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Understanding sustainable outcomes in the digital age: The vital role of digital leadership in leveraging the impact of green innovations

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A B S T R A C T

The increasing complexities posed by green organizational challenges and technological advancements require a thorough grasp of the vital capabilities needed to maintain the firm's sustainable performance. This study aims to explore the associations of green technological innovation and management innovation to sustainable performance and estimate to what extent digital leadership moderates these associations. The resource-based view (RBV) and socio-technical system theory (STS) are leveraged to conceptualize the research model. By adopting a survey-based approach on data gathered from 419 manufacturing and service firms, the PLS-SEM is the statistical approach conducted to test the validity of predictions The outcomes demonstrated that green technological innovation, green management innovation, and digital leadership are positively linked to sustainable performance. Furthermore, higher digital leadership strengthens the linkage of green technology and management innovation to sustainable performance. The outcomes made a powerful contribution to the current literature on green innovations and digital transformation, and substantial recommendations were inferred for organizations aiming to achieve environmental, social, and economic performance.

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1. Introduction

Integrating digital technologies into business operations has become essential for organizations seeking to maintain competitiveness, particularly as the demand for sustainable practices continues to rise (Grybauskas et al., 2022). However, numerous real cases revealed that adopting fresh technologies in the service and manufacturing sectors does not ensure business success (Tabrizi et al., 2019), it is maintained that many aspects must be arranged with digitalization initiatives to ensure satisfactory performance (Sahoo et al., 2024). In the crucial role of digitalization for future accomplishment, one of the critical factors to consider is the formulation of a comprehensive digital vision, mindset, and skills for people within the organization (Hensellek, 2022). The array of roles that leaders undertake to drive and sustain digital transformation constitute digital leadership. Digital leadership encompasses many roles and abilities to guide digital transformation within organizations (McCarthy et al., 2022). In the digital age where organizations are forced to offer digitalized products with digitalization of processes and business models, developing novel abilities and behaviors for leaders is mandatory (Shin et al., 2023).

On the other hand, contemporary discussions are placing growing emphasis on approaches directed towards lessening the adverse effects of environmental decline arising from pollution and inefficient utilization of natural resources (Wen & Zhang, 2024). This idea aligns with the sustainable development goals (SDGs) (UN, 2024). The necessary tactics to realize sustainable

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performance at the micro-level, including environmental, social, and economic performance, have attracted considerable focus from scholars and practitioners (Ghorbani, 2023; Ullah Khan et al., 2023; Zhou et al., 2022). Progressing towards these sustainability objectives requires active participation not just from governments but also from businesses (Mahajan et al., 2024; Niesten et al., 2017). In this context, one of the aims of SDGs is to promote innovation and enhance the technological capacities of industrial sectors (G9), especially within developing and least-developed economies in Africa (UN, 2024).

Since the digitalization process enhances environmental doubt and makes the sustainable management process more complex and uncommon, the ability of leaders to stimulate their subordinates is deemed fundamental in gaining employee acceptance of new digital projects and fostering creativity and involvement (Shin et al., 2023). With the pervasive progressions in information technologies and management practices, researchers have focused on leadership in the context of digital technology to achieve economic performance. Multiple studies have underscored the significance of green innovations in attaining sustainable outcomes, indicating that the adoption of eco-friendly technologies is seen as a key driver of sustainable performance (Cisneros Chavira et al., 2023; Hao et al., 2022; Rupasinghe et al., 2024; Tian, Siddik, et al., 2023; Ullah et al., 2024). Even with this bulk of studies, a recent systematic review suggested that sustainable development and environmental performance are the areas where green innovation research needs further exploration (Rupasinghe et al., 2024).

Besides, by adopting a people managerial perspective, studies have emphasized the substantial implication of leadership approaches in attaining sustainable outcomes, including responsible leadership, environmental leadership, and green transformational leadership (He et al., 2023; Lathabhavan & Kaur, 2023; Su et al., 2020; Ullah Khan et al., 2023; Xin & Wang, 2023; Younis & Hussain, 2023). However, the association between digital leadership and sustainable performance is not fully understood (Lyu, 2024), particularly through the contextualization of green innovation forms, such as green management innovation and green technological innovation (Niu et al., 2022; Sarfraz et al., 2022; Tian, Han, et al., 2023). Additionally, it is assumed that digital leadership plays a moderate role in the influence of digitalization capabilities at the workplace on firm performance (Chatterjee et al., 2023). However, there is a scarcity of studies analyzing the role of digital leadership in the realm of sustainable orientation and green innovations (Sarfraz et al., 2022). Against this context, this study underscores the crucial role of digital leadership in advancing firm performance, especially through its direct and moderating influence. It emphasizes the importance of leveraging a digital leadership approach within organizations, as the relationship between green innovations and sustainable outcomes requires deeper investigation to effectively navigate modern organizational complexities.

To address the complexity of digitalization and sustainability phenomenon within organizations, we developed a research model relying on resource-based theory (RBV) and Socio-Technical System (STS). The RBV explains the linkage of green innovations to sustainable performance since this theory highlights the significant role of firms' rare and valuable resources in achieving success and increasing competitive edge (Barney et al., 2011). In this context, green innovations have been viewed as a substantial intangible resource that organizations struggle to replicate, meanwhile impact positively on firm ecological outcomes (Fernando & Wah, 2017). Furthermore, STS is a framework that accentuates the importance of interactions between social and technical aspects of the system (Mumford, 2006). Leadership involves coordinating the tasks of individuals to achieve the organization's objectives, representing a form of social influence (Barge & Schlueter, 1991). In essence, this study posits that firms aiming for performance in the realm of sustainability call and within the digital era, firms need to develop their capabilities to find a new manner to execute their operations and activities but also need to shift their focus toward the human element within the organization (Tigre et al., 2024). Hence, green innovation and digital leadership are centerpieces for firms to develop the ability to maintain desired levels of performance over the long term, while also considering environmental, social, and economic outcomes.

2. Literature review and hypothesis development

2.1 Underpinning theories

To address the complexity of digitalization, this study conceptualized model research in Figure 0. Drawing on RBV and STS theory, this research will contend that effective digital leadership within organizations can promote and amplify the significance of green technological and administrative innovation in attaining sustainability goals at the micro-level. We adopted RBV to explain the associations between green innovations and sustainable performance. This framework emerged and evolved in strategic management (Ferreira & Ferreira, 2024). It accentuates the significance of firm resources to achieve success and gain a competitive edge (Barney et al., 2011). For quite some time, green innovations have been regarded as a significant intangible resource that organizations struggle to replicate (Fernando & Wah, 2017; Ni et al., 2023). This powerful framework of RBV is extensively elected as theory-guided research to highlight sustainable performance dimensions through the initiatives of green innovations (Ali et al., 2024; Bonsu et al., 2024; Khanra et al., 2022; Ullah et al., 2024). In this setting, an organization that directs its resources and capabilities towards developing and adopting green innovative solutions across various aspects such as technology, processes, management, structure, and knowledge, is more likely to achieve long-term success without negative environmental and social effects. Furthermore, STS is a framework that highlights the importance of interactions between social and technical dimensions of digital transformation to achieve firm performance (Barba-Sánchez et al., 2024). Mumford (2006) posited that integrating the technology tools and platforms aimed at enhancing performance entails addressing not only technical concerns but also involves considerations of business processes, organizational behavior,

and orchestration (Mumford, 2006). Leadership is about organizing the activities of subordinates toward accomplishing the organizational goals, which is a form of social influence (Barge & Schlueter, 1991). Leadership also has been recognized as a bundle of competencies where intrapersonal (self-performance) and interpersonal (social skills) abilities are mixed with technical and intellectual knowledge to develop a compelling vision and manage diversity (Hogan & Kaiser, 2005). In the meantime, digital leadership includes both the human side with social dimensions and the technical side with digital matters (Oberer & Erkollar, 2018). Therefore, STS is suitable to sustain the assumption that digital leadership is primordial within the digital transformation process on one side and in the green initiatives as a business process on the other side to get the better of organizational sustainable performance.

2.2 Digital leadership

As information technologies continue to advance, business managers are exerting significant pressure on traditional organizational activities and structures, pushing for the development of new business models that are based on emerging technologies (Verhoef et al., 2021). Digital transformation (DT) refers to "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies" (Vial, 2019). For a successful digital transformation and industry 4.0 implementation, organizations must adopt strategic considerations across various domains, with effective digital leadership playing a key role in facilitating this transition (Avwokeni, 2024; Sahoo et al., 2024; Tagscherer & Carbon, 2023; Yao et al., 2023). Scholars and practitioners argued that digital technologies significantly impact the relationship between leaders and subordinates, which highlights active relationship management, participative leadership, and clear framework conditions (Gilli et al., 2024; Kraus et al., 2023). In effectively navigating digital transformation, new leadership roles emerge alongside conventional ones. To confront associated challenges, digital leaders must adopt roles such as early trend detection (digital pioneer), seeking staff input, and refining digital competencies (digital mentee) (Weber et al., 2022). Leadership is the most important phenomenon in human science (Hogan & Kaiser, 2005). Since leaders coordinate, build teams, develop mission and vision, motivate, and communicate (Bolton et al., 2013), leadership is a vital element in strategic management (Slavik et al., 2015). In an era of digitalization, digital leadership arises as a novel concept in response to the increasing integration of digital technologies within organizational operations and communication. It remains a subject of ongoing discussion, given its pivotal role in enabling organizations to navigate the challenges posed by digital disruption (Tigre et al., 2023). Mihardjo et al. (2019) argued that digital leadership involves combining culture and digital competencies to utilize new technologies within leadership, aiming to increase organizational value (Mihardjo et al., 2019; Mihardjo & Rukmana, 2018). However, numerous efforts have been made to elucidate the complexities of digital leadership by exploring the various dimensions it encompasses. Philip et al. (2023) conducted a qualitative investigation aiming to identify key competencies essential for effectively leading digital transformation. Their findings revealed that successful digital leadership hinges on a mixture of behavioral and strategic skills, notably visionary thinking, agility, data appreciation, data-driven decision-making, knowledge of strategy, and adaptability to change. Furthermore, they underlined that demonstrating behavioral competencies in digital leadership collectively outweighs exhibiting strategic competencies in propelling the digital transformation (Philip et al., 2023). In a digitally evolving environment, effective digital leaders demand skills to strive for social cohesion (i.e., foster teamwork), strong change management (i.e., inspire innovation), and conceptual digitization skills (i.e., ethical data management) (Gilli et al., 2024). Given the multifaceted nature of digital transformation, the competencies demanded by digital leadership vary according to the specific objectives of digitalization initiatives (Müller et al., 2024). Müller et al. (2024) introduce the concept of digital leadership competency portfolios, delineating it across technical, business, and interpersonal dimensions. Technical competencies relate to proficiency in hardware, software, data, and emerging technologies. Business competencies encompass strategic vision and benefit realization. People-oriented competencies include relationship-building and effective communication (Müller et al., 2024). Effective digital leadership requires general aspects such as creativity, adaptability, empowerment, data analysis, collaboration, knowledge sharing, empathy, and diversity awareness (Tagscherer & Carbon, 2023).

Through focusing on the golden triangle of leadership, sustainability, and digitalization, scholars have directed their attention toward exploring leadership within the realm of digital technology to enhance sustainable performance (Lyu, 2024; Memon & Ooi, 2023). Although digital leadership enhances business success, insufficient research exists in the organizational literature, urging further academic exploration of digital leadership traits and styles (Marcel De Araujo et al., 2021). In this context, the present research aims to explore empirically further the ongoing inquiry into the role of digital leadership as a foundational element in augmenting the impact of green innovations on sustainable outcomes (Sarfraz et al., 2022).

2.3 Green innovations

In the contemporary era, as environmental degradation continues to intensify, presenting a substantial peril to human existence, there is a growing emphasis among individuals, businesses, and governments on embracing sustainable practices within organizations (Niesten et al., 2017; Ullah Khan et al., 2023). In business research with various contexts and methodologies, scholars have extensively examined the crucial element contributing to sustainable performance, which revolves around green innovations (Karimi Takalo et al., 2021; Rupasinghe et al., 2024).

Green innovations refer to organization practices engaged in reducing energy consumption and pollution emissions, recycling wastes, and designing eco-friendly products (El-Kassar & Singh, 2019). It also refers to the production and exploitation of a product, process, organizational structure, and business method that is novel to the organization, which results in a reduction of environmental risk compared to relevant alternatives (Ben Arfi et al., 2018). For that reason, green innovations entail several green constructs within the organization's life cycle (Dang et al., 2024). For instance, two primary categories of green innovations are distinct: green technology innovation and green management innovation (Anzola-Román et al., 2024; Khan et al., 2024; Li et al., 2018). The first is the inclusion of new technologies, processes, and materials to control the negative effects of firm operations, while the second encompasses incorporating new policies, processes, and organizational structures to adopt eco-conscious practices. The adoption or development of new green solutions is driven by both external and internal pressures (Z. Chen & Liang, 2023; Haryono & Sari, 2024). For example, the possible pressures could be aligning with market competition, meeting consumer expectations, or adhering to governmental mandates necessitating innovative approaches.

Another driving factor might involve seeking optimal strategies for cost reduction and bolstering competitiveness within the market. Regardless of its source, the fresh advancement in technology aimed at enhancing environmental practices and fostering the progression towards a more sustainable future has to play a key role in ensuring the success and competitiveness of businesses (Khan et al., 2024). Similarly, green management innovation, a subset of green and management innovation, promises economic growth and environmental protection, while also serving as a source of competitive edge by enhancing firms' efficiency, quality, and productivity, ultimately impacting overall performance (Ma et al., 2018). Nevertheless, green non-technological innovation, particularly green management innovation has received less attention compared to technological innovation (Ma et al., 2018). Hence, the current study aims to investigate the impact of both green innovation technology and management on sustainable performance.

2.4 Sustainable performance

In 2015, the United Nations (UN) introduced the Sustainable Development Goals (SDGs), comprising 17 objectives aimed at fostering a more globally sustainable future. Businesses play a crucial role in supporting various SDGs by integrating them into their strategic management and sustainability initiatives (Domingo-Posada et al., 2024; García-Sánchez et al., 2020; Tsalis et al., 2020). In the pursuit of sustainable development goals (SDGs), businesses play a significant role which can be demonstrated through strategic initiatives such as entrepreneurship focused on sustainability, the adoption of corporate social responsibility practices, the promotion of green innovations, utilization of clean energy, and the implementation of responsible production methods, among other approaches, each with varying levels of emphasis (Mio et al., 2020). At the micro-level, organizations aspire to achieve more social, economic, and environmental outcomes set forth by their green initiatives. An exact description of form sustainable performance has not been universally agreed upon yet. However, it is broadly understood as a "*strategic objective for corporations to attain environmental, social, and economic performance"* (Piwowar-Sulej & Iqbal, 2023). The combined three aspects of sustainability represent the evaluation of sustainable performance (Büyüközkan & Karabulut, 2018). As illustrative instances, though not exhaustively comprehensive, the environmental dimension emphasizes ensuring unpolluted air and water, preserving resources, and promoting environmentally friendly products. Simultaneously, the social dimension highlights the importance of fostering social relationships, human well-being, cultural diversity, fairness, and equity. Lastly, the economic dimension strives for profitability and sales (S. Wang et al., 2022). To attain these sustainable outcomes, several studies have placed the subsequent role of resources and capabilities reorchestration, as green management systems, green innovations, and leadership style are the precursors (Abbas & Khan, 2023; Khan et al., 2024; Lestari & Sunyoto, 2023; Piwowar-Sulej & Iqbal, 2023; Ullah Khan et al., 2023).

2.5 Hypotheses development

The present research framework is constructed based on RBV and STS. Drawing from RBV, we hypothesize that incorporating green innovation as valuable resources and capabilities will improve the sustainable outcomes of firms. Furthermore, through the lens of STS, we argue that competencies in digital leadership will merge technological and social aspects, enabling the efficient deployment of green novel initiatives and thereby securing sustainable performance. Fig. 1.

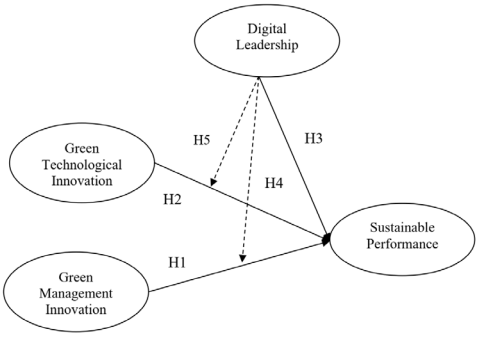


Fig. 1. Conceptual model of the research

2.5.1 Green innovations and Sustainable performance

The adoption and execution of new environmentally friendly strategies within the organization, such as advancements in operational and managerial systems, exemplify the ecological focus of the entity. When organizations attempt to confront sustainability challenges by encouraging green innovations and patent applications, they can enhance their corporate value and profitability (Aguilera-Caracuel & Ortiz-de-Mandojana, 2013; Hao et al., 2022). These measures not only offer positive financial outcomes but also have the potential to create environmental benefits (Bhat et al., 2024) collectively achieve economic growth, and positively enhance society's well-being (R. Chen et al., 2023). A study in the China context revealed that green innovation and patent applications that decrease pollution emissions have the potential to influence the corporate green reputation (Z. Chen et al., 2023). Several studies have highlighted those green innovations involving sustainable advancements in business operations through the improvements in traditional technologies, products, and managerial methods to enhance the organization's sustainable performance across environmental, economic, and social aspects (Cisneros Chavira et al., 2023; Rupasinghe et al., 2024; Tian, Siddik, et al., 2023; Ullah et al., 2024). The conjunction of green technological innovation with the green management system related to knowledge and green culture improves organizational capabilities to achieve sustainable development goals (S. Wang et al., 2022). In the context of SMEs and large companies, a recent study showed that several green innovation constructs can sustain a green competitive edge (Dang et al., 2024). Planning to green innovation, recyclable materials, emission reduction, and energy savings serve as boosters of environmental and financial performance (Su et al., 2020). Integrating AGVs into supply chains enhances productivity, slashes cost, accelerates delivery times, reduces energy consumption and emissions, and bolsters safety measures, thus giving a significant competitive edge (Bechtsis et al., 2017). Implementing environmentally friendly management techniques by adjusting strategies to meet environmental standards and enhancing current management systems is crucial for enhancing organizational performance across environmental aspects such as waste reduction, economic factors like profitability, and social elements such as safety (Elshaer et al., 2023). The linkage between green innovation dimensions and sustainable performance dimensions is understood by the RBV, implying that green innovation is an organizational ability and resource (intangible) that can attain a competitive edge as it reduces pollution, saves costs, reinforces positive reputation (Bonsu et al., 2024; Ullah et al., 2024). Thus, given that our research model embraces both technological and management green innovation, we propose the following hypotheses:

H_1: *Green management innovation has a positive link with sustainable performance.*

H_2: *Green technological innovation has a positive link with sustainable performance.*

2.5.2 Digital leadership and sustainable performance

The success of digital leadership entails both digital skills and social skills. This is the essence of STS, explaining that the implementation of a new technological system must bring into line the human aspect within the process of development (Appelbaum, 1997) and organizational adaptability and innovativeness (Stanley & Aggarwal, 2023). The people are the foundation stone of the organizational green orientation (Joshi et al., 2023; Ma et al., 2021), and are predominantly important in digital transformation and Industry 4.0 (Abbu et al., 2022; AlNuaimi et al., 2022). The managers called leaders, in the middle management position, are found to play a substantial role in fulfilling the subordinate's green behavior and abilities with sustainable performance and competitive edge (Janjua et al., 2024; Younis & Hussain, 2023). However, drawing from the capability theory, it was found that digital leadership empowers organizations to innovate, because leader digital skills enable the effective merging of resources, business skills, and information system skills, allowing for strategic planning of business processes, ultimately enhancing firm and brand performance (Benitez et al., 2022; Mihardjo et al., 2019; Mihardjo & Rukmana, 2018; T. Wang et al., 2022). In the digital era, leaders bear the responsibility of verifying the alignment between technological advancements implemented and the attainment of organizational performance objectives (Bechtsis et al., 2017). The absence of adequate digital leadership competencies for organizing tasks and addressing problems within a digitized setting presents an obstacle to transitioning traditional industries into Industry 4.0 (Avwokeni, 2024). It is worth mentioning that incorporating the concept of digital leadership in green and sustainable business to determine organization performance is not well-documented (Senadjki et al., 2024).

H_3: *Digital leadership has a positive link with sustainable performance.*

2.5.3 The moderating role of digital leadership

The explicit mechanisms through which digital leadership can take advantage of green innovations to achieve sustainable performance are not clearly defined. Some near associations exist, for example, digital leadership has a positive impact on responsible innovation (innovations that imply ethical, environmental, and societal dimensions) which leads to sustaining a competitive edge (Memon & Ooi, 2023). A study found that innovation capabilities have a positive direct impact on sustainable performance, while digital leadership moderates the association between social media marketing and performance (Borah et al., 2022). Research expands leadership and innovation literature, showing digital leadership influences green innovation, mediated by a commitment to environmental and social sustainability goals (Tian, Han, et al., 2023).

Given the complexity of management tasks and the prevailing business environment, leaders are required to exhibit a diverse array of personality traits and competencies to effectively safeguard the organization and attain a competitive advantage (Bolton et al., 2013; Haruna, 2022). Within the specific context of sustainability, digital leadership plays a pivotal role in facilitating the relationship between green innovations and sustainable performance by leveraging technological tools (Cortellazzo et al., 2019; Gilli et al., 2024), fostering organizational agility (AlNuaimi et al., 2022), changing a variety of work-related aspects (Chatterjee et al., 2023), and promoting a culture of innovation (Al Issa & Omar, 2024; S. Wang et al., 2022; T. Wang et al., 2022). Drawing that leadership is an essential tool in managing an organization (Slavik et al., 2015), organizations that recognize the significance of environmental concerns confronting the organization and incorporate them into the company's strategic plans are identified as a crucial factor that can moderate the influence of green products and green process innovation on environmental performance (Rehman et al., 2021). In terms of the above arguments, we assume that through effective digital leadership, organizations can integrate green innovations seamlessly into their operations and systems, thereby driving continuous improvement and long-term sustainability goals. Thus, the following hypotheses are developed.

H_4: *Digital leadership positively mediates the link of green management innovation with sustainable performance.*

H_5: *Digital leadership positively mediates the link of green technological innovation with sustainable performance.*

3. Methodology

3.1 Measurements

The approach to test the research model is to gather data using the survey method using a questionnaire administered to the representative of the organization at the exhibition. The survey through questionnaire is most commonly used in the context of sustainability management and digital transformation (Sarfraz et al., 2022). The questionnaire comprised three sections: an introduction to the study, variables, and sample profile. This study utilized a pre-existing scale to evaluate the constructs of the model (See Appendix 1). Green technological innovation was assessed using a five-item scale adapted from (Khan et al., 2024). Green management innovation was measured through a four-item scale adapted from (Ma et al., 2018). Sustainable performance was measured through an eight-item scale adapted from (Khan et al., 2024). Digital leadership was measured using a six-item scale adapted from (Erhan et al., 2022; Shin et al., 2023). However, the item “A digital leader raises awareness of the employees of the organization about IT risks” obtained a low loading value (< 0.708) and was therefore removed from the analysis (Hair et al., 2019).

3.2 Target population

Our research focuses on organizations with a sustainability orientation that are undergoing digital transformation to varying extents. Therefore, two screening questions were asked orally after a clear description of the research objectives. The first pertained to “the degree of digitalization processes implemented by the organization: Is your organization focused on digitalization?”. The subsequent question addressed "the organization's inclination towards sustainable practices: Does your organization prioritize sustainable practices?" In the absence of any efforts of digitalization or sustainability, the organization was overlooked, and then we moved to another organization. The organizations included in the sample were chosen from exhibitions hosted by Safex (Safex, 2024). Numerous companies participated in these exhibitions with the objective of networking and establishing partnerships. Each exhibition is centered around a specific theme, providing an ideal setting to gather data from exhibitors, who are concentrated in one location and generally inclined to share their experiences.

3.3 Sample size

Based on the proposed inverse square root method, a sample size of 155 is deemed necessary for PLS-SEM tests to achieve a minimum 80 percent power level, contingent on the path coefficient's effect size of 0.2, at a significance level of $P < .05$ (Kock & Hadaya, 2018). We collected 419 valid responses, which is significantly adequate to yield dependable results.

3.4 Ethical standards

The participation of organizational representatives in the survey was entirely voluntary. Following the disclosure of our affiliations and mission, we provided a clear explanation of the study's objectives. We assured participants that data handling procedures were designed to facilitate the predictive analysis of the phenomena under investigation, without divulging specific firm names or individual evaluations. Consequently, privacy concerns were duly addressed.

3.5 Analysis strategy

To assess the predictive efficacy of the research model, we employed the PLS-SEM approach due to the multifaceted nature of the associations involved (Hair et al., 2019). The smart PLS4 was used as a statistical package. Before presenting the structural findings, we assessed the validity of the model, utilizing path estimation to assess the effect, and relying on p-values and t-statistics to ascertain the significance of the associations.

4. Results

4.1 Sample profile

The most prevalent exhibition theme in which we collected data is "African pharmaceutical technologies", with 145 participants, constituting 35% of the total sample, followed by "electricity and renewable energy" at 103 participants, representing 25%, followed closely behind by "recycling and valorization of wastes" (24%). The participants in the "printing and packaging" theme comprised 68, making up 16.23% of the respondents in the dataset. Even if these organizations pertain to traditional activities, the study has already excluded firms that do not prioritize eco-friendly practices and ongoing digitalization. The sample is expected to represent the organizations that are actively committed to such initiatives. Regarding the firm category, dominated manufacturing firms dominate with 296 participants, making up 70.6% of the total, while dominated-services firms constitute 29.4%. Large companies lead with 209 participants, representing 49.9% of the total, followed by Medium-sized firms with 142 participants. In terms of respondent gender, males represent the majority with 297 participants, constituting 70.9%. Middle management positions are most prevalent with 216 respondents (51.6%), followed by lower management positions at 127 (30.3%), and higher management positions at 76 (18.1%). Finally, in educational background, individuals with Bachelor's degrees are the majority with 236 respondents (56.3%), followed by those with technical degrees at 103 (24.6%), and those with Master's degrees at 80 (19.1%).

Table 1
Sample characteristics (n= 419)

Characteristics	Classification	Freq (n)	Perc (%)
Exhibition themes	African Pharmaceutical Technologies	146	34.84%
	Electricity and Renewable Energy	103	24.58%
	Printing and Packaging	68	16.23%
	Recycling and Valorization of Wastes	102	24.3%
Firm category	Dominated-Manufacturing	296	70.6%
	Dominated-Services	123	29.4%
Firm size	Small	68	16.2%
	Medium	142	33.9%
	Large	209	49.9%
Gender	Male	297	70.9%
	Female	122	29.1%
Management position	Lower	127	30.3%
	Middle	216	51.6%
	Higher	76	18.1%
Educational background	Bachelor degree	236	56.3%
	Master degree	80	19.1%
	Technical degree	103	24.6%

Source: primary data output

4.2 Measurement model

Table 2
The items' loadings Cronbach's coefficients and AVEs

Indicators	Outer loadings	Cronbach's alpha	Composite reliability	AVE
Digital Leadership		0.956	0.966	0.851
DL1	0.909			
DL2	0.940			
DL3	0.914			
DL4	0.934			
DL5	0.914			
Green Management Innovation		0.883	0.919	0.74
GMI1	0.890			
GMI2	0.878			
GMI3	0.852			
GMI4	0.818			
Green Technological Innovation		0.871	0.903	0.652
GTI1	0.735			
GTI2	0.780			
GTI3	0.843			
GTI4	0.845			
GTI5	0.828			
Sustainable Performance		0.941	0.951	0.708
SP1	0.883			
SP2	0.904			
SP3	0.883			
SP4	0.810			
SP5	0.807			
SP6	0.848			
SP7	0.829			
SP8	0.756			

The results in Table 2 provided are from a measurement model evaluation. The outer loading values indicate the strength of the relationship between each indicator and its underlying construct. Higher values suggest a stronger association. Overall, all indicators demonstrate strong outer loadings, indicating that they effectively measure their respective constructs since their values are above 0.708 (Hair et al., 2019). The statistics of Cronbach's Alpha measures the internal consistency of a scale. A value above 0.7 is generally considered acceptable (Hair et al., 2019). The values provided for each construct meet this criterion. Like Cronbach's alpha, CR (composite reliability) assesses the internal consistency of a scale. Again, values above 0.7 are preferred (Hair et al., 2019). In this case, all constructs exceed this threshold, indicative of respectable reliability. In addition, the metric of Average Variance Extracted (AVE) assesses the amount of variance captured by the construct relative to the measurement error. AVE values above 0.5 are typically considered acceptable (Hair et al., 2019), indicating convergent validity. All constructs meet this criterion. We utilize the Fornell and Larcker's method of calculating the average variance extracted (AVE) to assess the discriminant validity of our measurements (Henseler et al., 2015). The AVE quantifies the proportion of variance accounted for by a construct through its constituent items in comparison to the variance attributed to measurement error. Ensuring discriminant validity entails that the square root of a construct's AVE exceeds the correlations between that construct and others within the model (Hair et al., 2019). In Table 0. We can conclude that the data satisfy the requirement of discriminant validity since the diagonal values (AVE) for each construct are greater than the correlations with other constructs. In addition, this table shows the correlations among each peer of constructs. The correlation values indicate that all associations as assumed by our research model are positive and strong. in particular, digital leadership, GTI, and GMI all exert a tolerable positive correlation with sustainable performance, $r = 0.777$, 0.756, 0.773 sequentially.

Table 3
Correlation matrix and Fornell and Larcker's criterion

	1	2	3	4
Digital Leadership	***0.922***			
Green Management Innovation	0.792	***0.86***		
Green Technological Innovation	0.539	0.451	***0.807***	
Sustainable Performance	0.777	0.773	0.526	***0.841***

Source: primary data output

4.3. Structural model

Fig. 2 presents the path model. Table 4 presents path estimates, T statistics, P values, Lower Limit of Confidence Interval (LLCI) at 5.00%, Upper Limit of Confidence Interval (ULCI) at 95.00%, and Variance Inflation Factor (VIF). To provide more robust results, we reported VIFs, the higher values indicate a significant issue with multicollinearity. Since these values are less than 3.3, the model remains non-contaminated by common method bias (Kock, 2017), and since are less than 5, the stability of regression estimates is reinforced (Hair et al., 2021).

Table 4
Direct effect results

	Path estimate	T statistics	P values	LLCI 5.00%	ULCI 95.00%	VIF	Decision
H1. GMI → SP	0.360	8.532	0.000	0.291	0.430	2.809	Supported
H2. GTI → SP	0.166	4.39	0.000	0.108	0.232	1.637	Supported
H3. DL → SP	0.407	8.689	0.000	0.327	0.481	3.123	Supported

Source: primary data output

The association between green management innovation and sustainable performance is positive and moderately strong (β = 0.36). The T statistic is 8.53, indicating that this relationship is statistically significant at a p-value of 0. The confidence interval ranges from 0.29 to 0.43, suggesting the precision of the estimate. These outcomes support H1. Furthermore, the path from green technological innovation to sustainable performance was also found to be positive (β = 0.16) and statistically at the p-value threshold (t = 4.39, p = 0.000). The confidence interval ranges from 0.10 to 0.23, supporting hypothesis H2. Moreover, the findings reveal a positive and significant association between digital leadership and sustainable performance (β = 0.40; t = 8.86; p < 0.050). The confidence interval ranges from 0.32 to 0.48, supporting hypothesis H3.

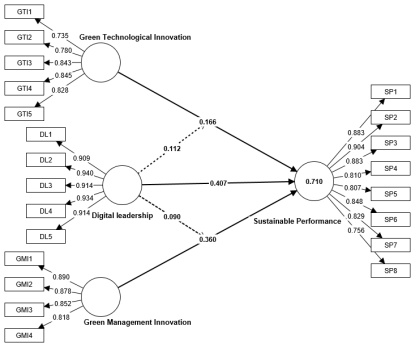


Fig. 2. Path model

4.4 The moderating analysis

Another objective of this study is to ascertain whether digital leadership can explain the linkage of green technology and management innovation to sustainable performance.

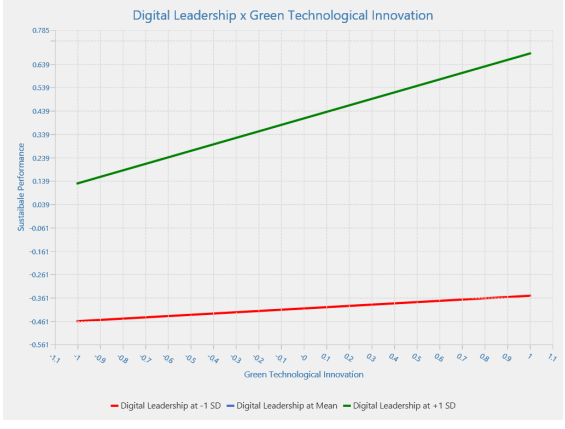
Table 5
Moderating effect results

	Path estimate	T statistics	P values	LLCI 5.00%	ULCI 95.00%	VIF	R^2 inclusion	R^2 exclusion
H4. DL × GTI → SP	0.112	3.458	0.000	0.061	0.165	1.387	0.710	0.67
H5. DL × GMI → SP	0.090	3.423	0.000	0.045	0.131	1.283		

Source: primary data output

Without the inclusion of the moderating effect of digital leadership, the R^2 value for sustainable performance was 0.67. With the inclusion of the interaction term, the R^2 increased to 71 %. With the interactions term, the result shows an increase of 3% in variance explained by the digital leadership and constructs of green innovations. Indeed, the findings revealed a positive and significant moderating impact of digital leadership on the relationship between green technological innovation and sustainable performance ($\beta = 0.112$, $t = 3.45$, $p = 0.000$), sustaining the H4. This demonstrates that with the increase in digital leadership, the relationship between green technological innovation and sustainable performance is strengthened. In addition, slope analysis is offered to better comprehend the nature of the moderating effect. As illustrated in Fig. 3, the slope of the line is distinctly steeper for high levels of digital leadership, signifying that at higher levels of digital leadership, the impact of green technological innovation on sustainable performance is stronger compared to lower levels of digital leadership.

Similarly, the result revealed a positive and significant moderating impact of digital leadership on the association between green management innovation and sustainable performance ($\beta = 0.09$, $T = 3.42$, $p = 0.000$). This shows that with the increase in digital leadership, the association between green management innovation and sustainable performance is reinforced. The slope of the line in Fig. 4 is steeper for high levels of digital leadership, signifying that at higher levels of digital leadership, the impact of green management innovation on sustainable performance is stronger compared to lower levels of digital leadership. Thus, higher digital leadership reinforces the association between green management innovation and sustainable performance, also supporting the H5. In conclusion, digital leadership moderates positively the effect of green management innovation and green management innovation on sustainable performance.



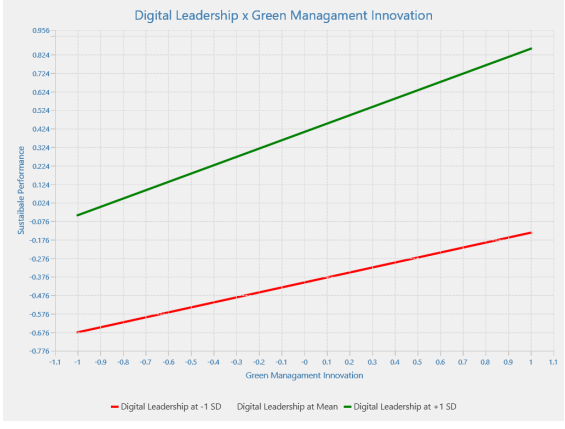


Fig. 3. The moderating effect of DL on the GTI-SP linkage

Fig. 4. The moderating effect of DL on the GMI-SP linkage

Source: primary data output

5. Discussion

The objective of the current study is to assess the impact of green technological innovation and green management innovation on sustainable performance, as well as to explore whether digital leadership can moderate these effects. The study gathered data from manufacturing and services organizations, relying on exhibitors' assessment of model indicators. The study unveiled important findings that significantly contribute to the literature on digital leadership, sustainability issues, and practices related to green innovations.

The results indicate that green technological innovations and green management innovations have a direct and positive influence on sustainable performance. These findings corroborate previous studies on sustainability management that highlighted that developing or acquiring innovations that advance sustainable operations and systems enhance an organization's environmental, economic, and social performance (Aguilera-Caracuel & Ortiz-de-Mandojana, 2013; Hao et al.,

2022; Ma et al., 2018; Rehman et al., 2021; Tian, Siddik, et al., 2023; Ullah et al., 2024). For organizations to sustain their competitive edge, they need to use resources effectively, mitigate environmental damage, and prioritize well-being. Achieving these goals can be accelerated by developing a mindset geared towards sustainability and implementing green new approaches (Cisneros Chavira et al., 2023). This finding is in line with the SDGs, particularly G9, which prioritize the importance of sustainable innovation capabilities in promoting both economic advancement and human welfare. (UN, 2024). In conjunction with governments, the organization can contribute to fostering SDGs (Mahajan et al., 2024) by implementing new approaches that capture the core principles of eco-friendly technological advancement and environmentally conscious management strategies (S. Wang et al., 2022) such as corporate social responsibility (Bhat et al., 2024), proof of green and sustainable certifications (Chrysikopoulos et al., 2024), green knowledge process (Khan et al., 2024), green information systems and technology (Mat Nawi et al., 2024).

This study additionally found that digital leadership can have a beneficial impact on sustainable performance. This is recognized through the importance of digital leadership behavior and capabilities in effectively addressing evolving sustainability issues (Erhan et al., 2022). As organizations incorporate digital technologies and platforms as fresh resources and processes, it presents challenges for all members (Tagscherer & Carbon, 2023). However, adept leadership in navigating employee, process, and digital aspects can facilitate seamless responses (AlNuaimi et al., 2022).

Moreover, the study revealed that digital leadership can act as a reinforcer of the association of green technological innovation and green management innovation with sustainable performance. Although no prior research has specifically addressed this interaction, the importance of leadership skills and traits, particularly in the digital realm, is evident in ensuring organizational resources and systems are effectively aligned to monitor performance (Bechtsis et al., 2017; Cortellazzo et al., 2019; Tigre et al., 2023). Through their skills and strategies, digital leaders can stimulate employees and partners to foster innovation within a specific organization or system (Cisneros Chavira et al., 2023; Sarfraz et al., 2022; T. Wang et al., 2022). Hence, digital leadership is a resource integrator that can effectively steer organizational strategies, technologies, and resources toward integrating and optimizing green initiatives within the overall business framework.

5.1 Theoretical contributions

The study contributes significantly to the body of knowledge on digital leadership, green innovations, and sustainability. Initially, prior studies have examined green innovation as a singular concept, or predominantly concentrated on green technological innovation, overlooking the significance of green management strategies in achieving sustainable performance (Ma et al., 2018). Our study sheds light on the extent to which both green technological innovation and green management innovation impact sustainable performance. This multifaceted approach is a pioneering empirical investigation within a single study.

Secondly, the competencies and behaviors of digital leaders are not only crucial for navigating digital transformation successfully but also directly influence sustainable performance. Our findings reveal that within organizations adopting digitalization processes and sustainable practices, the capabilities of digital leadership empower organizations to attain sustainable performance. Therefore, our research enhances our understanding of how digital leadership fosters sustainability objectives (Lyu, 2024). Thirdly, our study makes notable progress in clarifying how digital leadership strengthens the establishment of sustainable results by backing green innovation initiatives, encompassing not just processes and technologies but also managerial approaches. To the best of our knowledge, this study is the first to elaborate on the role of digital leadership within green innovations and sustainable performance. Lastly, this study pioneered the applicability of the STS theory to contextualize digital leadership (Sony & Naik, 2020). Drawing from this theory, we argue and empirically demonstrate that organizations should not solely focus on integrating new digital technologies and platforms (technical-related factors) to enhance performance but should also prioritize the social influence (human-related factors) of leaders who possess the competencies to inspire and educate the workforce about the goals and processes of digitalization.

5.2 Practical implications

Based on the findings of the study, there are some managerial implications for organizations aiming to contribute to a more environmentally responsible and socially conscious business landscape in the digital era. First, since green technological innovation has a positive association with sustainable performance, organizations have to invest in research and development for eco-friendly technologies and integrate sustainability goals into product design, manufacturing processes, and supply chain management. Second, the positive findings that innovations in green management impact sustainable performance highlight the significance of adopting sustainable management approaches. This includes incorporating eco-certification, which serves not only to validate green efforts but also to enhance the efficiency of current management practices. Likewise, instituting changes in organizational structure, developing sustainable metrics and data analytics, and dedicating resources to promote a green culture all through teamwork and stakeholders are essential steps to ensure effective responses to evolving sustainability challenges. Third, green management innovations also comprise the role of green knowledge management, hence developing and integrating green knowledge within the organizations can support organization capabilities to yield economic, environmental, and social outcomes (Abbas & Khan, 2023). Fourth, organizations seeking to incorporate new digital technologies and platforms should appoint leaders capable of guiding this transition. Those leaders must possess the skills to

inform, educate, and inspire employees in effectively addressing the challenges of new information systems and digital platforms (Chatterjee et al., 2023; Kwon & Park, 2017). Additionally, to adeptly tackle both digitalization and sustainability challenges, organizations are required to cultivate digital leadership abilities. Hence, it is crucial for organizations not only to concentrate on the technical aspects of digitalization but also on the participative process and social influence wielded by digital leaders (Oberer & Erkollar, 2018). For instance, digital leadership training, support and assistance of digital platforms, hiring people with digital skills, optimizing flat cooperation, developing management systems and capabilities for green practices, and monitoring digital changes for sustainability are concrete examples of solutions for digital leadership development and success in the sustainability landscape.

5.3 Conclusion

The present study aims to investigate the role of green technological innovation and green management innovations on sustainable performance, in conjunction with investigating the moderating role of digital leadership. Drawing data from manufacturing and service firms in Algeria, the study highlights significant insights into green innovations, digital leadership, and sustainable performance. The findings underscored that green technological and management innovations positively linked to firm sustainable performance, aligning with existing research emphasizing the importance of ecofriendly-focused innovations for organizational long-term performance. Moreover, the study showcases the vital role of digital leadership in fostering sustainable performance, acting as an optimizer for organizations aiming for digital transformations and sustainability challenges. Theoretical contributions include a multifaceted examination of green innovations' impact on sustainability and the role of digital leadership, enriching existing literature with empirical evidence.

5.4 Limitations

This study is not without limitations, addressing them could enhance the robustness and applicability of the study findings and contribute to a more comprehensive understanding of how organizations can effectively integrate digital leadership and foster sustainability initiatives. First, data collection was based on exhibitors' assessments regarding model indicators, which may introduce subjectivity and bias into the results. Hence, the reliance on hard data could enhance the accuracy and reliability of the outcomes. Second, while the study explored the impact of two constructs of green innovations (i.e., green management innovation and green technological innovation) on sustainable performance, it may have overlooked other factors that could influence sustainability outcomes. Hence, enlarging the scope of analysis to other variables of innovations such as green product innovation and green innovation capabilities. Third, the study provided a snapshot of the relationship between the model's constructs at a specific point in time. A longitudinal analysis could offer a deep understanding of how these associations evolve and the long-term sustainability implications. Fourth, while the study utilized the STS theory to contextualize digital leadership, it may have overlooked other theoretical perspectives or frameworks that could provide additional insights into the dynamics of sustainability and digitalization within organizations such as dynamic capabilities theory and transformational leadership theory.

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Appendix 1

Items

Green Technology innovation (Khan et al., 2024) Our organization continuously optimizes the processes by using cleaner methods or green technologies to make savings. Our organization is actively involved in the redesign and improvement of products or services to comply with existing environmental or regulatory requirements. Our organization specializes in recycling practices to ensure that end-of-life products are recovered for reuse in new products. Our organization is rigorously involved in "eco-labeling" activities to make our clients conscious of our sustainable management practices. Our "R and D" team ensures that the current technical advancement is included in developing new eco-initiatives.
Green management innovation (Ma et al., 2018) Our organization implements advanced environmental management techniques within the firm. Our organization implements advanced energy management. Our organization implements advanced knowledge management. We make a major change to the organization within the firm, i.e., management structure or integrating different departments.
Digital Leadership (Erhan et al., 2022; Shin et al., 2023) A digital leader raises awareness of the employees about the technologies that can be used to improve the organizational processes. A digital leader determines required ethical behaviors for IT implementations with all the stakeholders. A digital leader plays an informative role in reducing the resistance toward innovations brought by IT. A digital leader shares their own experiences about IT opportunities that will increase the contributions to colleagues for the structure of the learning organization. To increase participation in the corporate vision, a digital leader guides the employees of the organization regarding the IT tools that can be used. A digital leader raises awareness of the employees of the organization about IT risks (removed).
Sustainable Performance (Khan et al., 2024) Our organization has an initiative to reduce, reuse, and recycle. Our organization has an initiative to reduce the negative environmental impact of its products. Our organization has a policy to improve its energy efficiency. Our organization has competitive advantages in its sales and profit growth. Our organization has a competitive advantage in cost-saving and efficiency. Our organization has a competitive advantage in its value. Our organization has a policy to strive to be a good corporate citizen. Our organization has a policy to respect business ethics.