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Digital maturity and corporate sustainability: Evaluating efficiency dynamics in an emerging market context

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ABSTRACT

This study examines the impact of digital maturity (DM) on corporate sustainability efficiency (CSE) among companies listed on Borsa Istanbul in Turkey. Using panel data (2018–2022) from 30 non-financial firms, we construct a corporate digitalization index (CDI) as a proxy for DM through text mining analysis of digital-related terms in annual reports. CSE is evaluated via data envelopment analysis (DEA), utilizing environmental, social, and governance (ESG) scores of sustainability as inputs and profitability ratios as outputs. Panel regression analysis reveals a U-shaped curvilinear relationship, indicating that firms initially experience reduced efficiency due to high investment costs and adaptation challenges but subsequently achieve increased efficiency as they realize operational and strategic gains from advanced DM. These findings highlight the nonlinear dynamics of digital capability development, offering practical implications for firms aiming to optimize their sustainability strategies through effective digital transformation.

1. Introduction

The digital revolution has profoundly reshaped business operations, compelling firms to adopt data-driven strategies to sustain competitiveness in an increasingly dynamic environment [1,2]. At the forefront of this shift, digital transformation (DT) has redefined business processes, service customization, and automation, driving firms to reallocate resources, innovate business models, and strengthen stakeholder engagement [3–6]. While the broader DT literature primarily examines technological adoption and its impact on performance [7], this study shifts the focus to digital maturity (DM), which reflects a firm's ability to integrate, refine, and strategically leverage digital capabilities continuously rather than simply implementing new technologies [8]. Unlike one-time digital adoption, DM represents an ongoing capability-building process that drives long-term competitiveness and sustainability [9].

Prior research highlights DT's role in enhancing sustainability performance through greater accountability, supply chain efficiency, stakeholder engagement, and high levels of excellence practices internalization [4,10–14]. However, much of this research primarily emphasizes technological adoption rather than examining the strategic role of DM in embedding environment, social and governance (ESG) matters into corporate functions, which remains underexplored. Addressing this gap, this study investigates whether and how DM influences corporate sustainability efficiency (CSE).

The relationship between DM and CSE is especially relevant in emerging markets, where firms manage institutional inefficiencies, weak regulatory enforcement, and evolving sustainability pressures [15,16]. Firms in these economies operate within information asymmetries and fragmented ESG reporting standards, which challenge stakeholder trust and long-term investment decisions. While DT can facilitate ESG integration by improving corporate reporting and reducing information gaps [17], research remains inconclusive on whether DM, as a more advanced and strategic digital capability, consistently enhances CSE across different firms. Addressing this gap is critical, as varying levels of

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DM adoption may result in significant efficiency disparities among firms, particularly in environmental and social dimensions.

While firms in the advanced stages of DM can utilize digital tools to enhance ESG innovation and regulatory compliance, those in early-stage digital capability development often face high adoption costs, workforce adaptation challenges, and structural inefficiencies. These challenges raise questions about whether the relationship between DM and CSE follows a non-linear trajectory rather than a linear one. Existing studies acknowledge that DT can introduce both benefits and risks, including cybersecurity vulnerabilities, labor market disruptions, and increased environmental trade-offs [18,19]. However, how DM evolves across different phases of digital capability development and whether its impact on sustainability efficiency follows a nonlinear pattern remains underexplored. Firms may experience inefficiencies in the early stages before realizing sustainability benefits, suggesting that DM's impact on CSE may follow a nonlinear path [20].

Despite extensive research on the relationship of ESG performance and financial outcomes (e.g., [21–28]), relatively few studies have specifically explored how digital capabilities influence CSE [29]. CSE assesses how effectively firms balance ESG responsibilities with financial performance [30]. To address this, this study develops a corporate digitalization index (CDI) using text mining techniques to measure DM and employs data envelopment analysis (DEA) to benchmark CSE [31,32]. This methodology enables an objective, multi-dimensional assessment of how DM contributes to sustainable value creation.

Given its dual focus on digitalization and sustainability regulation, Turkey provides a highly relevant empirical setting for examining the DM–CSE relationship. Over the past decade, Turkey has introduced mandatory ESG reporting requirements, urging publicly listed firms to enhance sustainability disclosures and align corporate strategies with global sustainability standards. Concurrently, the Turkish government has prioritized DT as a national economic growth driver, pushing firms to accelerate digitalization efforts to remain competitive. These simultaneous regulatory and technological shifts create an ideal setting to analyze how firms in emerging markets integrate DM within their ESG strategies. Furthermore, Turkey's institutional context, characterized by regulatory volatility and sector-specific variations in digital adoption, provides a valuable empirical setting for examining the broader challenges and opportunities associated with DM-driven CSE.

Building on these foundations, this study makes several key contributions to the literature on DM, CSE, and sustainability performance. First, it enhances measurement frameworks by introducing the CDI as a novel proxy for DM and employing DEA to evaluate CSE, providing a rigorous, scalable, and data-driven alternative to traditional firm-level assessments. Second, it examines whether the relationship between DM and CSE follows a nonlinear pattern, investigating whether the sustainability benefits of digital capabilities emerge gradually or are preceded by transitional inefficiencies that delay improvements until firms fully align their digital strategies with ESG objectives. This nonlinear trajectory acts as a critical aspect of understanding how digitalization affects sustainability over time, which has been underexplored in literature. Third, it underlines the importance of structured DM adoption strategies, adaptive ESG policies, and targeted regulatory incentives to ensure that digital investments contribute to long-term sustainability improvements rather than generating unintended inefficiencies. In this sense, it emphasizes that digitalization gradually affects CSE because of its ability to boost transparency and accountability and improve stakeholder engagement in emerging markets where there is a mindful and instrumental paradigm shift due to advancement in digital technologies. Finally, by offering practical insights for firms and policymakers, this study contributes to a deeper understanding of how firms can optimize digital capability development to enhance corporate sustainability while mitigating potential risks and guaranteeing the well-being of future generations.

The remainder of this paper is structured as follows. The next section reviews the theoretical background along with a brief discussion of the pertinent literature. The third section details the data, variables, and methodology. The fourth section presents empirical findings, while the final section discusses theoretical and practical implications, along with study limitations and future research directions.

2. Theoretical background and literature review

From a theoretical perspective, the dynamic capabilities view (DCV), and stakeholder theory provide a complementary framework for understanding how DM influences CSE. While DCV emphasizes how firms internally develop and reconfigure digital capabilities to enhance sustainability performance [33–35], stakeholder theory highlights how external pressures (e.g., investor expectations and regulatory demands) drive firms to advance their DM in alignment with evolving ESG imperatives [36].

Rather than relying on static resources, DCV emphasizes that competitive advantage arises from a firm's ability to sense, seize, and transform capabilities in response to changes in the business environment [37]. Unlike the resource-based view (RBV), which treats resources as fixed assets that provide competitive advantage, DCV focuses on continuous strategic adaptation [38]. In this context, DM aligns closely with DCV, as it requires firms not only to adopt digital technologies but also to develop them dynamically in response to growing sustainability challenges.

Firms that exhibit high DM engage in an ongoing process of sensing new opportunities, seizing technological resources, and transforming digital capabilities to integrate sustainability into corporate strategy. Through sensing, firms identify occasions for improving sustainability by leveraging digital tools such as AI-driven ESG analytics, blockchain-enabled supply chain transparency, and real-time environmental monitoring [39]. Seizing involves acquiring and embedding digital solutions to drive sustainability improvements, such as predictive analytics for ESG risk management or digital reporting platforms for enhanced transparency [40]. Transforming refers to the continuous renewal and strategic deployment of digital competencies to ensure that firms remain aligned with sustainability goals despite evolving regulatory and stakeholder demands [41].

As firms develop more advanced digital capabilities, they strengthen their ability to embed ESG principles into business processes, enhance data-driven decision-making, and streamline sustainability reporting. Wu et al. [42] emphasize that digitally mature firms improve the preparation of integrated ESG reports, increasing transparency and attracting more stakeholder attention to sustainability efforts. Wang et al. [43] find that digitalization fosters green innovation, reduces environmental pollution, and enhances corporate social responsibility, particularly in firms that have invested in sophisticated digital capabilities. He and Chen [44] argue that digital capabilities enable firms to enhance workforce resilience, improve corporate governance, and adopt more sustainable operational models, helping them mitigate social and economic risks associated with rapid technological adoption.

Trueba-Castañeda et al. [45] suggest that adopting digitalization enables companies to enhance their environmental responsibility and achieve qualitative growth in reputation. Additionally, digitalization drives quantitative growth by boosting efficiency, reducing costs, improving product quality, and increasing customer satisfaction. Feng and Nie [46] using digital technology patent application data as a proxy for digital technology innovation, examines Chinese A-share firms for the years 2009 to 2021, revealing that digital technology innovation significantly enhances ESG performance, especially in small-sized firms, by improving internal control quality and human capital. To concisely synthesize recent empirical evidence on the interplay between digital capabilities and sustainability outcomes, Table 1 provides an overview of recent studies, summarizing their theoretical underpinnings, methodological approaches, and core findings related to DT, DM, and ESG performance.

While the advantages of DM in driving sustainability performance

Table 1
A summary of selected studies on digitalization and corporate sustainability performance link.

Author(s)	Variables	Theoretical perspective(s)	Sample/method	Key finding(s)
Xie et al. [27]	Corporate efficiency, return on assets, Tobin's Q, ESG performance	Legitimacy theory and stakeholder theory	6631 firms in 2015 from 74 countries and 11 sectors, DEA, OLS regression	Corporate transparency in ESG disclosures is positively associated with corporate efficiency at moderate disclosure levels. Additionally, most ESG activities exhibit a nonnegative relationship with corporate financial performance.
Broccardo et al. [47]	Sustainability performance, digitalization and profitability performance	N/A	353 listed firms on Italian Stock Exchange, partial least squares, structural equation modelling	There is a significant relationship between digitalization, sustainability, and profitability. Positive ESG outcomes contribute to enhanced economic performance.
Su et al. [48]	Digital transformation, dynamic capabilities (e.g., green innovation, social responsibility, operational management) and ESG performance	Ambidexterity theory, dynamic capabilities view and natural resource-based theory	A-share listed firms in China from 2011 to 2020, panel data regression	Digital transformation has a positive impact on ESG performance, and digital technology innovation can enhance ESG performance through dynamic capabilities such as green innovation, social responsibility, and operational management.
Wang et al. [43]	ESG evaluation and digital transformation	Digital ESG theory	2816 manufacturing firms listed on Chinas A-share, 2009–2020, OLS regression	Digital transformation contributes to ESG performance in general; labor-intensive firms benefit more from them than their counterparts.
Ying and Jin [6]	Digital transformation, corporate sustainability, exploratory innovation and exploitative innovation	Resource-based view and corporate innovation theory	A-share listed firms in China from 2013 to 2021, two-stage least-squares estimation	Digital transformation has positive effects on corporate sustainability. The higher the level of exploratory and exploitative innovation, the stronger the contribution of digitalization to sustainability.
Zhao et al. [49]	Digital transformation strategy, ESG performance and green innovation	Innovation value chain theory and dynamic capabilities view	224 large manufacturing firms in China, questionnaire, hierarchical regression analysis, bootstrap regression analysis.	Digital transformation strategy has a direct positive and significant impact on ESG performance. Green innovation plays a significant intermediate role in promoting the relationship between digital transformation and ESG performance.
Zhong et al. [39]	Digital transformation, ESG performance, management myopia, information transparency and innovation	Organizational ecology theory, natural resource-based view	A-share listed companies in Shanghai and Shenzhen from 2010 to 2020, panel regression	Digital transformation can significantly improve the ESG performance. There are three driving factors in promoting digital transformation: restraining the short-sightedness of management; improving the transparency of internal information and enhancing technological innovation.
He and Chen [44]	Digital transformation, ESG performance, labor skill levels and environmental regulation	N/A	A-share firms in China from 2010 to 2022, OLS regression	Digital transformation significantly augments ESG performance. Digitalization initiatives contribute to ESG performance enhancement by elevating the skill levels of the existing workforce.
Mahanta et al. [29]	Corporate efficiency, ESG performance and financial performance	Legitimacy theory, stakeholder theory and resource-based view	909 companies from 29 different countries, 2022, OLS regression	ESG integration enhances corporate efficiency, which subsequently translates into improved financial performance, suggesting that corporate efficiency mediates this relationship. This implies that firms can optimize financial outcomes by effectively leveraging ESG practices.
Yang and Han [14]	ESG performance and digital transformation	N/A	4646 China's A-share nonfinancial listed firms from 2009 to 2021, the fixed-effects multiple linear regression	Digital transformation exhibits a significant inverted U-shaped impact on ESG performance. While moderate digitalization enhances ESG outcomes, excessive digital transformation may lead to organizational conflicts and increased costs, ultimately undermining sustainability performance.

are well recognized, its effects on CSE are shaped by complex capability-building processes rather than following a uniform trajectory. According to DCV, firms develop digital competencies in stages, meaning that early investments in digital tools do not always yield immediate sustainability benefits [37]. Instead, entities must continuously refine and adapt digital resources to maximize their impact on ESG improvements. This process involves technological adaptation, workforce upskilling, and structural realignments, that may temporarily constrain CSE before firms achieve operational and strategic alignment with their digital investments [50]. Over time, as firms strengthen their absorptive capacity, defined as the ability to recognize, assimilate, and apply new knowledge, they can integrate digital solutions more effectively, potentially leading to long-term improvements in ESG performance [20]. This evolving nature of DM aligns with DCV, highlighting the importance of capability-building phases and continuous resource reconfiguration for achieving sustainable competitive and environmental advantages [35].

While DCV explains how firms enhance their digital capabilities, the stakeholder theory clarifies why firms develop DM as a strategic response to stakeholder expectations. Companies do not operate in isolation but within a network of investors, regulatory bodies, consumers, employees, and communities who demand higher corporate transparency, accountability, and ESG compliance. DM allows firms to meet these expectations more effectively by enhancing ESG disclosures, strengthening governance structures, and integrating stakeholder feedback into corporate decision-making [51,52].

Digitally mature firms are better equipped to improve ESG transparency by leveraging AI-driven compliance monitoring, blockchain-based ESG reporting, and automated supply chain tracking [53]. They also enhance corporate governance by adopting real-time analytics for risk management, refining board-level decision-making through digital dashboards, and automating regulatory reporting [54]. Additionally, DM fosters more effective social responsibility initiatives, as firms can use digital platforms to monitor labor rights, engage in community-driven sustainability projects, and optimize workplace conditions through digital management tools [55].

However, reliance on digital capabilities for sustainability management is not without challenges. Over-digitalization can create cybersecurity risks, privacy concerns, and algorithmic biases, which may erode stakeholder trust [18]. Additionally, firms in the early stages of DM often face resistance to digital adoption, requiring cultural and organizational shifts before the full benefits of digital capabilities can be realized. Furthermore, digital technologies may contribute to unintended sustainability trade-offs, as increased energy consumption, limited recycling options, and rising electronic waste present environmental concerns [19].

While DM facilitates ESG performance improvements, its widespread adoption introduces paradoxical sustainability risks. Some studies highlight the dual impact of digitalization on environmental and social performance, where technological advancements provide efficiency gains but also increase carbon footprints and resource depletion [56,57]. Firms relying heavily on data-intensive technologies may struggle with high energy demands, e-waste management challenges, and ethical concerns surrounding algorithmic decision-making [58]. To mitigate these risks, companies must integrate sustainable digitalization strategies that align with both technological and ESG objectives, ensuring that the long-term environmental and social impacts of digitalization remain manageable and beneficial.

From a governance perspective, DM enables firms to improve data-driven ESG risk management and regulatory compliance. AI-based ESG monitoring systems allow companies to anticipate regulatory penalties, optimize energy consumption, and enhance sustainability reporting accuracy. In environmental and social domains, DM enhances operational sustainability through IoT-based environmental tracking, cloud-based CSR management, and predictive analytics for energy efficiency [59].

Although prior literature acknowledges the relevance of digital capabilities to corporate sustainability, the exact nature of the DM–CSE relationship and its evolution across different stages of DM remains largely unexplored. Specifically, it remains unclear whether digital capabilities exert consistent and predictable impacts on CSE or if the relationship varies depending on firm characteristics such as size, risk, age, and industry type. Given this gap, a theoretically informed research framework is needed to empirically assess how DM influences CSE systematically and whether this relationship is uniform or varies according to specific firm-level characteristics.

Our research framework, illustrated in Fig. 1, thus integrates internal capability-building mechanisms from DCV with external pressures identified by stakeholder theory to investigate the DM–CSE relationship comprehensively. The framework explicitly considers firm-specific variables (size, risk, age, and industry) as critical controls influencing sustainability outcomes. By adopting a longitudinal panel-data approach, this study explores how firms dynamically evolve their DM over time, providing deeper insights into whether and how DM exerts consistent or varying influences on CSE.

3. Research methodology

3.1. Data

This study draws on a panel dataset of 30 non-financial firms listed on the Borsa Istanbul (BIST) 100 Index, covering the period from 2018 to 2022. Firms with fewer than five years of available ESG scores were excluded from the sample to ensure data validity and consistency. The final dataset comprises 150 firm-year observations, allowing for a robust panel data analysis.

Data were collected from multiple reliable sources, including the Public Disclosure Platform, the Thomson Reuters EIKON database, and firms' annual reports. These sources provided comprehensive information on corporate ESG scores, financial performance indicators, and firm characteristics, forming the foundation for the empirical analysis.

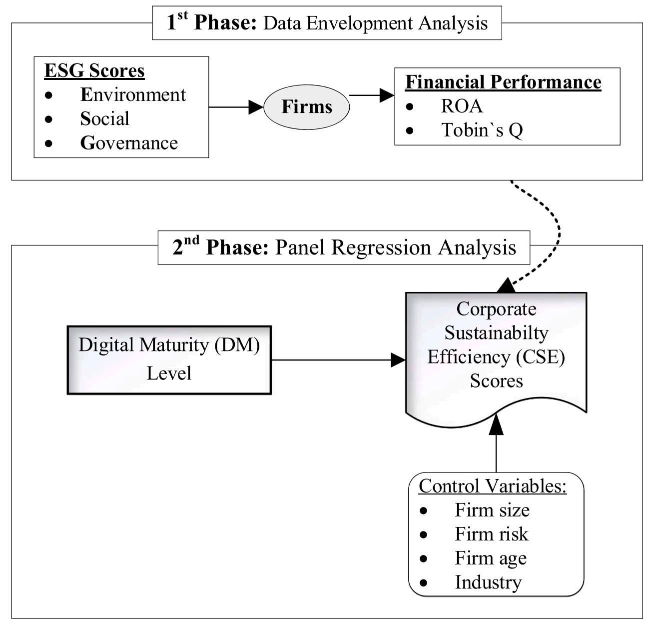


Fig. 1. Research framework.

3.2. Variables measurement

3.2.1. Dependent variable

This study employs CSE as the dependent variable, measured using DEA. DEA is a non-parametric method that evaluates firms' relative efficiency in converting sustainability-related investments into financial performance.

To construct the DEA model, ESG scores are used as inputs, reflecting the extent to which firms allocate resources toward ESG initiatives. The outputs include ROA and Tobin's Q, which represent the financial benefits derived from sustainability investments. ROA serves as a profitability metric, indicating a firm's ability to generate earnings from its assets, while Tobin's Q is a market-based valuation measure, capturing the firm's intangible value and investor expectations [60].

Firms that actively engage in sustainability practices, including environmental stewardship, social responsibility, and governance improvements, are expected to incur higher expenditures. However, these investments can translate into long-term financial benefits by reducing environmental liabilities, strengthening brand reputation, and enhancing market performance [29,27]. Strong ESG performance has been associated with increased customer loyalty, improved investor confidence, and lower financing constraints, contributing to superior financial outcomes [61,62].

This approach aligns with stakeholder theory and DCV, both of which suggest that firms effectively managing ESG factors can achieve competitive advantages, lower risk exposure, and enhanced financial performance [26]. In this context, DEA provides a rigorous efficiency-based framework to assess how well firms translate sustainability investments into financial gains through DM, offering a methodological complement to traditional ESG performance evaluations.

3.2.2. Independent variable

Given the absence of official data on the level of digitalization among firms listed on the BIST 100 Index, this study develops a CDI, following the approach of prior studies [47,48,63]. This index provides a systematic measure of DM by analyzing the frequency of digital-related keywords in firms' annual reports.

To construct the CDI, text mining analysis was applied using MAXQDA, a software designed for qualitative and mixed-method data analysis [64]. A total of 238 keywords associated with different levels of digital orientation were selected based on an extensive literature review. The analysis involved several key steps to ensure methodological rigor and data reliability. First, digital-related terms were extracted from relevant academic sources to create a comprehensive keyword database. Second, firm-level annual reports were processed, with PDF documents containing text conversion errors excluded to maintain data integrity. Finally, the frequency of identified keywords was normalized by dividing it by the total number of pages in each report, ensuring comparability across firms of varying document lengths.

This CDI score serves as the independent variable in this study, capturing firms' level of DM. By leveraging automated text analysis, the index offers an objective, replicable, and quantifiable measure of digitalization, minimizing potential biases in firm-level assessments. This approach enables a more systematic examination of DM and its implications for CES.

3.2.3. Control variables

To account for firm-specific factors that could influence CSE, this study incorporates firm size (SIZE), firm risk (RISK), firm age (AGE), and industry (IND) as control variables. These variables help ensure that the estimated relationship between DM and CSE is not confounded by other firm characteristics.

SIZE is measured as the natural logarithm of total assets, a widely used approach to capture differences in firm scale. Larger firms generally have greater resources to invest in digitalization and sustainability initiatives, which may influence their efficiency in integrating ESG practices into financial performance.

RISK is determined by the ratio of total liabilities to total assets, reflecting a company's financial leverage. Higher risk levels may affect a firm's ability to engage in long-term digital and sustainability investments due to financial constraints or heightened uncertainty in resource allocation.

AGE is included as the natural logarithm of the number of years since the company's founding. Older firms may have more established organizational structures and experience in sustainability practices, whereas younger firms may exhibit greater flexibility in adopting digital solutions.

IND is incorporated as a dummy variable to control for sectoral differences. It is assigned a value of "1″ for firms in the service industry and "0" for firms in the manufacturing sector. Given that digitalization levels and sustainability strategies often vary across industries, this classification ensures that industry-specific factors are accounted for in the analysis.

3.3. Data analysis

This study employs a two-stage analytical approach to examine the relationship between DM and CSE. In the first stage, DEA is applied to derive CSE as the dependent variable by evaluating firms' ability to transform ESG-related inputs into financial performance outcomes. In the second stage, panel regression analysis investigates the relationship between DM, as proxied by the CDI, and CSE, while controlling for firm-specific factors.

3.3.1. Data envelopment analysis

This study utilizes DEA to assess the CSE by evaluating the efficiency of companies' ESG performance in relation to their financial indicators. DEA is a nonparametric, linear programming method that analyzes decision-making units (DMUs) with multiple inputs and outputs. Unlike conventional regression-based approaches, DEA does not impose a predefined functional form but derives efficiency scores directly from the data [65]. It establishes a frontier formed by a DMU set exhibiting best practices. Then, it assigns efficiency scores to other non-efficient units according to their distance from the frontier [31]. This attribute makes it particularly effective for benchmarking firms operating under diverse conditions. Since DEA allows endogenously weighting different outcomes and resources concerning the analyzed units, it has mainly been adopted in various applications characterized by the presence of multiple objectives, including sustainability research such as Henriques et al., [66], Mahanta et al. [29] and Xie et al. [27]. Additionally, the DEA allows adjustments to integrate ESG concerns into profitability models featured by conventional inputs and outputs.

The slack-based measure (SBM) DEA model was chosen for this study, incorporating a non-oriented and variable returns to scale (VRS) specification. The SBM model, proposed by Tone [67], enhances efficiency analysis by directly addressing input excesses and output shortfalls, offering a more comprehensive evaluation compared to radial DEA models such as CCR [31] and BCC [68], which assume proportional input-output changes. The non-oriented approach ensures that both input reductions and output expansions are simultaneously considered, making it an appropriate choice for assessing the efficiency of ESG implementation relative to financial performance. Additionally, the VRS assumption allows for variations in operational scale among firms, reflecting the heterogeneous nature of ESG investments and their financial impact [65].

The primary objective of employing the SBM-VRS model is to determine the optimal scale for firms in implementing ESG practices efficiently in relation to financial performance. This model provides a detailed breakdown of inefficiencies at different operational scales, offering actionable insights to guide corporate ESG strategies and optimize financial performance. A fractional programming model of non-oriented VRS SBM for DMU f is shown in formulation (1)–(5) below:

$$Min\ CSE_f = \frac{1-\left(\frac{1}{m}\right)\sum_{i=1}^{m} s_i^- \Big/ x_{if}}{1+\left(\frac{1}{r}\right)\sum_{k=1}^{r} s_k^+ \Big/ y_{kf}} \tag{1}$$

Subject to

$$\sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{if} \quad for\ i = 1, 2, \ldots, m \tag{2}$$

$$\sum_{j=1}^{n} y_{kj}\lambda_j - s_k^+ = y_{kf} \quad for\ k = 1, 2, \ldots, r \tag{3}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{4}$$

$$\lambda_j, {s_k}^+, {s_i}^- \geq 0 \quad for\ all\ i,\ j,\ k \tag{5}$$

In Eqs. (1)–(5), x_i denotes ESG input variables, including environmental, social, and governance performances, and y_r denotes the financial performance outputs, the ROA, and Tobin's Q. s_i^- and s_k^+ represent the input excess and output shortfall, where λ_j is a non-negative intensity variable utilized to construct an ideal composite DMU with m inputs and r outputs for n DMUs. Eqs. (2) and (3) indicate a DMU's input and output levels as a linear combination of a composite ideal input and output and the slacks, respectively. Eq. (4) imposes the variable return to scale condition. The DMU f is efficient if $CSE_f{}^* = 1$, equivalently, all slacks are zero ($s_k^{+*} = s_i^{-*} = 0$). Firms with an efficiency score of 1 are on the frontier, indicating that they effectively convert sustainability efforts into financial gains. In contrast, companies with scores below 1 are inefficient, implying that they underutilize their ESG investments relative to peer firms.

3.3.2. Panel data analysis

To examine the impact of CDI on CSE, we performed a panel regression analysis using Stata. The model specification is presented in Eq. (6). To control for time-specific effects, we included year-fixed dummies to account for unobserved heterogeneity across different periods. CSE was regressed on CDI and its squared term (CDI^2) to test for a potential U-shaped relationship. A statistically significant and negative coefficient for CDI^2 would indicate an inverted U-shaped relationship, whereas a statistically significant and positive coefficient would provide evidence of a U-shaped relationship [69].

$$CSE_{i,t} = \alpha + \beta_1 CDI_{i,t} + \beta_2 CDI^2_{i,t} + \beta_3 SIZE_{i,t} + \beta_4 RISK_{i,t} + \beta_5 AGE_{i,t} + \beta_6 IND_{i,t} + \sum_{k=1}^{5} \lambda_k Year + e_{i,t} \quad (6)$$

4. Empirical findings

4.1. Descriptive statistics

Table 2 presents the descriptive statistics and pairwise correlations among the study variables. The mean CSE score is 0.288 (SD = 0.343), indicating relatively low and variable efficiency across firms. CDI has a mean of 2.609 (SD = 2.046), with values ranging from 0.283 to 10.905, reflecting substantial variation in DM. SIZE averages 16.844 (SD = 1.109), while RISK has a mean of 0.641 (SD = 0.197), suggesting moderate variability. AGE, measured in natural logarithmic form, has a mean of 3.742 (SD = 0.428), indicating that most firms in the sample are relatively young. The binary variable IND has a mean of 0.4, signifying that 40 % of the sample comprises service industry firms.

Among the ESG subcomponents, the environmental score (Escore) ($M = 62.046$, SD = 24.556) and the social score (Sscore) ($M = 71.739$, SD = 21.927) exhibit substantial variation, while the governance score (Gscore) ($M = 57.986$, SD = 20.549) also shows notable dispersion. Financial performance indicators reveal moderate profitability, with ROA averaging 0.079 (SD = 0.079) and Tobin's Q showing a mean of 0.757 (SD = 0.763), spanning from −0.228 to 6.843.

Pairwise correlations highlight significant associations among key variables. CSE is positively correlated with ROA (0.470, $p < 0.05$) and Tobin's Q (0.447, $p < 0.05$), suggesting that firms with higher CSE tend to achieve superior financial performance. CDI is moderately correlated with SIZE (0.218, $p < 0.05$) and more strongly with Escore (0.356, $p < 0.05$), indicating that firms with greater DM tend to be larger and environmentally proactive. SIZE is negatively associated with CSE (−0.319, $p < 0.05$), implying that larger firms may exhibit lower CSE despite their positive correlation with Escore (0.503, $p < 0.05$) and Sscore (0.362, $p < 0.05$). RISK is negatively correlated with both CSE (−0.195, $p < 0.05$) and ROA (−0.313, $p < 0.05$), reflecting that riskier firms tend to have lower CSE and profitability. Additionally, IND is negatively correlated with AGE (−0.457, $p < 0.05$), indicating that service firms are generally younger than manufacturing firms.

Table 3 presents the average CSE scores calculated using DEA model for the sampled firms between 2018 and 2022. The results indicate fluctuations in average CSE over this period, beginning at 0.351 in 2018 and experiencing a noticeable increase to a peak of 0.582 in 2020 before slightly declining to 0.473 in 2022. This temporal variation emphasizes the importance of examining the factors influencing CSE, including the potential role of DM.

Table 3
Average CSE scores between 2018 and 2022.

Years	2018	2019	2020	2021	2022
Mean	0.351	0.425	0.582	0.581	0.473
SD	0.288	0.254	0.307	0.309	0.293

4.2. Estimation results

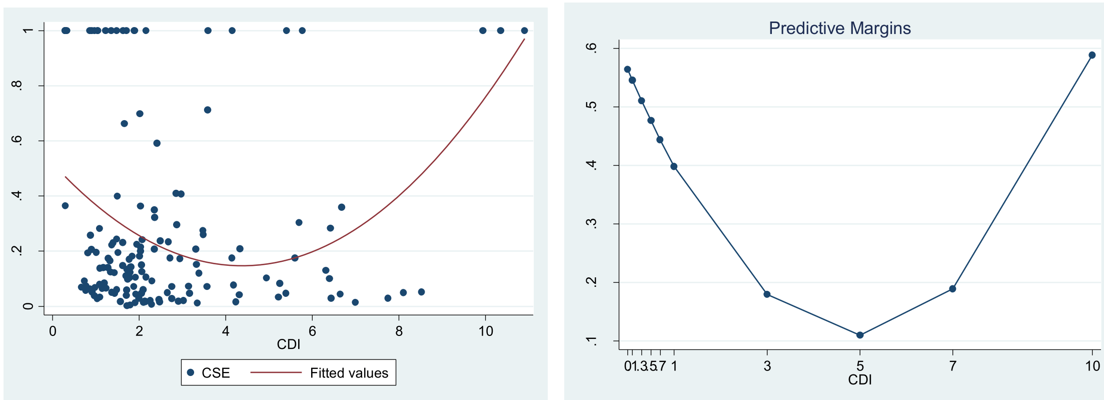
Panel (a) in Fig. 2, the red line represents the quadratic fit for the association between CDI and CSE, suggesting a curvilinear, U-shaped relationship. At lower levels of DM, increasing digitalization is associated with a decline in efficiency. This could be due to initial challenges in adopting digital technologies, such as transition costs, learning curves, or inefficiencies during the early phases of DM, and in recruiting qualified staff that can use these technologies. At a certain level of DM (around CDI = 4), efficiency appears to be at its lowest. This may show a phase where companies struggle to integrate digital tools effectively before reaping the benefits. After surpassing this turning point, efficiency starts to improve as DM increases, suggesting that once a firm fully integrates and optimizes digital tools, continuously develops the digital skills of the employees, and better manages the risks associated with digital operations, efficiency gains in sustainability start to materialize. Thus, digitally mature firms can capitalize on greater opportunities, positively impacting both profitability and sustainability performance. These findings highlight the importance of long-term commitment and management during digital transition and align with prior studies' findings [47,49,70].

In the panel data analysis, we first estimated a fixed effects regression model and conducted an F-test to determine if any firm-specific attributes were present. The results indicated that a pooled OLS model was not appropriate. We then conducted a Hausman [71] test to determine the most suitable model for the data. The result indicated that the random effects model is better. Table 4 reports the results. In Table 4, the linear term is negatively ($\beta = -0.184$, $p < 0.01$) and the squared term of CDI is ($\beta = 0.019$, $p < 0.01$) positively associated with CSE. Following Haans et al. [69] and Lind and Mehlum [72], we validated our findings using the "utest". The null hypothesis of the "utest" posits that the relationship is monotone or an inverse U shape. The alternative hypothesis is that the relationship is U shape. In Model 1, the overall "utest" results yields a t-value of 3.47 ($p < 0.01$), suggesting that the null hypothesis is rejected. This finding, along with Fig. 2, confirms the U-shaped relationship between CDI and CSE. The nonlinear relationship between the CSE and CDI is shown in panel (b) of Fig. 2. This figure is drawn after running regression equation to visualize predicted

Table 2
Descriptive statistics and pairwise correlations.

Variables	Mean	SD	1	2	3	4	5	6	7	8	9	10	11
1. CSE	0.288	0.343	1										
2. CDI	2.609	2.046	0.024	1									
3. SIZE	16.844	1.109	−0.319*	0.218*	1								
4. RISK	0.641	0.197	−0.195*	0.113	−0.145	1							
5. AGE	3.742	0.428	−0.064	−0.013	0.199*	−0.076	1						
6. IND	0.400	0.492	−0.084	0.180*	0.105	0.269*	−0.457*	1					
7. Escore	62.046	24.556	−0.412*	0.356*	0.503*	0.115	0.317*	−0.080	1				
8. Sscore	71.739	21.927	−0.381*	0.389*	0.362*	0.216*	0.249*	0.002	0.792*	1			
9. Gscore	57.986	20.549	−0.391*	0.187*	0.272*	0.204*	0.021	0.146	0.493*	0.462*	1		
10. ROA	0.079	0.079	0.470*	0.253*	−0.026	−0.313*	0.071	−0.229*	0.083	0.056	−0.036	1	
11. Tobin's Q	0.757	0.763	0.447*	0.009	−0.113	0.136	−0.013	−0.004	−0.067	0.078	−0.049	0.457*	1

Notes: Number of observations: 150; SD: Standard deviation; * $p < 0.05$.



(a) **(b)**

Fig. 2. The nonlinear relationship between CDI and CSE.

Table 4
Panel regression results.

	(1)
Variables	CSE
CDI	−0.184***
	(0.052)
CDIsq	0.019***
	(0.004)
SIZE	−0.130***
	(0.036)
RISK	−0.527***
	(0.200)
AGE	−0.019
	(0.115)
IND	−0.007
	(0.105)
Observations	150
Number of firms	30
Lind and Mehlum [72] utest	
Overall utest	3.47
	(0.000)***
Lower bound slope	−0.174
	(0.000)***
Upper bound slope	0.223
	(0.000)***
Extreme point	4.934

Notes: Numbers in parentheses are robust standard errors, except for Lind and Mehlum [72] utest, which are p-values.
*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

(marginal) CSE values at different CDI values while controlling other factors.

Panel (a) in Fig. 3 illustrates the relationship between the environmental performance score (Escore), ROA, and CDI. The colors represent different levels of CDI, with blue indicating lower CDI and red indicating higher CDI. Most of the data is concentrated in the blue region, indicating that many firms have lower levels of DM. These firms exhibit a broad range of profitability (ROA), but their Escore tends to be lower to mid-range. As DM increases (green/yellow areas), we observe a wider distribution of environmental scores. Firms with moderate CDI may experience better environmental performance, but the relationship is not strictly linear. High-CDI firms (red areas) are mainly concentrated at higher Escore levels, suggesting that firms with advanced DM tend to have better environmental performance. However, these firms are not necessarily the most profitable, implying that strong environmental performance driven by digital orientation may not always align with immediate financial gains. DM enhances environmental performance by improving resource efficiency, monitoring emissions, and adopting sustainable practices. Profitability and digitalization show mixed effects, possibly because digital investments in sustainability require long-term commitment and may not yield immediate financial gains. There may be an optimal digitalization level where firms can balance environmental performance with profitability.

Panel (b) in Fig. 3 visualizes the relationship between Sscore, ROA, and CDI. Most firms operate at low levels of CDI. These firms display a wide range of Sscore, but many have relatively low ROA. This suggests that firms with poor social performance and low DM may struggle with profitability. As DM increases, firms with moderate Sscore values (40–80) show higher ROA. This implies that digitalization can enhance the financial benefits of social responsibility. Digital tools may help firms improve labor conditions, stakeholder engagement, and transparency, leading to better financial performance. The highest levels of CDI appear in firms with very high social performance (Sscore above 80). However, the distribution of ROA in these firms is mixed, implying that while some highly digitalized, socially responsible firms achieve strong financial returns, others struggle. Hence, DM positively affects the link between social performance and ROA, but the effect is not uniform. Firms with moderate to high social performance benefit more from DT in terms of profitability, whereas extremely high social performance does not always guarantee financial gain, implying that firms should balance social initiatives with financial sustainability.

Panel (c) in Fig. 3 illustrates the relationship between Gscore, ROA, and CDI. A significant portion of the firms operate at low CDI (blue regions). These firms exhibit low to moderate corporate governance scores (Gscore $\leq$ 50) and varying ROA, with many clustering around lower profitability. This suggests that firms with poor corporate governance and low digitalization tend to struggle financially. As Gscore increases (around 40–70), DM also rises (cyan/green areas). In this range, ROA appears to be more dispersed, with some firms experiencing better financial performance. This implies that improved corporate governance, combined with moderate digitalization, may enhance profitability. The highest levels of CDI are observed in firms with Gscore above 70. These firms display mixed profitability, meaning that while some companies achieve high returns, others still face financial challenges. In summary, the analysis reveals a positive association between corporate governance performance and DM levels. The impact of digitalization on profitability is more pronounced for firms exhibiting moderate to high governance scores. Nevertheless, the attainment of high governance scores does not invariably ensure superior profitability, underlining the importance of effective management practices, strategic alignment, and industry-specific contingencies in realizing the full potential of digitalization.

Regarding the control variables, the panel regression analysis results indicate that SIZE and RISK exhibit statistically significant relationships with CSE. Specifically, SIZE is negatively associated with CSE (β =

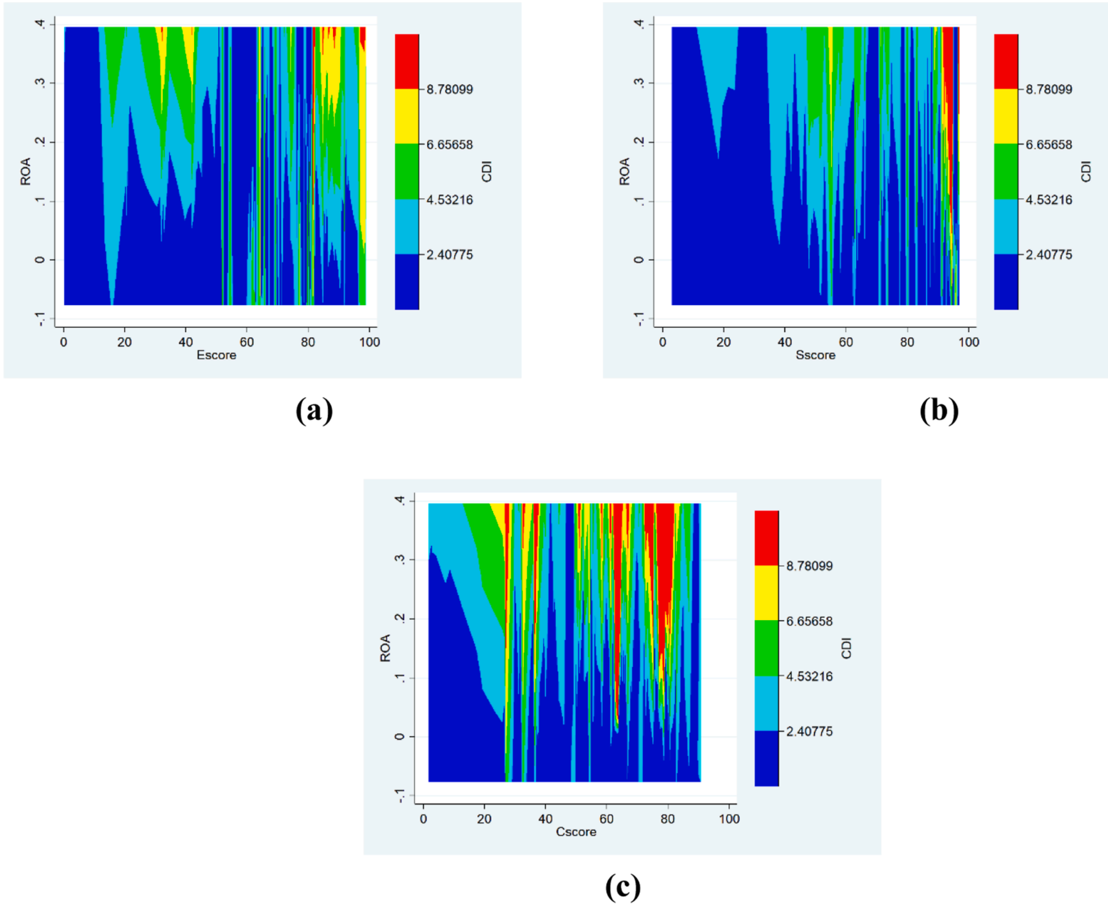


Fig. 3. The relationship between CDI, ROA and ESG scores.

−0.130, $p < 0.01$), suggesting that larger firms have lower CSE. Similarly, RISK demonstrates a negative relationship with CSE ($\beta = -0.527$, $p < 0.01$), indicating that firms with higher risk levels exhibit reduced efficiency in translating ESG investments into financial performance. The remaining control variables, AGE and IND, are not statistically significant predictors of CSE in the regression analyses.

5. Discussion and implications

5.1. Discussion of the findings

The findings of this study provide insightful evidence concerning the complex dynamics underlying the relationship between DM and CSE. Our empirical results extend previous studies by highlighting the non-linear characteristics of this relationship, highlighting the complex developmental processes through which DM influences CSE over time.

Initially, firms at the early stages of DM experience a decline in CSE. This observed initial downturn can be explained by significant upfront investments in technology infrastructure, costs related to workforce adaptation, and necessary organizational realignments that accompany digital capability-building processes. Such transitional inefficiencies align closely with theoretical expectations from the DCV, which posits that firms often encounter resource-intensive developmental stages before achieving capability maturity and strategic alignment [35,50]. These short-term inefficiencies reflect learning curves and organizational inertia that prevent firms from immediately capitalizing on digital initiatives for enhanced CSE. This phenomenon is consistent with prior empirical studies (e.g., [20]), emphasizing that digital initiatives may initially yield limited or delayed sustainability outcomes.

Over time, as firms further develop and refine their digital capabilities, these initial inefficiencies begin to diminish, ultimately giving way to positive sustainability efficiencies. This transition stresses a key insight emerging from our findings: firms achieve substantial sustainability improvements only after surpassing certain thresholds of digital capability development. More advanced stages of DM enable firms to benefit significantly from improved data-driven decision-making, streamlined operational processes, ameliorated ESG reporting accuracy, and more effective stakeholder engagement. These findings align well with empirical evidence reported in earlier studies, such as those by Wu et al. [42], Wang et al. [43], and Mahanta et al. [29], which confirm that firms with advanced digital capabilities experience enhanced ESG performance through refined operational processes, better governance structures, and greater transparency in sustainability disclosures. Additionally, this progression supports Warner and Wäger's [20] argument regarding the incremental and sometimes delayed nature of sustainability benefits associated with digital capabilities, highlighting the critical role of strategic alignment and sustained investment.

Regarding control variables, our results identify statistically significant negative impacts of SIZE and RISK on CSE. Specifically, firm size shows an inverse relationship with CSE, suggesting that larger firms in our sample exhibit a comparatively lower CSE. Although seemingly counterintuitive given common assumptions that larger firms have greater resources for sustainability investments, this result aligns with prior empirical findings indicating that organizational complexity and bureaucratic inertia in larger firms can negatively affect operational efficiency and ESG responsiveness [27,73]. Similarly, firms characterized by higher financial leverage exhibit significantly lower CSE. This negative relationship implies that greater financial risk, reflected through higher debt-to-asset ratios, may constrain firms' ability to flexibly allocate resources toward long-term sustainability initiatives due to short-term financial pressures. This finding is consistent with existing studies showing that firms with elevated risk profiles typically face restrictions in investing adequately in ESG activities, thus limiting sustainability outcomes [61,62].

5.2. Theoretical implications

From a theoretical standpoint, this study advances the DCV by emphasizing the role of DM as a dynamic process rather than a static technological asset. The findings clearly highlight that sustained competitive advantage and improvements in ESG performance depend on firms' ability to continuously sense emerging sustainability opportunities, seize digital resources, and strategically transform these resources to align with evolving sustainability imperatives. This perspective features continuous resource reconfiguration and strategic adaptation [37,38], reinforcing the argument that the dynamic integration and redeployment of digital capabilities are fundamental for meaningful and sustained ESG outcomes. In contrast to previous studies that primarily emphasize immediate technological adoption, this research underlines the critical role of adaptive capability-building processes, including ongoing organizational learning, strategic resource alignment, and the proactive integration of digital solutions into sustainability initiatives.

Moreover, by integrating stakeholder theory alongside DCV, this study enriches the theoretical discourse by illustrating why firms pursue DM as a strategic response to external sustainability demands. Stakeholder theory posits that firms operate within dynamic networks consisting of investors, regulatory bodies, consumers, employees, and communities, each imposing evolving pressure for increased ESG transparency, compliance, and accountability [36]. Our empirical findings support this perspective, demonstrating that digitally mature firms are more adept at strategically managing stakeholders' expectations by enhancing ESG disclosures, strengthening governance mechanisms, and embedding external feedback into their decision-making processes. Hence, DM emerges as both a dynamic internal capability and a strategic response mechanism enabling firms to align with external sustainability expectations effectively.

Furthermore, this study contributes theoretical insights into the evolutionary and adaptive nature of digital capability development by empirically uncovering the non-linear dynamics of the DM–CSE relationship. The results underline the notion that achieving CSE is neither immediate nor linear but involves distinct developmental phases characterized by varying levels of efficiency outcomes. Initially, firms encounter transitional inefficiencies due to substantial investment requirements, organizational inertia, and resistance to technological integration. However, over time, these firms refine their capabilities, strengthen their absorptive capacity, and systematically integrate digital innovations into their ESG strategies, eventually realizing significant CSE gains. This non-linear dynamic enriches the theoretical understanding offered by DCV, highlighting that the sustainability benefits of digital capability investments unfold dynamically rather than instantaneously or predictably.

5.3. Practical implications

This study offers critical implications for corporate managers, policymakers, and investors by providing an empirically grounded, efficiency-focused perspective on the integration of DM and CSE. By utilizing DEA, the study introduces a rigorous benchmarking approach, allowing stakeholders to systematically evaluate how effectively firms convert ESG-related investments into financial and competitive outcomes. This precise benchmarking can inform strategic decision-making, enabling managers to identify specific areas for improvement, particularly when balancing DM costs with anticipated sustainability benefits.

For corporate managers, the findings emphasize the strategic importance of adopting structured and phased approaches to DM. Given that the study reveals an initial decline in CSE due to substantial upfront investments, organizational inertia, and employee adaptation challenges, managers must proactively manage these transitional risks. Firms should anticipate potential short-term inefficiencies by incorporating strategic initiatives such as incremental digital investments, workforce training programs, and culture-building practices that facilitate smoother digital integration. Furthermore, the results underline the necessity of aligning DM initiatives closely with ESG objectives, ensuring that digital strategies enhance, rather than undermine, long-term sustainability goals.

From a policy standpoint, the study highlights the need for supportive regulatory frameworks and targeted incentives to foster DM and sustainable innovation simultaneously. Policymakers can leverage these insights by designing targeted digitalization incentives such as subsidies for early-stage technological investments, digital infrastructure support, and workforce reskilling programs aimed specifically at mitigating the transitional costs associated with DM. Additionally, establishing national benchmarks or standards based on the developed CDI can encourage firms to transparently disclose their DM levels, facilitating comparative analyses and better-informed policymaking.

For investors, understanding the curvilinear relationship between DM and CSE provides guidance for investment strategies. Recognizing that firms at different stages of digital capability development exhibit varying levels of ESG efficiency, investors can use this insight to evaluate long-term sustainability potential and risk profiles more accurately. Such evaluation criteria can inform investment decisions, helping investors prioritize companies demonstrating coherent and strategic integration of DM and ESG practices, thereby mitigating potential short-term inefficiencies.

5.4. Limitations and future research

Despite providing valuable insights, our study has several limitations that should be acknowledged and addressed in future research. First, our sample comprises only publicly listed companies due to data availability constraints regarding corporate digitalization and ESG scores. Consequently, the findings might not capture the complete spectrum of DM and sustainability practices among firms operating in other organizational contexts, such as privately held companies or small enterprises. Future research may extend the analysis to include a broader set of firms, allowing for deeper comparative assessments of how digital capabilities influence sustainability outcomes across diverse organizational forms.

Second, as our empirical context focuses exclusively on Turkish companies, this geographical constraint may limit the generalizability of our findings to other emerging markets. Institutional variations, differences in digital infrastructure, regulatory environments, and cultural attitudes towards ESG issues may influence the nature and trajectory of DM. Therefore, subsequent studies should replicate our analytical approach in other emerging economies to verify whether the identified curvilinear relationship holds across different institutional settings. Future studies could conduct cross-country comparisons to provide deeper insights into the contextual complexities underlying the DM and CSE relationship.

Third, the present study relies on secondary data derived from publicly disclosed annual reports, where the extent of information regarding digitalization might be constrained by corporate confidentiality concerns. Although text mining provides a robust method to quantify corporate digitalization objectively, it may not fully capture firms' internal digital strategies or the actual depth of DM. Future research can mitigate this limitation by employing primary data collection methods such as surveys, interviews, or in-depth case studies to capture richer, qualitative aspects of DM. Such methods can yield more robust and multidimensional data, enhancing the validity, accuracy, and interpretability of findings regarding firms' digital capability development.

Fourth, our empirical model incorporates specific control variables (firm size, risk, age, and industry) to isolate the primary relationship of interest. Nevertheless, additional factors (e.g., leadership orientation, organizational culture, and technological infrastructure) that may affect digitalization adoption strategies and sustainability practices have not been explicitly examined. Future research could incorporate these variables, offering more detailed insights into the contingent factors that shape the DM–CSE relationship.

Finally, while the SBM-VRS model employed in this study provides valuable efficiency insights, it carries inherent limitations. Despite its strengths, the SBM-VRS model's detailed and precise efficiency evaluation, while insightful, can be complex to interpret compared to simpler DEA models. Furthermore, because SBM-VRS is sensitive to the data set employed, results might vary depending on the selected inputs, outputs, and the sample's efficiency frontier. Future studies may explore alternative DEA models or complementary methodological approaches to cross-validate and enrich efficiency estimations.

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

During the preparation of this work, the authors edited the manuscript using ChatGPT4o and Grammarly. After using these tools, they reviewed and edited the content as needed and took full responsibility for the content of the published article.

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CRediT authorship contribution statement

Mustafa K. Yilmaz: Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **Mine Aksoy:** Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Ekrem Tatoglu:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. **Erkan Bayraktar:** Writing – review & editing, Visualization, Software, Resources, Investigation, Formal analysis.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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