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constraints, coordinated interventions across multiple CBMC components are required to unlock transformation pathways and generate cumulative impacts on sustainability performance.

The implementation of eco-design strategies, modular product architectures, and material recovery systems can help decouple production growth from raw material extraction. By extending product lifecycles and increasing resource efficiency, SMEs can reduce environmental pressures on forest resources while maintaining competitiveness within industrial clusters.

4. Discussion

4.1. Systemic Dynamics of CE Transition in Timber SMEs

This study advances current circular economy (CE) literature by moving beyond descriptive barrier identification toward a systemic, integrative explanation of how structural constraints shape business model innovation pathways in SMEs. These findings challenge the conventional assumption that circular transitions in small and medium-sized enterprises (SMEs) are predominantly operational, instead reinforcing the view that they are structurally constrained and systemically embedded processes [24,26]. In line with recent advances in CE research, the results demonstrate that financial, technological, and network-related barriers are interconnected structural drivers shaping firms' capacity to implement circular business model innovation [27,28].

The dominance of financial and technological barriers reveals reinforcing feedback mechanisms within SME systems, consistent with studies that highlight bidirectional dependencies between access to capital and technological upgrading in circular transitions [27,29]. From a path-dependency perspective, initial financial constraints restrict technological investments, which in turn limit productivity improvements and future investment capacity, generating cumulative disadvantage effects. This dynamic aligns with the concept of structural lock-in, widely discussed in recent CE literature as a key inhibitor of systemic transformation in resource-constrained contexts [30,31].

The Matrix of Cross-Impact Multiplications Applied to Classification (MICMAC) results further confirm that CE adoption in timber-based SMEs is governed by systemic interactions among structural constraints rather than isolated operational barriers. This finding corroborates recent empirical and review-based studies demonstrating that CE transitions in SMEs are shaped by interdependent financial, technological, and institutional factors embedded within broader socio-economic systems [25,32]. In particular, the identification of financial and technological constraints as high-driving variables is consistent with cross-sectoral evidence showing that these dimensions exert disproportionate influence over system-wide innovation capacity [26,28].

From a theoretical standpoint, the results reinforce the growing consensus that CE transitions should be conceptualized as systemic processes involving multi-level interactions between firm capabilities, institutional frameworks, and innovation ecosystems [33,34]. The observed interdependence among barrier dimensions supports this systems perspective, indicating that constraints such as limited access to finance and weak technological capabilities reinforce one another through feedback loops within complex production systems [27,29].

The strong correlation between financial and technological barriers further illustrates these reinforcing dynamics. Similar patterns have been identified in recent studies on SME circular transitions, where limited capital availability constrains digitalization and eco-innovation, thereby reducing firms' capacity to generate performance improvements that could enable reinvestment [29,31]. This cyclical constraint structure ultimately leads to structural inertia, delaying or preventing transitions toward circular production models.

Moreover, these findings highlight the critical role of regional innovation ecosystems in enabling CE transitions. Recent literature emphasizes that SMEs' capacity to adopt circular practices depends not only on internal resources but also on access to external knowledge networks, institutional support, and collaborative infrastructures [33,34]. Weak integration within such ecosystems significantly constrains firms' ability to engage in circular innovation processes. Therefore, CE transitions should be understood as multi-level transformations involving both firm-level capabilities and ecosystem-level dynamics. This reinforces the argument that circular transitions in SMEs are not merely firm-level adaptations, but system-level transformations embedded in complex socio-economic structures.

4.2. Circular Business Model Alignment and Early-Stage Transition Patterns

The analysis of Circular Business Model Components (CBMC) alignment indicates that timber SMEs remain in relatively early stages of the circular transition, with partial and uneven adoption of circular practices. This finding is consistent with recent systematic reviews highlighting that CE implementation in SMEs is still largely exploratory and heterogeneous across firms and sectors [25,35].

With an average alignment level of 45%, most firms continue to operate under predominantly linear value-creation logics. This pattern aligns with empirical evidence suggesting that SMEs tend to prioritize incremental operational improvements—such as waste reduction and efficiency gains—over radical business model transformation [36,37]. While these practices contribute to environmental performance, they do not necessarily entail fundamental changes in the mechanisms for value creation, delivery, or capture.

The block-level analysis further reveals that the lowest levels of alignment occur in Value Proposition and Key Partnerships, indicating critical gaps in strategic integration. This finding is supported by recent studies demonstrating that SMEs face significant challenges in redesigning value propositions toward circular offerings due to financial and technological constraints [28,38]. Circular value creation often requires investments in eco-design, modularity, and service-based models, which remain difficult to implement in resource-constrained environments.

Similarly, the low performance in Key Partnerships reflects structural limitations in the development of collaborative ecosystems. Recent research emphasizes that circular value chains depend on strong inter-organizational collaboration, industrial symbiosis, and network coordination [33,35]. The absence of such collaborative structures limits SMEs' ability to engage in reverse logistics, resource recovery, and closed-loop production systems.

Overall, these findings confirm that operational circularity does not automatically translate into business model circularity. Instead, the transition requires deeper strategic reconfiguration, reinforcing the need to address structural barriers that constrain business model innovation.

4.3. Linking Structural Barriers with Circular Business Model Transformation

A key contribution of this study is the empirical demonstration of the relationship between systemic barriers and the configuration of circular business models in SMEs. The results show that high-driving structural barriers directly affect the weakest CBMC components, particularly Value Proposition and Key Partnerships.

This relationship is consistent with recent research indicating that financial and technological constraints are primary inhibitors of circular business model innovation [28,37]. Without sufficient financial resources, SMEs face significant limitations in adopting eco-design practices, digital monitoring systems, and advanced manufacturing technologies required for circular production [29].

Simultaneously, limitations in knowledge networks and collaborative infrastructures constrain the development of strategic partnerships necessary for reverse logistics systems and resource recovery processes. Prior studies emphasize that circular production systems require coordinated action among multiple stakeholders and that weak collaboration networks represent a major bottleneck in CE implementation [33,35].

These findings align with ecosystem-based perspectives on circular innovation, which highlight that business model transformation depends on the alignment between firm-level strategies and external enabling conditions [34,35]. However, this study advances the literature by empirically linking structural system dynamics with business model configuration, demonstrating how systemic barriers translate into misalignment across specific CBMC components.

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By identifying high-leverage variables, the study provides a basis for prioritizing strategic interventions that can generate cascading effects across business model dimensions. This integrative approach contributes to CE research by bridging structural analysis and business model innovation frameworks.

4.4. Policy and Managerial Implications

The findings provide important implications for policymakers and practitioners aiming to accelerate CE adoption in SME-based industrial sectors. From a policy perspective, the results underscore the need for integrated frameworks that simultaneously address financial, technological, and institutional barriers, consistent with recent CE policy research [27,32].

Improving access to finance is a critical priority, as financial constraints remain one of the most influential barriers to CE adoption. Instruments such as green financing, innovation subsidies, and risk-sharing mechanisms have been identified as key enablers of circular innovation in SMEs [27].

Technological capability development represents another strategic priority. Recent studies highlight the role of digitalization, Industry 4.0 technologies, and knowledge transfer in facilitating circular transitions [29,37]. Strengthening linkages among SMEs, universities, and research centers can accelerate the diffusion of innovation and reduce technological gaps.

Furthermore, the importance of collaborative networks is reinforced by recent research on circular ecosystems, which emphasizes the role of industrial symbiosis and inter-firm cooperation in enabling circular production systems [33,35]. Consequently, cluster-based policies and collaborative platforms should be promoted to enhance network integration.

From a managerial perspective, the findings highlight that circular transition strategies must adopt a systemic approach. Given the interdependence of structural barriers, isolated interventions are unlikely to be effective. Instead, coordinated strategies that simultaneously address financial, technological, and relational dimensions are required, as suggested by recent CE transition frameworks [25,34,37].

4.5. Limitations and Future Research

Despite its contributions, this study presents several limitations. First, the focus on a single industrial cluster limits the generalizability of the findings. Future research should apply the proposed framework across different sectors and geographic contexts to assess its broader applicability [25].

Second, the use of cross-sectional data restricts the ability to capture dynamic transition processes. Longitudinal studies are needed to better understand how structural barriers evolve and how circular business model transformation unfolds over time [30].

Third, the reliance on perception-based data may introduce subjective bias, as commonly acknowledged in CE research [24]. Future studies should incorporate objective performance indicators and longitudinal datasets to strengthen empirical robustness.

5. Conclusions

This study provides robust empirical evidence that circular economy (CE) transitions in small and medium-sized enterprises (SMEs) based in industrial clusters are governed by structurally embedded, highly interconnected barriers rather than by isolated operational constraints. By integrating Matrix of Cross-Impact Multiplications Applied to Classification (MICMAC) structural analysis with the Circular Business Model Canvas (CBMC), the research advances a novel, replicable analytical framework that links systemic diagnostics to business model transformation processes.

The results show that these structural barriers generate cascading effects across organizational processes, limiting SMEs' capacity to redesign production systems, develop circular value propositions, and implement advanced circular strategies. Consistent with these conditions, the CBMC assessment indicates that firms remain at an early stage of the circular transition, with an average alignment level of approximately 45% and critical gaps in the Value Proposition and Key Partnerships components.

From a theoretical perspective, this study advances CE research by demonstrating that transition processes in SMEs are structurally constrained and systemically interdependent. The integration of MICMAC and CBMC provides a novel and replicable approach that links structural system analysis with business model innovation, offering new insights into how systemic barriers translate into misalignment across key components of circular business models.

From a practical and policy perspective, the findings highlight that accelerating circular transitions requires prioritizing high-driving structural variables. Enhancing access to finance, strengthening technological capabilities, and fostering collaborative networks are essential to enable circular innovation in SME clusters. These interventions can support lifecycle extension, material recirculation, eco-design implementation, and industrial symbiosis, thereby improving both environmental performance and economic competitiveness.

Beyond its empirical context, the proposed framework offers a transferable tool for analyzing sustainability transitions in other resource-based sectors and emerging economies. By identifying structural leverage points and linking them to business model transformation, this study provides actionable guidance for designing system-oriented strategies that accelerate CE implementation at both firm and policy levels.

Future research should explore longitudinal applications of the proposed framework, incorporate objective performance indicators, and extend the analysis to cross-sectoral and international comparative contexts to validate its generalizability.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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