Driving SME Digital Transformation in Colombia: Analyzing Key Factors and Sustainable Development Goals (SDGs) Impact

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Abstract

This study identifies key factors influencing digitalization investment decisions in Colombian SMEs and their alignment with Sustainable Development Goals (SDGs). Analyzing 4,600 surveys from 2023, we employed multilayer perceptron Artificial Neural Networks with backpropagation algorithms for predictive modeling, supported by validation through confusion matrices and ROC curves (average AUC: 0.94). Results revealed the most significant predictors: understanding digitalization's possibilities and advantages (20.87%), employees using ICT (14.77%), average workforce size (10.68%), and e-commerce marketplace participation (7.32%). The study's originality lies in precisely quantifying each factor's relative importance, providing an empirical foundation for prioritizing digitalization initiatives, and analyzing strategic alignment with SDGs, particularly SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production). These methodologically robust findings offer valuable guidance for policymaking, business strategies, and interdisciplinary theoretical frameworks promoting sustainable digital transformation of Colombian SMEs within broader socioeconomic contexts, while addressing critical technological adoption barriers, enhancing regional competitive advantage, and establishing comprehensive implementation pathways for digital ecosystem development. These insights directly inform practical digitalization policies for SMEs by providing evidence-based prioritization of educational initiatives over direct technology investments, with significant implications for sustainable development and competitive advantage in emerging economies.

Keywords: digitalization, SMEs, Artificial Neural Networks, Sustainable Development Goals, e-commerce, digital investment.

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1. Introduction

Methodologies aimed at improving business processes and services, combined with the importance of data in the burgeoning Industry 4.0, position Big Data as a pivotal trend that opens new avenues for understanding and decision-making (Puyol, 2014). Recent studies underscore the critical role of data in modern business competition. The swift transition from analog to digital has facilitated self-managing processes that expand access to information, thereby transforming fields such as economics, law, and administration (Becerra *et al.*, 2018; Frau *et al.*, 2022). For instance, in the financial sector, the adoption of management practices significantly impacts the financial performance of Mexican microenterprises (Díaz *et al.*, 2019). In Colombia, identifying the main determinants of SMEs' financial performance provides vital information for formulating strategies, programs, and public policies aimed at optimizing the performance of this segment (Silva *et al.*, 2020).

Despite the recognized importance of digitalization, SMEs in Colombia face significant adoption challenges. According to extensive survey data covering nearly 87,000 small businesses across agriculture, manufacturing, commerce, and services sectors, only 27% of Colombian SMEs have adopted information and communication technologies (ICTs), specifically internet use in their business operations (Duran & Castillo, 2023). This low adoption rate indicates that a substantial majority of SMEs have yet to integrate digital technologies into their routine business activities. This lag is particularly concerning given that digitalization has been identified as a critical driver for competitiveness, especially in developing economies where traditional competitive advantages may be eroding (Duran & Castillo, 2023; Bhuiyan *et al.*, 2024). The technological infrastructure available for digital transformation in Colombia, while improving, remains a constraint—the national internet penetration rate, despite increasing from 7.3% in 2010 to 32.8% by 2017, still indicates substantial room for growth (Valdés *et al.*, 2019).

The digitalization of SMEs is also aligned with several Sustainable Development Goals (SDGs), which aim for a more sustainable and equitable future. Digitalization investment can significantly contribute to the following SDGs: (1) SDG 8: Decent Work and Economic Growth: Digitalization can increase the productivity and efficiency of SMEs, promoting economic growth and the creation of decent jobs (Stephenson *et al.*, 2021; Teng *et al.*, 2022). (2) SDG 9: Industry, Innovation, and Infrastructure: The adoption of digital technologies facilitates innovation and enhances the infrastructure of SMEs, which is crucial for industrial development (Mia *et al.*, 2024; Sharabati

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et al., 2024). (3) SDG 12: Responsible Consumption and Production: Digital technologies can help SMEs optimize their processes, reduce waste, and promote more sustainable practices (Philbin *et al*., 2022; Duran & Castillo, 2023). Integrating the SDGs into the analysis of SME digitalization investment emphasizes the relevance of digital transformation not only as a business strategy but also as a significant contribution towards sustainable and equitable development.

Multiple tools for information analysis have been developed, facilitating predictive, descriptive, and classificatory analyses. Descriptive analysis involves selecting criteria or factors to classify variables based on their impact on a specific event. This study focuses on factors influencing investment in the digitalization of SMEs in Colombia.

For descriptive analysis in factor selection, a range of techniques and methodologies is available, including probabilistic methods, evolutionary algorithms, and Artificial Neural Networks (ANN). This study employs ANN due to their capacity and precision for pattern classification, planning, prediction, control, and optimization, thanks to their non-linear and non-parametric adaptive learning properties (Salcedo *et al.*, 2017; Wang *et al.*, 2018; Gutiérrez *et al.*, 2021). Moreover, a new computational paradigm allows solving a wide range of statistical problems using non-linear mathematical models with minimal structure and model assumptions. An ANN "learns" the relationships between dependent and independent variables during the process, offering a flexible approach that does not require predefined hypotheses about these relationships.

While the existing literature provides a broad overview of the factors influencing SME digitalization (Tarutė *et al*., 2018; Clemente-Almendros *et al*., 2024), a clear research gap remains, which this study aims to address. Firstly, many studies identify these drivers qualitatively or through traditional linear models. A clear gap exists in quantifying the precise relative importance of each factor using advanced non-linear techniques like ANNs. This method is particularly suitable as it can model complex relationships without prior assumptions about the data distribution, a recognized advantage for multifaceted business phenomena (Salcedo *et al*., 2017; Wang *et al*., 2018).

Secondly, while general determinants are known from international studies, there is a specific need for empirical research focusing on the unique socioeconomic context of Colombian SMEs. While some foundational work exists (e.g., Silva *et al*., 2020), a granular, quantitative ranking of digitalization drivers in this specific region is missing. Finally, there is a significant opportunity, largely unaddressed in literature, to explicitly and quantitatively link these drivers of digitalization to specific Sustainable Development Goals (SDGs). This study addresses these gaps by applying an ANN model to a large dataset of Colombian SMEs to quantify the key drivers of digitalization and analyze their alignment with SDGs 8, 9, and 12.

This study is expected to contribute to the field in several ways. First, through the precise quantification of determinants in digitization processes of Colombian SMEs, providing a granular understanding of factor importance that has been identified as a critical research need (Gašperlin *et al*., 2021; Lokuge & Duan, 2023). Second, by establishing an explicit linkage between these factors and the Sustainable Development Goals (specifically SDGs 8, 9, and 12), addressing the need for research connecting digital transformation to sustainable development outcomes (Philbin *et al*., 2022). Third, through the application of ANN to model complex nonlinear relationships between organizational, socioeconomic, and technological variables, providing a methodologically robust empirical foundation for the formulation of business strategies and public policies aimed at sustainable digital transformation. This study aims to answer the following research questions: (1) What is the relative importance of internal versus external factors in SME digitalization investment decisions in Colombia? (2) How do factors related to digital knowledge and skills compare to infrastructural or market-related factors in predicting digitalization investment? and (3) How can the identified key drivers of digitalization be aligned with and contribute to specific SDGs?

The remainder of this paper is structured as follows: Section 2 presents a literature review on the determinants of SME digitalization, organized by internal and external factors, and their relationship to sustainable development. Section 3 describes the materials and methods employed, including data collection, preprocessing techniques, and the ANN modeling approach. Section 4 presents the results and provides a comprehensive discussion of the findings in the context of existing literature. Finally, Section 5 concludes with a summary of key findings, limitations, and suggestions for future research directions.

2. Literature review

In the rapidly evolving landscape of SMEs, digitalization has become a crucial factor for competitiveness and growth. However, the decision to invest in digital technologies is influenced by a complex interplay of factors, both internal to the organization and external in its environment (Tarutė *et al*., 2018; Ta & Lin, 2023; Clemente-Almendros *et al*., 2024; Packmohr *et al.*, 2024). This literature review organizes these factors into two main categories: internal organizational factors and external environmental factors, providing a comprehensive framework for understanding the determinants of SME digitalization investment decisions.

2.1 Internal organizational factors

Organizational characteristics play a significant role in shaping digitalization investments. Company size, often measured by the number of employees, can be a determining factor, as larger firms typically have more resources at their disposal to allocate towards technological advancements (Caputo *et al*., 2019; Packmohr *et al*., 2024). The industry sector in which an SME operates also impacts its digitalization needs, with some sectors, such as technology-intensive industries, requiring more substantial investments to maintain a competitive edge. Management commitment and leadership emerge as critical internal factors, with research indicating that managers and organizational leaders significantly influence the success or failure of digital transformation projects in SMEs (Anggraini & Pranggono, 2022). Organizational readiness represents another fundamental internal factor, encompassing infrastructure, financial health, and management

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commitment (Sharabati *et al*., 2024). A comprehensive assessment by Okfalisa *et al.* (2021) revealed that transaction preparedness—including cultural, educational, financial, and technological infrastructure components—constitutes the principal element in determining SMEs' readiness for digital revolution, with a vector value of 0.30. This suggests that SMEs must evaluate their internal capabilities across multiple dimensions before embarking on digitalization initiatives.

SMEs' self-knowledge and understanding of their capabilities represents another key internal factor. Digital transformation demands a comprehensive change in business philosophy, strategy, organization, and operations, requiring overall planning and clear objectives. Many SMEs, despite having strong desires for digital transformation, lack adequate knowledge about themselves and face challenges in technology application, business capacity building, and talent development (Teng *et al*., 2022; Alam *et al.*, 2022). To address these internal factors systematically, researchers have developed dynamic models that support management in strategic, digital, and organizational developments (Sándor & Gubán, 2021). These models incorporate both IT and organizational dimensions, including multiple components and subcomponents that address the complex nature of digital transformation in SMEs.

The availability of both financial and human resources is crucial for digitalization, as it often requires not only monetary investment but also the acquisition or development of specialized skills within the workforce (Rupeika-Apoga & Petrovska, 2022; Omrani *et al*., 2022; Dörr *et al*., 2023). The relationship between digitalization and human resources is bidirectional. While the existing skills and attitudes of employees influence digitalization decisions, the adoption of digital technologies also shapes the educational and professional development needs within SMEs (Omrani *et al*., 2022; Dörr *et al*., 2023: Plečko *et al*., 2023). Managers are increasingly challenged to develop models that balance investments in digital technologies with strategies for employee engagement, taking into account individual personalities, educational backgrounds, and cognitive domains (Caputo *et al*., 2019).

2.2 External environmental factors

Beyond internal organizational dynamics, SMEs' digitalization investment decisions are heavily influenced by a range of external factors operating in their business environment (Chatterjee *et al*., 2022). Market dynamics, particularly the level of competition, can drive SMEs to invest in digital technologies as a means of differentiation and efficiency improvement (Fareri *et al*., 2019). Regulatory frameworks stand as one of the most critical external considerations, with research identifying data security regulations, data privacy regulations, and copyright laws that protect intellectual property as the top three elements investors care about when considering investments in digital firms (Stephenson *et al*., 2021). This regulatory landscape significantly impacts SMEs' willingness and ability to engage in digital transformation initiatives.

The stability of the digital transformation strategy (DTS) at the national level plays a significant role in digitalization investment. Countries with stable and progressive governments are more likely to prioritize investment in digital infrastructure and internet access, creating favorable conditions for SMEs' digital transformation (Mia *et al*., 2024). Conversely, corruption acts as a major impediment to digitalization, deterring investors from contributing to digital infrastructure development in highly corrupt countries.

Geographic considerations also come into play. SMEs located in urban areas may have greater access to technological resources and be more exposed to digital trends, potentially accelerating their digitalization efforts (Huang *et al*., 2023; Holl & Rama, 2024). The size of the population in an SME's area of influence can affect the perceived need for digitalization, with larger markets potentially offering more opportunities for digitally-enabled growth. Additionally, the average income in the region can impact an SME's willingness to invest in technology, as higher-income areas may demand more sophisticated digital offerings from businesses (Thomä, 2023).

SMEs also face various external barriers that hinder digital adoption. These include resistance from other stakeholders, lack of standard architecture, limited internet access, contractual issues, privacy and security concerns, and regulatory underdevelopment (Philbin *et al*., 2022). These external barriers can significantly impact the relationship between digitalization and firm performance, particularly regarding supply chain competency and operational efficiency.

As SMEs navigate the digital transformation era, it becomes evident that successful digitalization is not merely about implementing new technologies. It requires a holistic approach that considers the integration of existing skills into evolving professional profiles while also fostering the development of new competencies (Fareri *et al*., 2019). This dynamic process of skill adaptation and development is essential for SMEs to effectively manage and leverage digital trends in their respective markets (Rusly *et al*., 2021; Omrani *et al*., 2022; Ta & Lin, 2023).

According to the above, the determinants of SME digitalization investment are multifaceted, encompassing organizational, market-related, and socio-demographic factors. By understanding and addressing these various influences, SMEs can make more informed decisions about their digital investments, ensuring that they are maximizing available resources and positioning themselves for success in an increasingly digital business environment. The empirical analysis in this study aims to quantify the relative importance of these factors specifically in the Colombian context, providing valuable insights for both practitioners and policymakers to develop targeted strategies for enhancing SME digitalization.

3. Material and methods

This section details the methodological framework used to identify and quantify the factors influencing digitalization adoption in Colombian SMEs. In the first subsection, details on the population, sampling and data collection process of the study are presented. Then, in the second subsection, the dependent variable and the independent variables proposed for the study are highlighted. Finally, the third subsection presents the data analysis process, and the predictive model applied.

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3.1 Population, sample, and data collection

The data for this study was collected through an online survey conducted during the first semester of 2023. The survey was specifically designed to target SME managers and owners in Colombia. The distribution was carried out in collaboration with the Ibero-American Network for SME Strategic Analysis (FAEDPYME), a reputable academic network that facilitates access to a broad and diverse population of companies.

The initial dataset comprised 4,600 surveys. After applying a listwise deletion method to handle cases with missing data, the final valid sample for analysis consisted of 4,573 firms. This substantial sample size provides a solid foundation for the statistical analyses performed. A brief characterization of the sample is presented in Tables 1, 2 and 3, showing a diverse representation of firms across different sectors, sizes, and ages, which enhances the generalizability of the findings.

Table 1. Descriptive statistics of the sample by sector.

Sector		Frequency	Percentage	Valid percentage	Cumulative percentage
Valid	Industry	1435	31,4	31,4	33,1
	Construction	278	6,1	6,1	39,2
	Commerce	569	12,4	12,4	51,6
	Services	1617	35,4	35,4	87,0
	Other	595	13,0	13,0	100,0
	Missing	79	1,7	1,7	1,7
	Total	4573	100,0	100,0	

Source: Own elaboration using SPSS.

Table 2. Descriptive statistics of the sample by size.

Size		Frequency	Percentage	Valid percentage	Cumulative percentage
Valid	Microenterprise	2276	49,8	50,5	50,5
	Small Enterprise	1351	29,5	30,0	80,5
	Medium Enterprise	881	19,3	19,5	100,0
	Total	4508	98,6	100,0	
	Missing	65	1,4		
Total		4573	100,0		

Source: Own elaboration using SPSS.

Table 3. Descriptive statistics of the sample by age.

Age		Frequency	Percentage	Valid percentage	Cumulative percentage
Valid	Young	2753	60,2	60,6	60,6
	Mature	1790	39,1	39,4	100,0
	Total	4543	99,3	100,0	
	Missing	30	0,7		
Total		4573	100,0		

Source: Own elaboration using SPSS.

3.2 Variables under study

The dependent variable for this study is Digitalization Adoption. It is defined as a binary categorical construct representing whether a company exhibits a "High" or "Low" level of adoption. Given that "Digitalization Adoption" is a multidimensional concept, it was operationalized as a latent variable derived from eight items on the survey where managers rated their agreement on a 5-point Likert scale. The internal consistency of these eight items was evaluated using Cronbach's Alpha, which yielded a value of 0.933. This result indicates excellent reliability and confirms that the items cohesively measure the same underlying construct. Based on a composite score, each firm was classified as having either a "High Adoption" or "Low Adoption" level. This binary variable served as the target for the predictive model.

Subsequently, 15 independent variables were analyzed to predict the dependent variable. Table 4 provides a comprehensive list and description of these variables.

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Table 4. Description of independent variables.

Variable	Description	Type
Understanding digitalization possibilities	Perception of the benefits of digitalization.	Ordinal
Number of employees using ICT	The number of employees using ICT in their roles.	Continuous
Workers	on average (2022-2023)	Average number of total workers.
E-commerce on Marketplace	Use of platforms like Amazon.	Likert 1 – 5
Own website	If the company has its own website.	Likert 1 – 5
Sales expectations (2023-2024)	Company's sales outlook.	Ordinal
Number of Countries Exported to	Count of export destination countries.	Continuous
Use of social media for commercial purposes	Use of social media for business.	Likert 1 – 5
Digital banking	Use of digital banking services.	Likert 1 – 5
Region	Geographical location of the SME.	Categorical
Sector	Economic sector of the SME.	Categorical
Size	Classification by amount of employees/revenue.	Ordinal
Director/manager university education	If CEO has a university degree.	Binary
Company Age	Years since the company's foundation.	Continuous
CEO's gender	Gender of the Chief Executive Officer.	Binary

Source: Own elaboration.

3.3 Data analysis and predictive modeling

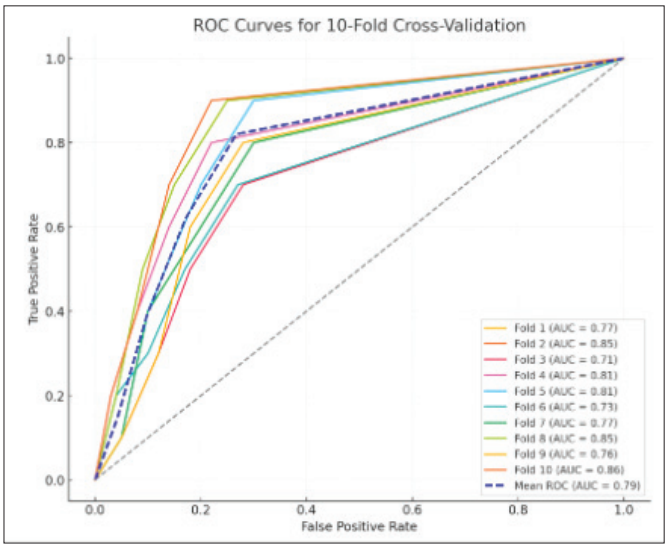
A supervised machine learning approach was employed for analysis. Moreover, all statistical analyses, model building, and generation of figures and tables were conducted using IBM SPSS Statistics, Version 28.

The core of the analysis is a multilayer perceptron ANN with a backpropagation algorithm. To ensure the quality and suitability of the data for the ANN model, a sequence of preprocessing steps was applied. First, an analysis of the dependent variable revealed an unequal distribution between the "High" and "Low" adoption categories. Then, an 80% training and 20% validation split was used for model development, a standard practice in similar studies (Sadati *et al.*, 2011). Consequently, the Synthetic Minority Over-sampling Technique (SMOTE) (Chawla *et al.*, 2002) was used to address a verified class imbalance in the dependent variable and standardizing all numerical independent variables to ensure their equitable influence on the model (Géron, 2022).

Specifically, normalization was applied to all numerical independent variables. This is a critical step because ANNs are sensitive to the scale of input data. Variables with larger ranges can disproportionately influence the model, hindering the learning process. We used StandardScaler, which transforms each feature to have a mean of zero and a standard deviation of one. This ensures that all variables contribute equally and helps the backpropagation algorithm to converge faster and more reliably.

As shown in Figure 1, model validation was performed using 10-fold cross-validation (Hastie et al., 2009), and overfitting was mitigated with dropout and L2 regularization (Srivastava et al., 2014; Goodfellow et al., 2016). Also, the model's performance (see Table 5) was evaluated using a confusion matrix (Precision: 81.7%, Recall: 85.0%, F1-Score: 83.3%) and ROC analysis, which yielded an average AUC of 0.94, indicating excellent discriminatory power (Fawcett, 2006).

Figure 1. ROC Curves for 10-Fold Cross-Validation.



Source: Own elaboration.

Table 5. Metric derived from confusion matrix.

Metric	Formula	Value
Precision	$\frac{TF}{TP+FP}$	81.7%
Recall	$\frac{TF}{TP+FN}$	85.0%
F1-Score	$2x\frac{Precision\ x\ Recall}{Precision+Recall}$	83.3%

Source: Own elaboration.

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4. Results

After implementing these techniques, the model demonstrated an average accuracy of 94% in cross-validation as shown in Table 5, with a significant improvement in predicting the minority class. Detailed model results are presented below. These enhancements ensure that our neural network model is robust and balanced, providing reliable and generalizable results. We invite future studies to validate these findings in different municipalities to ensure their applicability in varied contexts. The segmentation of training and testing sets is crucial in ANNs. Once established, synaptic weights are adjusted and fixed, enabling the ANN for use. The network's learning algorithm minimizes the error between the desired output and the network output by backpropagating the error to ensure each neuron receives the approximate participation error. Gómez (2021) cites authors who assert that a larger training set reduces the error function, confirming adequate neural network performance. This aligns with our findings and supports the robustness of our methodology.

Table 5. Performance metrics.

Performance Metrics		**Average AUC**		**Confusion Matrix**		
Metric	Value	Metric	Value		Predicted: Low Digitalization	Predicted: High Digitalization
Accuracy	92.0%	AUC	0.94	Actual: Low	850	150
Precision	94.4%			Actual: High	190	3,410
Recall	91.7%					
F1-Score	93.0%					
AUC	0.94					

Source: Own elaboration.

The results shown in Table 6 illustrate the significant factors influencing digitalization investment. The most critical factor is "Understanding digitalization possibilities and advantages" with a relative importance of 20.87%, indicating its crucial role in the digitalization process. Following this, "Number of employees using ICT in their job roles" represents the second most influential factor at 14.77%, highlighting the importance of human capital in digital transformation. The average workforce size during 2022 and 2023 emerges as the third most significant factor with 10.68% relative importance.

Other notable factors include e-commerce presence on marketplaces (7.32%), having an own website (7.01%), sales expectations for 2023 and 2024 (6.04%), and international market reach measured by the number of countries exported to (5.74%). The use of social media for commercial purposes (5.23%) and digital banking (4.65%) also appear as relevant variables. Geographic region (4.55%), industry sector (3.83%), and company size classification (3.39%) show moderate importance.

Interestingly, factors traditionally considered significant in business studies show relatively lower importance in our model: the director/general manager's university education (2.45%), company age (2.43%), and CEO's gender (1.03%). This quantitative ranking provides valuable insights into which factors most strongly predict digitalization investment decisions in Colombian SMEs.

Table 6. Relative importance of variables.

Independent Variables	**Relative Importance**	**Normalized Importance**
Understanding digitalization possibilities and advantages	20.87%	100.0%
Number of employees using ICT in their job roles	14.77%	70.8%
Workers, on average, during the years 2022 and 2023	10.68%	51.2%
E-commerce on Marketplace (Amazon or equivalent)	7.32%	35.1%
Own website	7.01%	33.6%
Sales expectations for the years 2023 and 2024	6.04%	28.9%
Number of Countries Exported to	5.74%	27.5%
Use of social media for commercial purposes	5.23%	25.1%
Digital banking	4.65%	22.3%
Region	4.55%	21.8%
Sector	3.83%	18.4%
Size	3.39%	16.3%
Does the director/general manager have a university education?	2.45%	11.7%
Company Age	2.43%	11.7%
CEO's gender	1.03%	4.9%

Source: Own elaboration with SPSS software.

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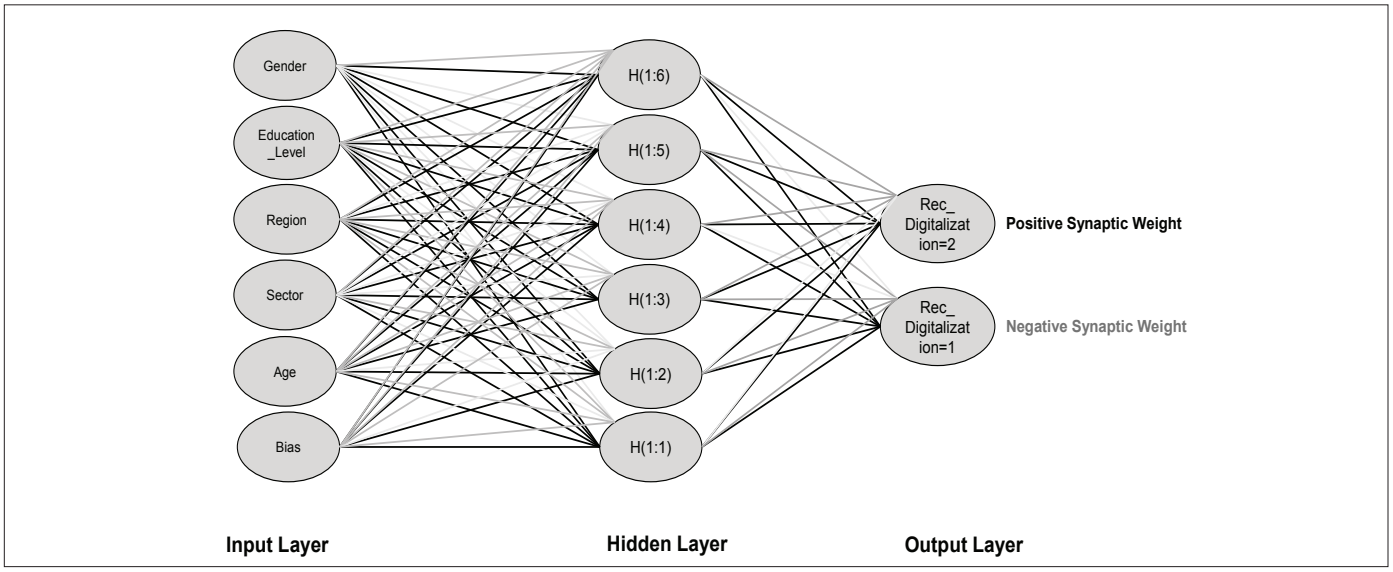
The quality of ANN predictions can be measured using the Mean Squared Error (MSE) function, calculated as follows in Equation (1).

$$MSE = \frac{1}{M}\sum_{i=1}^{M}(real_i - estimated_i)^2 \quad (1)$$

The ANN model classifies factors and determines the importance of variables influencing the model's outputs. The variables categorized by importance are illustrated in Figure 2. This network includes an input layer, a hidden layer, and an output layer, connected by synaptic weights. The input layer includes bias (a constant input for improved data fitting), age of SMEs, industry sector, geographical region, education level of directors or managers, and gender of CEOs. The hidden layer consists of six neurons (H(1:1) to H(1:6)) applying the hyperbolic tangent activation function to introduce non-linearity. The output layer represents two possible outcomes of the digitalization recommendation (Rec_Digitalization=1 and Rec_Digitalization=2). Synaptic weights, both positive (black) and negative (grey), indicate relationships between connected neurons. Finally, the model employs a hyperbolic tangent activation function in the hidden layer to capture non-linear relationships, and a softmax function in the output layer for classification probabilities.

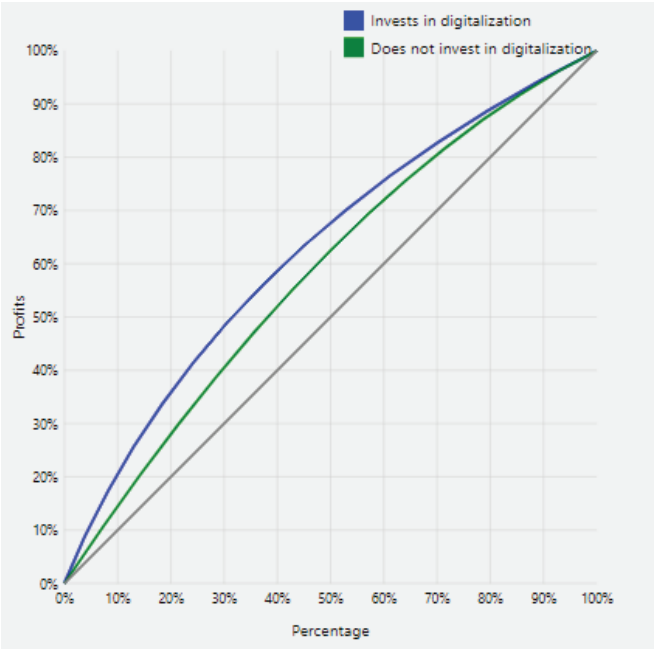
Figure 2. Neural network architecture.



Source: Own elaboration with SPSS software.

The interpretation of ROC curves is possible by the area under the curve, which should always be greater than or equal to 0.5. In the interval (0.75; 1), it indicates good to excellent tests. For each variable in the output layer, the area under the curve and characteristic values shows which were the most accurate outputs of the multilayer perceptron, as shown in Figure 3. The values obtained through ANN learning algorithm evaluation and ROC area values reveal that our model achieves excellent discrimination ability.

Figure 3. ROC curve of the behavior of the results.



Source: Authors with data from survey using SPSS.

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These results provide clear answers to the research questions posed. Regarding the relative importance of internal versus external factors in SME digitalization investment decisions in Colombia, our findings indicate that internal factors, particularly understanding digitalization possibilities (20.87%) and digital human capital (14.77%), have significantly greater weight than external factors such as region (4.55%) or sector (3.83%). Concerning how digital knowledge factors compare to infrastructural or market-related factors, knowledge-related factors (20.87%) exceed the importance of infrastructure factors (7.01% for own website) and market factors (6.04% for sales expectations). These findings provide an empirical foundation for linking the key drivers of digitalization with SDGs 8, 9, and 12, which will be examined in the following section.

5. Discussion of the results

The results obtained through our neural network analysis reveal significant patterns in the factors influencing digitalization investment in Colombian SMEs. The most revealing finding is the primacy of "understanding the possibilities and advantages of digitalization" as the most influential factor (20.87%), suggesting that the most significant barrier to SME digitalization may be cognitive rather than technical or financial. This confirms and expands the findings of Eller *et al.* (2020), who emphasized the importance of digital literacy, and Ghobakhloo *et al.* (2021), who identified understanding and awareness of digital technologies as critical factors for adoption. Our study provides quantitative validation of these qualitative observations, underscoring the need for educational initiatives in fostering digital transformation. The second most important factor, "number of employees using ICT in their job functions" (14.77%), highlights the relevance of human capital in the digitalization process. This finding aligns with the observations of Bouwman *et al.* (2019), who found that business model innovation practices, which often involve intensive ICT use, enhance the performance of SMEs undergoing digitalization. It also corresponds with research by Omrani *et al.* (2022) and Dörr *et al.* (2023), who emphasize that the relationship between digitalization and human resources is bidirectional: while existing skills influence digitalization decisions, the adoption of digital technologies also shapes the educational and professional development needs within SMEs.

The importance of company size (10.68%), e-commerce presence (7.32%), and having an own website (7.01%) highlights the role of resources and digital infrastructure in the transformation process. These findings align with research by Packmohr *et al.* (2024) and Caputo *et al.* (2019), who found that larger SMEs tend to have more resources for digital initiatives. The significance of e-commerce and website presence reflects the growing importance of online presence in the digital economy, a trend also noted by Taiminen and Karjaluoto (2015). Additionally, our findings on the importance of international market reach (5.74%) support the work of Cenamor *et al.* (2019), who found a strong relationship between digital capabilities and international performance in SMEs. The multifaceted nature of digitalization revealed in our study, including social media use (5.23%) and digital banking (4.65%), aligns with observations by Ardolino *et al.* (2021) and Li *et al.* (2018), who noted that digital transformation in SMEs often occurs across multiple business dimensions simultaneously. Interestingly, while still influential, factors such as company age (2.43%), CEO's education level (2.45%), and CEO's gender (1.03%) had comparatively lower importance, contrasting with earlier research by Barba-Sánchez *et al.* (2019) but suggesting that operational and strategic factors may outweigh leadership characteristics in driving digitalization investment.

Our results establish significant connections between the identified digitalization factors and the SDG. The high importance of understanding digitalization (20.87%) and ICT use by employees (14.77%) directly aligns with SDG 8 (Decent Work and Economic Growth), as these capabilities are fundamental for increasing productivity and generating quality jobs in the digital economy (Stephenson *et al.*, 2021; Teng *et al.*, 2022). The relevance of e-commerce presence (7.32%) and having an own website (7.01%) contributes to SDG 9 (Industry, Innovation, and Infrastructure) by facilitating business model innovation and enhancing SMEs' digital infrastructure (Mia *et al.*, 2024; Sharabati *et al.*, 2024). Regarding SDG 12 (Responsible Consumption and Production), factors such as sales expectations (6.04%) and international reach (5.74%) can drive more sustainable practices when SMEs optimize their processes to meet growing sustainability demands in global markets (Philbin *et al.*, 2022; Duran & Castillo, 2023).

Our findings suggest differentiated implications according to SME size and sector. For microenterprises (49.8% of our sample), the main challenge appears to be understanding digitalization possibilities, making educational programs particularly beneficial. For small enterprises (29.5%), developing digital capabilities among employees emerges as a priority, while medium-sized enterprises (19.3%) should focus on more sophisticated e-commerce strategies and digital international presence. Regarding sectors, our results indicate that service (35.4%) and industrial (31.4%) companies could benefit more from digitalization than other sectors, as digitalization can transform service delivery models and provide significant opportunities for process automation in industry.

Several limitations could affect the interpretation of our results. The cross-sectional nature of the study provides only a snapshot at a specific moment, limiting our understanding of how these factors may evolve over time. Although geographical location was considered as a variable, a more detailed analysis of regional differences within Colombia could provide additional valuable information. The focus on SMEs could limit the applicability of the findings to larger companies or technology startups, and the study's reliance on proxy variables to measure digitalization suggests that a more direct approach could provide more precise results in future research.

6. Conclusions

This study has identified and precisely quantified the determinants of digitalization investment in Colombian SMEs, This study has identified and precisely quantified the determinants of digitalization investment in Colombian SMEs, highlighting four fundamental findings:

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(1) understanding the possibilities and advantages of digitalization emerges as the most influential factor (20.87%); (2) human capital with digital competencies constitutes the second most relevant factor (14.77%); (3) company size, measured by the average number of workers, represents the third most important factor (10.68%); and (4) presence on e-commerce platforms (7.32%) and having an own website (7.01%) complete the five main factors. The primary theoretical contribution of this study lies in the innovative application of artificial neural networks to precisely quantify the relative importance of factors influencing SME digitalization in the Colombian context. This methodological approach has allowed modeling complex non-linear relationships between organizational, socioeconomic, and technological variables, providing a more nuanced understanding than traditional linear models. The results obtained confirm the importance of cognitive and human capital factors identified in previous studies (Eller *et al*., 2020; Ghobakhloo *et al*., 2021) but provide a solid empirical basis for their hierarchization and prioritization.

Furthermore, this study establishes explicit links between digitalization factors and SDGs, particularly SDGs 8, 9, and 12. Understanding the advantages of digitalization and developing digital skills directly contribute to SDG 8 (Decent Work and Economic Growth) by improving business productivity and competitiveness. E-commerce presence and digital platforms align with SDG 9 (Industry, Innovation, and Infrastructure) by strengthening digital infrastructure. Finally, process optimization through digital technologies favors SDG 12 (Responsible Consumption and Production) by enabling more efficient and sustainable operations. These connections highlight how strategic digitalization initiatives can simultaneously advance business objectives and broader sustainability goals, creating value at both organizational and societal levels.

The results of this study have significant implications for both public policy makers and business leaders. SME digitalization support programs should prioritize education and awareness about the advantages of digitalization, as well as digital skills training for employees. The finding that understanding the advantages of digitalization is the most influential factor (20.87%) suggests that educational campaigns could be more effective than direct technology investments for some companies. For microenterprises, which constitute almost half of the studied sample, training programs adapted to their limited resources are especially important. Small businesses would benefit from strategies to integrate talent with digital skills, while medium-sized enterprises could leverage their greater scale to implement more sophisticated e-commerce strategies. At the sectoral level, service and industrial companies present the greatest potential to benefit from digital transformation. Public policy initiatives should consider these differences, designing specific programs by size and sector to maximize their impact.

This study presents certain limitations that open the door to promising future research lines. Its cross-sectional nature offers only a snapshot of a specific moment, suggesting the usefulness of longitudinal studies to examine how factors influencing digitalization change over time and in response to external events such as health or economic crises. A deeper sectoral analysis could provide valuable information for sector-specific digitalization strategies. Additionally, given that understanding the advantages of digitalization emerged as the most influential factor, it would be valuable to investigate which types of interventions are most effective in improving this understanding among SME owners and managers. Finally, it would be interesting to examine the long-term impact of digitalization on SME productivity, competitiveness, and sustainability, as well as to deepen how digitalization strategies can be more effectively aligned with the SDGs and quantify their impact on these objectives. Comparative research between different countries or regions could provide insights into how cultural, economic, and political factors influence business digitalization, further enriching our understanding of this critical transformation process.

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