Measuring digital maturity in MSMEs: An integrated statistical model of digitization, innovation, and sustainability

Medición de la madurez digital en las MIPYMES: Un modelo estadístico integrado de digitalización, innovación y sostenibilidad

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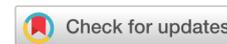
Abstract

The literature on digital transformation in micro, small, and medium-sized enterprises (MSMEs) has advanced in a fragmented manner, often focusing separately on digitalization, innovation, or sustainability. This fragmentation has limited understanding of digital maturity within firms and reduced the effectiveness of public policies. The objective of this study is to develop and apply an integrated multivariate statistical model to construct a synthetic index that jointly captures digitalization processes, organizational innovation, and sustainable practices. The Multidimensional Index of Digital Strategy, Innovation, and Sustainability (IMEDIS) represents a methodological contribution that overcomes unidimensional approaches and provides a comparable and representative measure of digital maturity. Based on a sample of 654 Brazilian MSMEs, multivariate statistical techniques were applied to create a typology of digital maturity. The main conclusion is that digital maturity does not result solely from technology adoption but from the interaction of digital strategies, innovation, and sustainability, revealing strong structural heterogeneity across firms. IMEDIS is a useful tool for diagnosing, monitoring, and evaluating public policies and digital strategies for MSMEs, offering an analytical framework transferable to different national contexts.

Keywords: digital maturity; sustainable innovation; IMEDIS; multivariate analysis; Brazilian MSMEs
JEL Classification: C01; L25

Resumen

La literatura sobre transformación digital en micro, pequeñas y medianas empresas (MIPYMES) ha avanzado de manera fragmentada, a menudo centrándose por separado en la digitalización, la innovación o la sostenibilidad. Esta fragmentación ha limitado la comprensión de la madurez digital dentro de las empresas y ha reducido la efectividad de las políticas públicas. El objetivo de este estudio es desarrollar y aplicar un modelo estadístico multivariado integrado para construir un índice sintético que capture conjuntamente los procesos de digitalización, la innovación organizacional y las prácticas sostenibles. El Índice Multidimensional de Estrategia Digital, Innovación y Sostenibilidad (IMEDIS) representa una contribución metodológica que supera los enfoques unidimensionales y proporciona una medida comparable y representativa de la madurez digital. Con base en una muestra de 654 MIPYMES brasileñas, se aplicaron técnicas estadísticas multivariadas para crear una tipología de madurez digital. La principal conclusión es que la madurez digital no resulta únicamente de la adopción de tecnología, sino de la interacción de las estrategias digitales, la innovación y la sostenibilidad, lo que revela una fuerte heterogeneidad estructural entre las empresas. IMEDIS es una herramienta útil para diagnosticar, monitorear y evaluar políticas públicas y estrategias digitales para las MIPYMES, ofreciendo un marco analítico transferible a diferentes contextos nacionales.

Palabras clave: madurez digital; innovación sostenible; IMEDIS; análisis multivariado; MIPYMES brasileñas
Clasificación JEL: C01; L25

1. Introduction

In an increasingly globalized market, micro, small, and medium-sized enterprises (MSMEs) must adapt their strategies to remain competitive (Gonzalez-Tamayo et al., 2023; Ortiz García de las Bayonas et al., 2023). Digital transformation and digital strategy have become two key factors for improving organizational performance (Hanelt et al., 2021; Li et al., 2022; Proksch et al., 2024). Within the framework of corporate strategy, digital strategy leverages digital resources to create differential value among firms (Bharadwaj et al., 2013; Proksch et al., 2024) and entails aligning digital assets with business objectives (Canhoto et al., 2021; Ghosh et al., 2022).

Furthermore, digitalization fosters innovation by increasing the likelihood of developing new products (Agostini et al., 2019; Radicic & Petković, 2023), optimizing production processes, and promoting an innovation-oriented culture (Cassaro et al., 2024; Fichman et al., 2014; Sebastian et al., 2020). In addition, digitalization can act as a catalyst for sustainability in MSMEs by integrating technologies that optimize resources and enable circular practices (Becker & Schmid, 2020; Costa Melo et al., 2023; Dey, Malesios, De, et al., 2022; Parviainen et al., 2022), while supporting the development of more responsible and resilient business models in response to market and sustainability challenges (Arroyabe et al., 2024; Sebastian et al., 2020; Teece, 2010). This synergy reinforces the complementarity between financial and environmental performance, generating competitive advantages (Dey, Malesios, Chowdhury, et al., 2022; Lopez-Torres, 2023).

Society increasingly demands environmentally responsible and socially inclusive business practices, making it essential to consider the performance–innovation–sustainability framework, which has become a prerequisite for competitiveness (Guerrero-Baena et al., 2024; Kantabutra, 2024; Wu & Tham, 2023). Research on digital transformation, green innovation adoption, and sustainable performance reveals a strong correlation with MSME performance (Dey, Malesios, Chowdhury, et al., 2022). However, these three dimensions are rarely assessed in an integrated and simultaneous manner, particularly in large samples of Latin American MSMEs (Machado et al., 2024). This gap is also evident when examining the lack of studies at the intersection of digital transformation and sustainable development in MSMEs (Philbin et al., 2022) and the importance of combining conditions to explain innovation-related outcomes (Sycheva & Verdu-Jover, 2025). Despite the recognized potential of MSMEs to drive innovation and advance toward a more sustainable economy, there is a lack of robust instruments to assess, in a unified way, the strategic maturity of these firms in terms of digitalization, innovation, and sustainability (Khurana et al., 2022).

Measuring strategic maturity in MSMEs by integrating their degree of digitalization, innovation, and sustainability is important for several reasons. Such measurements can help evaluate how these dimensions interact to generate sustainable competitive advantages, avoiding isolated approaches that limit impact (Costa Melo et al., 2023; Lopez-Torres, 2023; Molina-Sánchez et al., 2022). An integrated assessment also helps identify gaps and opportunities to improve efficiency, reduce impacts, and foster innovation (Agostini et al., 2019; Burlea-Schiopoiu & Mihai, 2019).

The literature offers various measurement instruments, such as digital maturity models and indices (Gökalp & Martinez, 2022; Spremić et al., 2024; Thordsen & Bick, 2023); scales and constructs focused on innovation management (Acosta-Prado et al., 2021; Carrasco-Carvajal et al., 2023; Nappi & Kelly, 2022; Tikas, 2023), capabilities, and open innovation (Abbu et al., 2022; Moreira et al., 2024); and sustainability metrics and indicators, including approaches aligned with triple bottom line (TBL)/environmental, social, and governance (ESG) frameworks (Blum et al., 2025; Ibáñez-Forés et al., 2023; Mengistu & Panizzolo, 2023; Nielsen, 2023), as well as studies addressing pairs of dimensions (e.g., digitalization–innovation or digitalization–sustainability; Bilal et al., 2024; Gomez-Trujillo & Gonzalez-Perez, 2022; Hassan et al., 2024; Robertsone & Lapiņa, 2023). However, these instruments rarely integrate digitalization, innovation, and sustainability simultaneously and operationally, either due to conceptual fragmentation or isolated, non-comparable measures, which hinders systemic diagnosis. Consequently, there is a lack of a synthetic, comparable, and statistically grounded measure that enables integrated diagnosis, benchmarking, and support for managerial decision-making, as well as the design and monitoring of incentive policies, particularly in emerging contexts.

The objective of this research is to develop and apply an integrated multivariate statistical model to construct a synthetic index for the strategic evaluation of MSMEs, considering the dimensions of digital maturity, organizational innovation, and environmental sustainability. Based on this indicator, the study seeks to determine organizational profiles of groups of firms according to their level of digital maturity. To achieve this, we used a sample of 654 Brazilian MSMEs that participated in the survey "Digitization and Sustainable Development of MSMEs," coordinated by the Ibero-American Observatory of Micro, Small, and Medium-Sized Enterprises (FAEDPYME). Specifically, the research seeks to:

1. Generate an index that measures the digitalization, innovation, and sustainability of MSMEs.
2. Determine profiles or clusters of firms based on this index.

The Brazilian context is particularly relevant given the significant impact of MSMEs on employment generation and value creation. In Brazil, MSMEs represent approximately 96% of all active organizations (SEBRAE, 2024), playing a strategic role in socioeconomic development and in achieving the Sustainable Development Goals (SDGs). Moreover, 66% of MSMEs are at the initial level of digital maturity, while only 3% qualify as digital leaders (Sichel et al., 2023).

This study contributes to the literature in several ways. From a theoretical and methodological perspective, it responds to recent calls for systemic approaches that combine digital transformation, innovation, and sustainability in MSMEs (Dey, Malesios, De, et al., 2022; Martins, 2022). It also expands the application of integrated multivariate statistical methods to measure firms' digital maturity and identify differentiated segments, generating essential insights for guiding public policy actions aimed at promoting MSMEs. The construction of the Multidimensional Index of Digital Strategy, Innovation, and Sustainability (IMEDIS) represents a methodological contribution by applying, in a sequential manner, exploratory factor analysis (EFA), *K*-means clustering, and discriminant analysis, providing empirical evidence of the validity of this statistical combination in an emerging context (Ferenhof et al., 2014).

The following section presents the theoretical framework articulating digital transformation, innovation, and sustainability. Next, the methodological procedures are detailed. Subsequently, the results and identified profiles are discussed. Finally, implications, limitations, and future research agendas are outlined.

2. Theoretical framework

In this section of the article, the theoretical categories that underpin the measurement architecture of IMEDIS are presented. These categories are related to organizational mechanisms, sustainability aspects as a source of competitive advantage, organizational robustness and resilience, as well as contextual barriers and constraints. The articulation of these dimensions is structured in the framework that summarizes the analytical categories used in the construction of IMEDIS.

2.1 Digital transformation and digital maturity in MSMEs: Foundations and measurement

Digital transformation (DT) has evolved beyond the mere adoption of technologies to be understood as an organizational and strategic process that entails redefining business models, routines, management practices, and value creation mechanisms (Baiyere et al., 2020). Despite the growing body of literature, fragmentation persists across fields such as technology, operations, and sustainability, which hinders integrated explanations of how MSMEs convert digital resources into performance and competitiveness (Costa Melo et al., 2023). Moreover, economic approaches that link digitalized dynamics with real-economy indicators reinforce the need to conceptualize DT as a systemic phenomenon rather than an isolated information technology (IT) initiative (Maroto Acín & Melle Hernández, 2001).

Within this context, the notion of digital maturity emerges as a diagnostic tool. In general terms, digital maturity models aim to assess levels of preparedness and development across dimensions such as processes, technology, people, and governance, providing benchmarks to identify a firm's current position and the requirements for advancement (Elhusseiny & Crispim, 2023). This logic is particularly relevant for MSMEs, given that the heterogeneity of capabilities and constraints makes it insufficient to evaluate only the presence of digital tools. Studies in the European context suggest, for instance, that higher digital maturity tends to be associated with greater openness to collaboration and innovation, indicating that digitalization and innovation are connected through organizational and relational capabilities rather than solely through infrastructure (Tutak & Brodny, 2022).

Nevertheless, this research agenda faces two recurring limitations. First, maturity instruments tend to privilege technological dimensions, paying less attention to management, learning, and strategic integration capabilities. Second, the use of non-comparable metrics across studies and contexts restricts benchmarking and evidence-based decision-making. To address these challenges, multivariate methods have been employed to condense variables and classify business profiles, such as combining exploratory factor analysis and clustering techniques to categorize MSMEs according to Industry 4.0 adoption (Pech & Vrchota, 2020). However, the simultaneous inclusion of innovation and sustainability variables within the same measurement architecture remains largely unexplored, particularly in MSMEs.

2.2 Organizational mechanisms: Dynamic capabilities, innovation, and open innovation

Innovation in MSMEs is best understood as a capability and a process rather than as an isolated outcome. This perspective requires considering learning, knowledge recombination, routines, internal coordination, and external interaction as mechanisms that enable the transformation of resources into new products, services,

processes, or management practices. In this regard, the logic of dynamic capabilities posits that firms innovate by identifying opportunities, mobilizing resources, and reconfiguring competencies over time, particularly in unstable environments and under the constraints typical of MSMEs. Complementarily, open innovation emphasizes that, beyond internal efforts, innovation may depend on collaboration with customers, suppliers, universities, and networks, thereby expanding access to knowledge and accelerating learning cycles.

Recent evidence from micro and small enterprises indicates that open innovation and innovative performance tend to be articulated through dynamic capabilities, forming a chain of processes that explains how firms convert external interactions into effective innovation (Sesabo et al., 2023). This perspective is highly relevant to digital transformation, as digitalization enhances the ability to integrate data, connectivity, and coordination, strengthening both internal learning and external collaboration—provided that managerial routines and competencies exist to absorb, interpret, and apply knowledge.

However, significant tensions also arise. In particular, the acceleration of digital change can generate internal asymmetries, with technological advances outpacing equivalent progress in competencies, governance, and culture. Moreover, digital decisions often require balancing data capture, efficiency, and responsibility, reinforcing the need for instruments that measure not only adoption but also strategic maturity and associated innovative capacity.

2.3 Sustainability as a competitive strategy

In MSMEs, sustainability has evolved from a normative approach toward a strategic dimension linked to competitiveness, reputation, and resilience. In the literature, this agenda typically integrates economic and environmental dimensions and, where applicable, social aspects, aligning with perspectives such as the triple bottom line and ESG indicators, as reflected in various studies and sectoral reports. Similarly, the circular economy broadens the debate by prioritizing waste reduction, closed-loop systems, and value chain reconfiguration, with direct implications for processes, innovation, and business models (Dey, Malesios, De, et al., 2022). Empirical findings in MSMEs also show that leadership commitment and measurement systems explain a significant portion of the adoption of circular practices, highlighting that sustainability depends on managerial and monitoring capabilities rather than mere intention (Dey, Malesios, Chowdhury, et al., 2022).

Within this context, the concept of sustainable digital transformation becomes relevant, understood as the capacity of digitalization to enable sustainable outcomes when guided by strategy, metrics, and organizational capabilities. A recent synthesis of the literature on DT and sustainable development in SMEs underscores that digitalization should be considered a means to achieve sustainability objectives rather than an end in itself, emphasizing that integration involves not only technologies but also business characteristics such as strategy, structure, culture, competencies, and leadership (Philbin et al., 2022). In other words, analysis must go beyond technological presence and capture how firms organize and direct digital resources toward innovation and sustainability.

Nevertheless, the agenda remains marked by integration gaps. Reviews indicate that many studies still address DT and sustainability in parallel or partially, limiting diagnoses that reveal synergies and potential trade-offs. Consequently, instruments focused exclusively on environmental aspects may fail to reflect the enabling role of digitalization, while DT metrics may underestimate sustainability conditions that, in practice, influence investments, priorities, and social legitimacy.

2.4 Barriers and contextual constraints to digital transformation: Emphasis on brazilian MSMEs

In MSMEs, digital transformation is shaped by internal and external barriers that affect both the pace and quality of the process. Broadly, these barriers can be grouped into interdependent categories: resources and infrastructure; skills and qualifications; culture and resistance to change; governance and security; as well as external constraints such as access to financing, suppliers, and support networks (Brink & Packmohr, 2023; Chen et al., 2024; Omowole et al., 2024; Sagala & Őri, 2024). This framework is relevant because barriers influence not only technology adoption but also the ability to convert digitalization into innovation and performance.

Recent evidence from the Brazilian context reinforces this point. Based on MSMEs in Brazil, Cassaro et al. (2024) show that digital transformation, characterized by digitalization strategies and technology use, is positively associated with innovation. However, implementation barriers can weaken this relationship, with more visible effects in relatively larger firms within the MSME segment, indicating that obstacles do not manifest uniformly across organizational profiles. For measurement purposes, this implies that assessing only the presence of technology may lead to misleading conclusions about readiness, as barriers often limit the conversion of digitalization into innovation.

At the institutional level, public policies also act as conditioning factors. Brazil has established guidelines and programs to expand digital infrastructure, stimulate innovation, and support firms, such as the National System for Digital Transformation and the Brasil Mais Produtivo program, aimed at improving productivity and management through digital transformation. Evaluations highlight benefits in productivity at low cost and within short timeframes, but also reveal limitations in systemic effectiveness and spillover effects, suggesting the need to articulate these initiatives with other policies and diagnostic instruments (CEPAL-IPEA, 2018). Similarly, sectoral initiatives such as PADIS face challenges related to coordination, continuity, and alignment with complementary instruments, affecting predictability and long-term planning capacity (Zulke, 2017).

In summary, the discussion on barriers and constraints confirms that DT is not a linear process. Its progress depends on the interplay between internal capabilities and external conditions, which increases the relevance of tools capable of diagnosing digital maturity alongside innovation and sustainability, providing actionable insights for managers and for the design of public policies.

2.5 Integration of categories in the construction of IMEDIS: Correlations between dimensions and implications

At this point, the logic of dynamic capabilities offers a central explanation. Innovation depends on the ability to identify opportunities, mobilize resources, and reconfigure competencies over time, a dynamic that intensifies when external collaboration and open innovation are present (Sesabo et al., 2023). Thus, digital transformation can act as an enabler of innovation by expanding access to data and networks, but its effects are conditioned by the existence of routines, competencies, and processes that allow firms to absorb and apply knowledge, including that originating from external partners (Sesabo et al., 2023; Tutak & Brodny, 2022). At the same time, evidence from Brazil indicates that the relationship between digital transformation and innovation is not automatic. Implementation barriers can weaken this link, reducing the firm's ability to convert digital efforts into innovative outcomes, thereby increasing the risk of fragmented initiatives and limited returns (Cassaro et al., 2024).

Sustainability, in turn, is not a parallel dimension but a strategic vector that can be driven by innovation and enabled by digital transformation, provided it is guided by metrics, capabilities, and coherent managerial decisions (Philbin et al., 2022). This integration becomes even more relevant when considering practices such as the circular economy, which require process redesign, continuous improvement, monitoring, and coordination along the value chain, often supported by digital technologies to ensure traceability and efficiency (Dey, Malesios, Chowdhury, et al., 2022; Dey, Malesios, De, et al., 2022).

Nevertheless, the literature indicates that most studies address digitalization, innovation, and sustainability in a partial manner, making it difficult to compare firms, diagnose priorities, and guide investments in an integrated way (Costa Melo et al., 2023; Philbin et al., 2022). Furthermore, the need for integration is reinforced from a configurational perspective: Organizational outcomes, such as behaviors and effects associated with innovation, may arise from different combinations of conditions rather than from a single isolated factor (Sycheva & Verdu-Jover, 2025). This implies that assessing digitalization, innovation, and sustainability separately can lead to incomplete diagnoses, failing to capture synergies, compensations, and potential trade-offs among dimensions. For example, a firm may show progress in digitalization without achieving innovation due to capability limitations or implementation barriers, or it may innovate without generating sustainable benefits due to the absence of metrics and strategic orientation toward sustainability (Cassaro et al., 2024; Philbin et al., 2022).

Consequently, a joint operationalization is justified to observe integrated patterns and segment organizational profiles based on combinations of dimensions. Against this backdrop, IMEDIS is theoretically grounded as an integrated measurement instrument that simultaneously captures digital maturity, organizational innovation, and environmental sustainability, incorporating the notion that the effects of digitalization depend on capabilities, are conditioned by barriers, and can generate sustainable outcomes when guided by strategy and metrics (Cassaro et al., 2024; Philbin et al., 2022; Sesabo et al., 2023; Sycheva & Verdu-Jover, 2025). This synthesis underpins the construction of the index, requiring that operationalization go beyond technological proxies to include elements capable of explaining the conversion of digitalization into innovation and sustainability, thereby supporting diagnosis, segmentation, and benchmarking in MSMEs.

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Table 1. Integration map of the analytical categories used in the construction of IMEDIS

Analytical Category	Role in Theoretical Logic	Relationship with Other Dimensions	Implications for Measurement in IMEDIS
Digital Transformation	Strategic and organizational process that reconfigures activities, routines, and value creation, going beyond information technology (Baiyere et al., 2020; Costa Melo et al., 2023).	Enables new ways of operating and learning, potentially fostering innovation and enabling sustainable practices when guided by strategy and organizational capabilities (Philbin et al., 2022).	Capture not only technology adoption but also strategic orientation, managerial use, and the integration of digital technologies into processes and decision-making (Elhusseiny & Crispim, 2023).
Digital Maturity	Measure of readiness and stage-based evolution in technology, processes, and people, useful for diagnosis and benchmarking (Elhusseiny & Crispim, 2023).	Higher levels tend to be associated with collaboration and openness to innovation but depend on organizational culture and internal alignment (Lin et al., 2020; Tutak & Brodny, 2022).	Build dimensions that differentiate stages and profiles, avoiding the reduction of maturity to infrastructure alone (Elhusseiny & Crispim, 2023).
Dynamic Capabilities	Mechanisms for sensing opportunities, mobilizing resources, and reconfiguring competencies, sustaining adaptation and innovation (Sesabo et al., 2023).	Convert digital resources into organizational change and innovation, linking digital transformation to value creation (Cassaro et al., 2024; Sesabo et al., 2023).	Measure learning, reconfiguration, and coordination routines that explain why firms with similar technologies display different performance levels (Sesabo et al., 2023).
Open Innovation	Access to and use of external knowledge to innovate through collaboration and networks (Sesabo et al., 2023).	Depends on dynamic capabilities to absorb and transform external knowledge; is enhanced by digital connectivity (Sesabo et al., 2023; Tutak & Brodny, 2022).	Include indicators of cooperation, networks, and external integration mechanisms associated with innovation (Sesabo et al., 2023).
Organizational Innovation	Outcome and process of creating and implementing novelties in products, processes, and management practices (Cassaro et al., 2024).	May be stimulated by digital transformation, but effects are conditioned by barriers and capabilities, especially in MSMEs (Cassaro et al., 2024).	Capture innovative practices and outcomes and their association with digitalization and sustainability, enabling comparable firm profiles (Cassaro et al., 2024).
Sustainability	Strategic dimension of performance and legitimacy, associated with environmental and economic outcomes and, where applicable, social outcomes (Bartolacci et al., 2020; Lopez-Torres, 2023).	Digital transformation can enable sustainability, but effects depend on strategic orientation, metrics, and organizational capabilities (Philbin et al., 2022).	Include environmental practices and measurement mechanisms that allow sustainability to be assessed as part of strategy rather than as a peripheral action (Philbin et al., 2022).
Barriers to Digital Transformation	Constraints that limit implementation and reduce the ability to convert digital transformation into innovation (Cassaro et al., 2024).	Moderate the relationship between digital transformation and innovation, generating the risk of "digitalizing without transforming" in constrained contexts (Cassaro et al., 2024).	Incorporate variables related to resource constraints, resistance, and skills to interpret firm profiles and guide recommendations (Cassaro et al., 2024).
Configurational Logic of Combinations	Explains that outcomes may emerge from different combinations of conditions rather than from a single factor (Sycheva & Verdu-Jover, 2025).	Supports the need to jointly observe digitalization, innovation, and sustainability, as synergies and trade-offs depend on configurations (Sycheva & Verdu-Jover, 2025).	Justifies integrated measurement through an index and subsequent profile segmentation, capturing patterns of combinations across dimensions (Sycheva & Verdu-Jover, 2025).

Source: Prepared by the authors (2025)

3. Methodology

3.1 Empirical basis, data collection, and data systematization

The study adopted a quantitative approach, integrating different multivariate statistical methods to analyze organizational characteristics of Brazilian MSMEs that have undergone digital transformation. Initially, exploratory factor analysis (EFA) was applied to identify latent factors from the observed variables in the FAEDPYME survey database for the year 2022 (FAEDPYME, 2022). Subsequently, cluster analysis (CA) was employed to segment MSMEs into four distinct groups based on the extracted dimensions. To further deepen the understanding of the elements that differentiate each group, discriminant analysis (DA) was used. Based on the factors extracted through EFA, the Multidimensional Index of Digital Strategy, Innovation, and Sustainability (IMEDIS) was developed with the purpose of providing an integrated assessment of the level of strategic maturity, innovation, and environmental sustainability of the firms analyzed.

The 654 observations used in this article were drawn from the survey conducted by the Ibero-American Observatory of Micro, Small, and Medium-Sized Enterprises in Brazil, entitled "Digitalization and Sustainable Development of Brazilian and Ibero-American MSMEs in 2022." The data collection procedure employed non-probabilistic sampling, which limits the generalization of the results to the entire population of Brazilian MSMEs (FAEDPYME, 2024), as it excludes firms that have not adopted digitalization. This limitation arises from the study's focus on the strategies of companies that had already implemented digital transformation. Consequently, there is a bias resulting both from the non-random selection of the sample and from the restriction of the empirical universe to firms that had already adopted digital transformation.

The study adopts a cross-sectional data collection design, as this type of approach allows for the assessment of correlations among variables and offers advantages such as faster execution, lower cost, fewer losses, the possibility of direct observation of phenomena, and the use of a wide range of alternative methods for statistical data analysis (Zangirolami-Raimundo et al., 2018). The research relies on data systematization and the application of multivariate statistical methods to achieve its objectives and address the research problem (Creswell, 2021).

3.2 Data collection instrument and measurement of variables

Based on the questionnaire developed by FAEDPYME for the year 2022, the blocks of variables corresponding to the following constructs were selected: the importance of information and communication technologies (ICTs) for MSMEs; firms' digitalization strategies; barriers to the development of digitalization; environmental criteria; the performance indicator; and the construct related to innovations implemented over the last two years. The variables composing each of these constructs are listed in the Appendix. The selection of these constructs is grounded in the economic, social, and environmental dimensions of organizational sustainability and in their interface with digital transformation, which in turn feeds back into the adoption of sustainable practices (Philbin et al., 2022). Within this logic, organizational strategies guide the adoption of digital resources for innovation and sustainability.

The variables selected for the application of multivariate statistical techniques were those for which at least 50% of respondents provided valid answers. This criterion was adopted to preserve variable representativeness, reduce bias associated with high levels of missing data, and ensure the stability of the correlation matrix, thereby supporting the adequacy of the factor matrix. Variables with a low response rate tend to compromise factorability tests in exploratory factor analysis (EFA), such as the Kaiser-Meyer-Olkin (KMO) measure, communalities, and factor loadings. Accordingly, the following variables were excluded: conducting e-commerce through marketplaces, services to cover cybersecurity, data analytics and big data software, robotization and sensorization, and environmental certifications (e.g., ISO 14001/EMAS).

3.3 Integrated multivariate statistical procedures

The initial multivariate technique employed was exploratory factor analysis (EFA), with the aim of constructing a reduced set of latent variables representative of the research dataset. In this context, each factor reflects a distinct pattern of covariation among the variables and must be logically interpreted according to the level of correlation between each variable and the latent factor. To explain the structure of variance and covariance in the data, the principal components method was applied (Hair et al., 2009).

Six factors were retained, each presenting an eigenvalue greater than one. This criterion proved to be appropriate, as the extracted factors clearly express the dimensions used in the construction of the Multidimensional Index of Digital Strategy, Innovation, and Sustainability (IMEDIS), thereby ensuring the integration of these dimensions. The criterion of an eigenvalue greater than one was adopted because it is a commonly used and appropriate procedure for factor retention, in line with established practices in multivariate analyses.

The adequacy of EFA to the data was assessed using the following statistical indicators: the Kaiser-Meyer-Olkin (KMO) measure; Bartlett's test of sphericity, which tests the hypothesis that the correlation matrix is an identity matrix; factor loadings, which measure the association between each variable and the latent factor and should exceed 0.500; and communalities, which represent the proportion of variance shared by a variable with all other variables in the study and should also exceed 0.500. The number of extracted factors was defined by eigenvalues equal to or greater than one, explaining 61.07% of the total variance of the variance-covariance matrix. An orthogonal rotation of the factor matrix was performed using the Varimax rotation method.

Nevertheless, it is recommended that future studies apply confirmatory factor analysis (CFA), preferably using independent samples, in order to validate the factor structure identified through EFA.

After factor extraction and estimation of factor scores, it was possible to construct the Multidimensional Index of Digital Strategy, Innovation, and Sustainability (IMEDIS) based on the algebraic structure proposed by de Santana (2007). This approach allows for balancing the contribution of each factor to the measurement of a firm's IMEDIS. Otherwise, an index constructed as a simple average of factors would implicitly assume equal weights for all factors, whereas weighting factors by the proportion of total explained variance renders the index more representative of the integration among sustainability dimensions, digitalization strategies, and innovation. The index is formally defined in Equation (1).

$$IMEDIS_i = \sum_{i=1}^{K} \left(\frac{\theta_i}{\sum \theta} F_{ij} \right) \quad (1)$$

where θ_i = percentage of variance explained by factor i, K = number of factors chosen by factor i, and F_{ij} is the standardized factor score i, using the range method of MSME j.

IMEDIS is a continuous and standardized measure derived from the integration of digital practices, innovation, barriers, strategies, sustainability, and the performance of MSMEs. It can be used to diagnose, monitor, and inform public policy actions. As a synthetic (composite) index, it combines the dimensions under study and, from an analytical standpoint, outperforms simple indices calculated as arithmetic means. Its value captures the implicit effects of heterogeneity among MSMEs, rather than merely reflecting performance in a single dimension. By integrating these dimensions, the index accounts for their relative importance, and the resulting measure expresses the balance of forces among them. In this way, it represents a methodological advance in explanatory power grounded in theoretical support.

A sensitivity analysis was conducted to assess the robustness of IMEDIS. Figure 1 shows a strong correlation between the self-weighted simple index and the synthetic index weighted by explained variance, indicating that higher values of the simple index are associated with higher values of the synthetic index. The correlation coefficient is 0.945 and is statistically significant at the 1.0 percent level. In terms of means, the simple index averaged 0.626, whereas the synthetic index averaged 0.585. This difference suggests that weighting factors by their share of total explained variance adjusts the index value and enhances robustness by incorporating MSME heterogeneity. In this sense, the decision to weight by explained variance is appropriate and does not compromise the interpretation of the results.

Figure 1. Scatter plot of the values of the simple index and the synthetic index
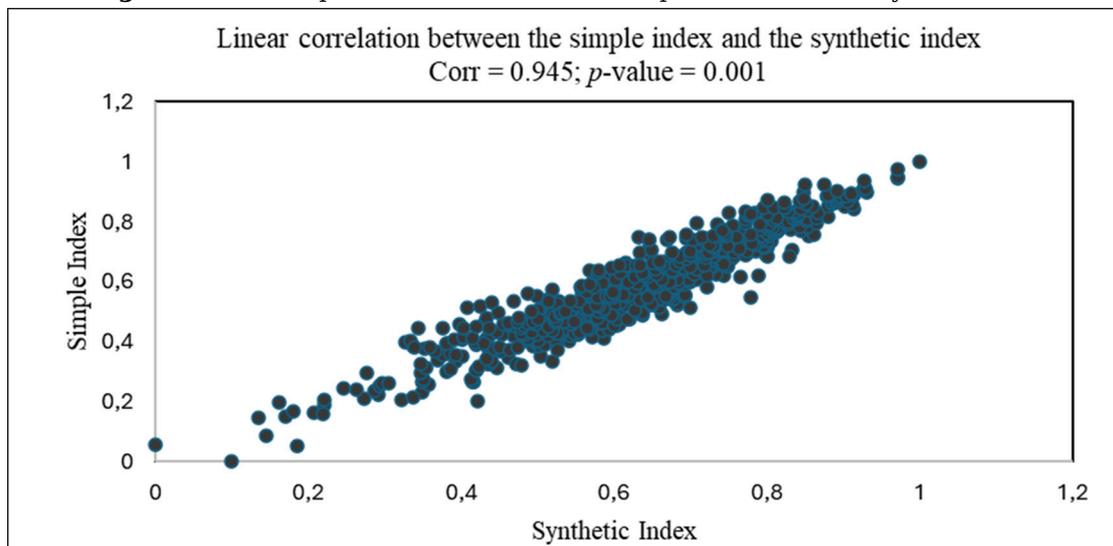
The factors generated by the exploratory factor analysis (EFA) were used to create four distinct groups through the application of cluster analysis using the non-hierarchical K-means method. Cluster labeling was based on the pattern of the mean factor scores within each cluster, thereby indicating the predominance of specific factors in each group of MSMEs. This method was chosen because it is more suitable for the objectives of the study than hierarchical clustering techniques and is compatible with the use of continuous factor scores. The number of clusters was determined based on the criteria of parsimony and interpretability, which allows each group to be classified according to the predominance of factors within each cluster.

To statistically validate the clusters, discriminant analysis was applied based on the latent factors obtained from the EFA (Hair et al., 2009). Discriminant analysis assesses the internal consistency of the typology to be created. It should be noted that this method does not have a causal explanatory purpose. To evaluate the significance of the discriminant functions, Wilks' lambda test was applied, in which values close to zero indicate strong discrimination, and vice versa. The discriminant functions were tested based on their eigenvalues, which indicate the relative importance of each discriminant function. The percentage of explained variance indicates how much of the variability among groups is explained by each discriminant function (Hair et al., 2009).

To assess the practical relevance of the proposed typology, the chi-square test of independence was applied to evaluate whether the size of the companies is similarly distributed among the clusters. The test is appropriate because it does not impose any causal relationship, is descriptive-inferential, and respects the exploratory nature of the research.

4. Results

4.1 Empirical findings

The latent variables obtained through EFA confirm the adequacy of the data for this method. The KMO measure is 0.806, and Bartlett's test of sphericity yields a test statistic of approximately 2,711.01, statistically significant at less than the 1.0 percent level. The anti-image matrix indicates that the selected variables are suitable for EFA, with off-diagonal values approaching zero, suggesting the absence of multicollinearity among the variables. The communalities for all variables exceed 0.500, indicating that more than half of the variance of each variable is explained by the model. Finally, the six factors extracted through EFA account for 61.07 percent of the total variance in the dataset.

Table 2 summarizes the internal correlations among the items comprising each latent factor and identifies the variables within each construct that exhibit strong correlations. This supports the use of these variables to represent the factors extracted through EFA and reinforces the robustness of the multivariate approach.

Table 2. Level of reliability of the factors according to Cronbach's Alpha test

Factor	Cronbach's Alpha
Automation and Digital Transformation Strategies	0.910
Efficiency in the Use of Renewable Resources	0.900
Commercial and Profitable Performance of the Company	0.820
Technological Innovation: Products and Processes	0.832
Barriers to Digital Innovation	0.721
Digital Maturity	0.657

Table 3 summarizes the factor loadings obtained from the EFA and allows for the identification of the degree of association between the variables and each factor. The results indicate that the variables reflect the constructs defined by the FAEDPYME research, albeit in a more reduced form. This finding is further corroborated by the results of Cronbach's alpha, which confirm the internal consistency of the constructs.

Table 3. Rotated component matrix

Variables	Factors						Communality
	F1	**F2**	**F3**	**F4**	**F5**	**F6**	
EST6	**0.816**	0.040	0.110	0.068	0.057	-0.018	0.688
EST5	**0.794**	0.045	0.100	0.090	0.033	0.083	0.659
EST7	**0.794**	0.053	0.132	0.077	0.123	0.044	0.674
EST3	**0.782**	0.025	0.066	0.108	0.090	0.121	0.638
EST4	**0.777**	0.022	0.125	0.073	-0.016	0.111	0.650
EST8	**0.765**	0.078	0.147	0.068	0.124	0.027	0.634
EST2	**0.754**	0.015	0.089	0.108	0.147	0.088	0.618
AMB5	0.065	**0.813**	0.062	0.130	0.017	-0.075	0.692
AMB4	0.070	**0.801**	0.103	0.120	0.089	-0.047	0.654
AMB3	0.016	**0.787**	0.086	0.091	0.049	0.131	0.681
AMB6	0.111	**0.730**	0.062	0.148	0.038	0.001	0.573
AMB2	-0.020	**0.709**	0.037	0.087	-0.019	0.218	0.561
AMB1	0.006	**0.709**	0.075	0.125	0.068	0.162	0.555
DES3	0.065	0.047	**0.759**	0.110	0.073	0.134	0.511
DES6	0.180	0.126	**0.739**	0.056	-0.042	-0.086	0.514
DES2	0.195	0.087	**0.736**	0.173	-0.019	0.006	0.618
DES5	0.154	0.046	**0.725**	0.145	-0.032	-0.069	0.618
DES1	0.079	0.094	**0.723**	0.166	0.058	0.161	0.607
INOV1	0.051	0.168	0.135	**0.770**	0.036	0.196	0.595
INOV3	0.166	0.134	0.192	**0.747**	-0.003	0.020	0.578
INOV2	0.079	0.101	0.030	**0.707**	0.047	0.281	0.681
INOV7	0.186	0.150	0.157	**0.685**	0.066	-0.154	0.641
INOV6	0.073	0.206	0.227	**0.648**	0.104	-0.157	0.599
BARR3	0.141	-0.024	0.005	0.053	**0.766**	0.074	0.579
BARR2	0.070	0.017	-0.035	0.091	**0.748**	0.097	0.554
BARR8	0.060	0.062	0.040	-0.009	**0.708**	0.034	0.583
BARR5	0.125	0.131	0.017	0.047	**0.686**	-0.085	0.615
TEC2	0.107	0.130	0.075	0.061	0.030	**0.745**	0.594
TEC1	0.261	0.159	0.022	0.049	0.091	**0.667**	0.549
% variance	15.94	12.74	10.26	9.62	7.72	4.78	
Cumulative variance	15.94	28.68	38.94	48.56	56.28	61.07	

KMO = 0.806; Bartlett's test = 2711; p < .001

The results of applying cluster analysis to the factor scores (Table 3), using the *K*-means method, are summarized in Table 4 and show the creation of four groups with distinct profiles of MSMEs. This number of clusters is adequate considering the interest in segregating the largest possible number of groups.

Table 4. Profiles based on the averages of the factor scores in each cluster

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Case number	138	132	230	154
%	21.1	20.18	35.17	23.55
Automation and Digital Transformation Strategies	-1.16	0.20	0.67	-0.13
Efficiency in the Use of Renewable Resources	0.25	-0.05	0.01	-0.19
Commercial and Profitable Performance of the Company	-0.43	-0.61	0.30	0.46
Technological Innovation: Products and Processes	0.24	-1.17	0.24	0.41
Barriers to Digital Innovation	0.55	-0.28	0.59	-1.14
Digital Maturity	0.14	-0.44	0.11	0.08

Discriminant analysis (DA) was used to statistically validate the obtained clusters, since the method identifies the factors that best discriminate the groups (Hair et al., 2009), which reinforces the quality of the typology constructed from the cluster analysis (CA). The Wilks' lambda test value = 0.100 (χ^2 = 1490.522, df = 18, p < 0.001) confirms the statistical significance of the three functions and shows that the factors obtained in the EFA are able to adequately distinguish the four clusters. The classification matrix of cases within the clusters shows that 93.7% of cases were classified into their original clusters. This indicates that the DA had high predictive power, with Clusters 3 (Intermediate) and 4 (High Maturity) showing the highest percentage of appropriate allocations, at 98.3% and 94.8%, respectively, while Clusters 1 (Low Maturity) and 2 (Emerging) reached 92.8% and 85.6%. These results demonstrate the consistency of the integrated statistical model and the ability of the factors to discriminate the organizational profiles of Brazilian MSMEs, thus validating the segregation.

4.2 Interpretation of results

After obtaining the factor loadings, the factors were interpreted by examining the correlation patterns between the variables and each factor, considering loadings equal to or greater than 0.600 as indicative of moderate to strong associations. The classifications were made in accordance with Table 1, which presents the analysis categories. In this process, only correlations with an intensity of at least 0.600 were retained, reflecting an intermediate to strong level of association. The interpretation adopts an exploratory perspective consistent with the assumptions and limitations of exploratory factor analysis (EFA).

Factor 1 explains 15.96 percent of the total variance according to the EFA and shows strong correlations with variables related to digitalization strategies, such as process automation and the use of digital technologies. Based on these associations, Factor 1 was labeled Automation and Digital Transformation Strategies. This factor reflects the coexistence of practices related to digital infrastructure and process automation in MSMEs, without implying causal relationships or any form of strategic intentionality.

Factor 2 explains 12.74 percent of the total variance and exhibits strong correlations with variables related to water and energy management. It was labeled Efficiency in the Use of Renewable Resources. This factor captures a pattern of association among environmental management practices adopted by MSMEs, particularly those aimed at improving efficiency in the use of natural resources.

Factor 3 was labeled Profitable Commercial Performance and reflects the association between the use of operational digital tools and performance indicators (Bouwman et al., 2019).

Factor 4 explains 9.62 percent of the total variance and is correlated with variables related to product and process improvements, as well as the launch of new products. It was labeled Technological Innovation in Products and Processes, representing the grouping of innovation-related activities rather than the confirmation of consolidated innovative outcomes.

Factor 5 explains 7.72 percent of the variance and is associated with variables indicating financial, cultural, and organizational constraints. It was labeled Barriers to Digital Innovation and reflects the concentration of obstacles to the digital and technological advancement of MSMEs.

Factor 6 explains 4.78 percent of the total variance and correlates with variables related to the presence of proprietary websites and sales through e-commerce. It was labeled Digital Maturity, representing a higher level of digital presence among MSMEs, without implying strategic sophistication or direct effects on performance.

Regarding the cluster profiles based on the average factor scores for each group, Table 4 shows that Cluster 1 comprises 21.10 percent of the sample and is characterized by a low level of digital strategy and severe barriers to digital innovation. It was classified as MSMEs in transition, with low levels of digitization and significant barriers to innovation, reflecting low digital maturity.

Cluster 2 represents 20.18 percent of the surveyed MSMEs and is characterized by limited technological innovation in products and processes, low performance, and low levels of automation and digital transformation strategies. These characteristics led to its classification as emerging MSMEs in innovation and digitization processes.

Cluster 3 includes 35.17 percent of the sample and is characterized by a high level of automation and digital transformation strategies, moderate performance, and substantial barriers to innovation and digital performance. Accordingly, this cluster was classified as MSMEs with strong adoption of digitization strategies and moderate performance and innovation, but facing intermediate barriers to innovation.

Cluster 4 comprises 23.55 percent of the surveyed MSMEs and is characterized by relatively few barriers to digital innovation, strong commercial performance, a solid level of technological innovation in products and processes, and low resistance to the adoption of digitization and automation strategies. This cluster was therefore classified as efficient and innovative MSMEs with low resistance to digital transformation, reflecting high digital maturity.

The Multidimensional Index of Digital Strategy, Innovation, and Sustainability (IMEDIS) was calculated according to Equation 1 presented in the methodology section. The index was standardized using the range method (Fávero et al., 2009) and stratified into four bands based on IMEDIS values, as summarized in Table 5.

Table 5. Classification of strata based on IMEDIS

Classification	n	M	SD	Minimum	Maximum
High maturity	164	0.795	0.064	0.710	1.000
Intermediate	165	0.647	0.035	0.589	0.709
Emerging	161	0.529	0.035	0.469	0.587
Low maturity	164	0.370	0.097	0.000	0.468

Based on Table 5, there is a relatively balanced distribution of MSMEs across strata. The low- and high-maturity strata present the highest standard deviations, indicating greater heterogeneity among firms within these groups.

In the high-maturity stratum (0.795 ± 0.064), firms have not only adopted digitization but have also consolidated innovation and sustainability practices. These companies appear to have developed sufficient capabilities to leverage technological implementation effectively, which ultimately contributes to improved performance (Proksch et al., 2024).

Companies classified in the intermediate stratum (0.647 ± 0.035) are in transition and have implemented specific initiatives related to digital transformation, innovation, and sustainability. However, this alignment remains partial, limiting their ability to fully exploit the benefits of digital technologies and to translate them into continuous improvements in products, services, and processes (Gyamerah et al., 2025).

In the emerging stratum (0.529 ± 0.035), MSMEs are at an early stage of digitization, with relatively low strategic effectiveness. This situation is largely associated with financial and technological constraints, as well as limited human capital capable of enhancing process productivity (Agostini et al., 2019; Ortiz García de las Bayonas et al., 2023).

The low-maturity stratum (0.370 ± 0.097) comprises MSMEs that remain largely disconnected from digital processes and show limited engagement in digitization, innovation, and sustainability strategies. The relatively high standard deviation indicates the coexistence of firms that are substantially lagging behind and others with some potential to adopt digital technologies.

Figure 2 indicates that Clusters 1 and 2 are predominantly composed of low-maturity firms. This reflects the near absence of structured digital transformation and innovation processes, particularly in Cluster 2. Cluster 1, with a predominance of emerging firms, includes MSMEs characterized by limited digitization and significant barriers to innovation, largely stemming from financial constraints, restricted access to credit, and limited investment in technological infrastructure and workforce training (Pelletier & Raymond, 2020).

Figure 2. Distribution of maturity types according to IMEDIS by MSME clusters
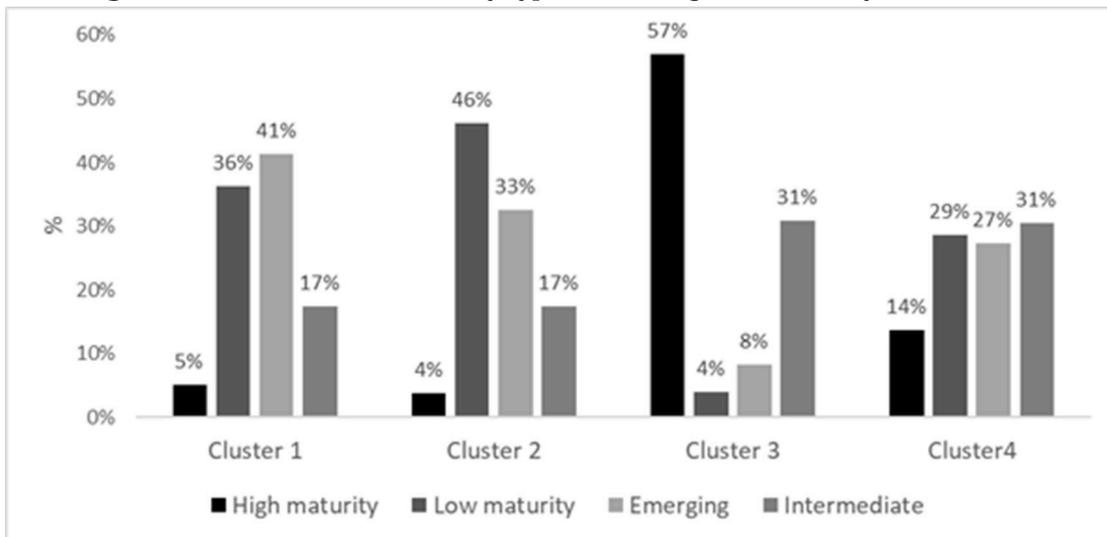
Cluster 3 comprises the highest proportion of firms classified in the high- and intermediate-maturity strata. It is characterized by strong adoption of digitization strategies, while still facing barriers to innovation in products and processes. This configuration is reflected in the moderate performance observed among firms in this cluster (Nunes et al., 2024).

In Cluster 4, the distribution of MSMEs across maturity strata is relatively uniform according to the IMEDIS classification, with the exception of the high-maturity stratum. This cluster groups firms characterized by low resistance to digital transformation, active innovation strategies, and relatively few barriers to the adoption of digitization.

The results indicate no statistically significant association between company size and cluster membership, suggesting that the identified profiles are not determined by firm size but rather by patterns related to digitalization, innovation, and sustainability. With regard to the region and sector variables, additional analyses were not conducted due to the highly asymmetrical distribution of these categories in the sample, which would compromise the statistical validity and interpretation of contingency table tests. This limitation is acknowledged and discussed as a constraint of the empirical data used in the study.

5. Discussion and conclusions

5.1 Main findings

This study developed and validated an integrated multivariate statistical model to examine the relationship between digital transformation, innovation, and sustainability in 654 Brazilian micro, small, and medium-sized enterprises (MSMEs), resulting in the construction of the Multidimensional Index of Digital Strategy, Innovation, and Sustainability (IMEDIS). Through exploratory factor analysis (EFA), six latent factors were identified: Automation and Digital Transformation Strategies; Efficiency in the Use of Renewable Resources; Commercial Performance; Technological Innovation in Products and Processes; Barriers to Digital Innovation; and Digital Maturity. Together, these factors explain 61.07 percent of the total variance in the data.

Cluster analysis identified four distinct groups of firms, reflecting different patterns of digital maturity, innovation, and sustainability. Based on weighted factor scores, a maturity typology was established, comprising four strata: low, emerging, intermediate, and high digital maturity. Discriminant analysis confirmed the strong predictive capacity of the model (Wilks' $\lambda = 0.10$), with 93.7 percent of cases correctly classified. These findings indicate that digital strategies, technological innovation, economic performance, and barriers to innovation are the primary discriminating elements among clusters and underscore the structural heterogeneity of Brazilian MSMEs in their digital and sustainable transition processes.

5.2 Theoretical implications

From a theoretical perspective, the findings advance the literature on digital maturity, innovation, and sustainability by empirically demonstrating that these processes do not evolve in a linear or homogeneous manner across MSMEs. The study reinforces approaches grounded in dynamic capabilities and absorptive capacity, showing that digitalization alone is insufficient to generate sustainable performance. IMEDIS contributes to recent debates by demonstrating that differences in maturity levels are associated with

organizational factors, structural barriers, technological absorptive capacity, and differentiated adoption of sustainable practices. In this sense, the index offers a theoretical contribution by integrating, within a single metric, dimensions that are traditionally examined in a fragmented manner.

Furthermore, the findings indicate that firms with similar structural characteristics may exhibit different degrees of internalization of innovation and sustainability practices, highlighting the mediating role of organizational culture and adaptive capacity in the relationship between strategy, digitalization, and performance.

5.3 Practical and policy implications

From a practical standpoint, IMEDIS emerges as a diagnostic, monitoring, and evaluation tool within the public policy cycle targeting MSMEs. The maturity typology enables differentiated policy design tailored to the specific needs of each stratum. For low-maturity firms, policies should prioritize the development of technological human capital, expansion of digital connectivity, improved access to credit for basic infrastructure, and mentoring programs. In the emerging stratum, actions focused on managerial training in data analytics, access to management software, and participation in technological networks are essential. Firms with intermediate maturity require incentives for the adoption of ESG practices, improvements in energy efficiency, and the transition toward more resilient and sustainable business models. High-maturity firms, in turn, require policies centered on research, development, and innovation (R&D&i), internationalization, and advanced digitalization, including Internet of Things (IoT), big data analytics, and intelligent automation. These guidelines complement existing Brazilian programs, such as SinDigital, BMP, and PADIS, contributing to more efficient allocation of subsidies, enhanced systemic impact, and reduced policy fragmentation.

5.4 Study limitations

Despite its statistical robustness and methodological consistency, the study has limitations. The sample is non-probabilistic and cross-sectional, which constrains causal inference and limits the generalizability of the findings. The data are self-reported and therefore subject to potential social desirability bias. Moreover, the exclusion of variables with high non-response rates may have reduced the ability to capture relevant nuances in MSMEs' digital and sustainable transformation processes.

5.5 Directions for future research

Future research should employ longitudinal designs to track the evolution of IMEDIS over time and apply structural equation modeling to provide confirmatory validation of the proposed model. The inclusion of indicators related to the circular economy, governance, social capital, and organizational resilience is also recommended, as is the replication of the index in other Ibero-American countries for comparative analysis. Mixed-methods approaches combining quantitative and qualitative techniques may further deepen understanding of the mechanisms linking digitalization, innovation, and sustainability to organizational performance.

In summary, by integrating multivariate statistical techniques into a single composite index, this study offers a meaningful theoretical and methodological contribution as well as a scalable practical tool. IMEDIS connects digital transformation, innovation, and sustainability to evidence-based managerial and public policy decisions, contributing to the development of a more competitive, resilient, and sustainability-oriented MSME ecosystem aligned with the Sustainable Development Goals (SDGs).

Acknowledgments

Data Availability Statement

The research data is available, and those interested should request it via email from the corresponding author at the journal.

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Appendix A Items composing the constructs

Table A1. Items composing the importance of information and communication technologies (ICTs) for MSMEs

Variable	Item
TEC1	We sell through our own e-commerce portal (via the Internet)
TEC2	Use of social media for commercial purposes
TEC4	Teleworking (home office)
TEC6	ERP systems (integrated management systems)
TEC7	Location technologies, Internet of Things (IoT)
TEC12	We sell through our own e-commerce portal (via the Internet)

Source: Adapted from Andrade et al. (2022), Colim et al. (2021), Khin and Ho (2019), Pinochet et al. (2021) and Subramaniam et al. (2021)
Prepared by the authors based on the FAEDPYME database (2022)

Table A2. Items composing the construct "digitalization strategies of MSMEs"

Variable	Item
EST1	We allocate significant resources to digitalize the business
EST2	The business model is assessed and updated in terms of digitalization
EST3	Our employees are prepared for the company's digital development
EST4	Our managers have good training in digitalization
EST5	The level of process automation in my company is high
EST6	We use digitalization in the company's organizational management
EST7	In our company, training for digital transformation is carried out on a regular basis
EST8	We allocate significant resources to digitalize the business

Source: Adapted from Carrasco-Carvajal et al. (2023) and Heredia et al. (2022)
Prepared by the authors based on the FAEDPYME database (2022)

Table A3. Items composing the construct "barriers to the development of digitalization in MSMEs"

Variable	Item
BARR1	Insufficient broadband connection
BARR2	Lack of financial resources in the company
BARR3	High investment costs
BARR4	Digitalization may be poorly received by employees
BARR5	Lack of well-qualified personnel who are difficult to find and retain
BARR6	Lack of knowledge about technology providers
BARR7	Information technology security requirements (cybersecurity)
BARR8	Lack of business culture to promote (stimulate) digital transformation

Source: Adapted from Bertolami et al. (2018), Savchenko (2023), and Siebel (2019)
Prepared by the authors based on the FAEDPYME database (2022)

Table A4. Items composing the construct "environmental criteria used by MSMEs"

Variable	Item
AMB1	Environmental criteria for supplier selection
AMB2	Environmental criteria for the management of plastic packaging and derivatives
AMB3	Environmental criteria for process design
AMB4	Environmental criteria for energy management in the company
AMB5	Environmental criteria for water management in the company
AMB6	Environmental criteria for waste management

Source: Adapted from Agência CanalEnergia (2023) and Dey, Malesios, Chowdhury, et al. (2022)
Prepared by the authors based on the FAEDPYME database (2022)

Table A5. Items composing the construct "MSME performance indicator"

Variable	Item
DES1	Quality of products
DES2	Efficiency of production processes
DES3	Customer satisfaction
DES4	Speed of adaptation to market changes
DES5	Rapid sales growth
DES6	Profitability
DES7	Employee satisfaction
DES8	Level of absenteeism at work

Source: Adapted from Helmold and Samara (2019), Mehralian et al. (2018), and Salimi and Rezaei (2018)
Prepared by the authors based on the FAEDPYME database (2022)

Table A6. Items Composing the Construct "innovations implemented by MSMEs over the last two years"

Variable	Item
INOV1	Changes or improvements in existing products/services
INOV2	Launch of new products/services to the market
INOV3	Changes or improvements in production processes
INOV4	Acquisition of new capital goods
INOV5	New changes or improvements in organization and/or management
INOV6	New changes or improvements in the purchase and/or acquisition of inputs
INOV7	New changes or improvements in the company's commercial and/or sales activities

Source: Adapted from Abad-Segura et al. (2020), Gomez-Trujillo and Gonzalez-Perez (2022), Martínez-Peláez et al. (2023), Mhlanga (2020), and Wang et al. (2022)
Prepared by the authors based on the FAEDPYME database (2022)