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The Impact of Digital Transformation and Green Innovation on Sustainable Supply Chains

Salsabil Abougalil[1], Gamal Abd Elasser A.Said[2], Mohamed Gamil[3] and Saurav Negi[4]

[1]MSc Researcher, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

[2]Manager of Education Port Training Institute, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

[3]Assistant Professor of Logistics and Supply Chains, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

[4]Modern College of Business and Science, Muscat, Oman.

Emails: Salsabil.Abougalil@gmail.com, jamalabdelnasser@hotmail.com, mohamedgamil@aast.edu, Saurav.negi@mcbs.edu.om

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Abstract

***Purpose**: The purpose of the research is to explore the effects of digital transformation practices on sustainable supply chains through the mediating role of green innovation. The research aims to fill a theoretical gap in digital transformation research in sustainable supply chain tracks in Egypt, where it is under-researched.*

***Methodology:** The present study is a cross-sectional study that follows the quantitative research methodology and uses the survey list for collecting primary data by conducting it on a random sample of 266 managers of industrial exporting companies in Egypt. The research is exploratory research using regression modeling, which combines theory with data to test hypotheses and explain behavior.*

***Findings:** The study findings indicate that there is a statistically significant effect of digital transformation on supply chain sustainability by enhancing operational efficiency, transparency, and resilience while also promoting environmental and social accountability. Green innovation mediates the relationship between digital transformation and supply chain sustainability, as it plays a pivotal role in enhancing sustainable supply chains by integrating eco-friendly practices, improving resilience, and fostering competitive advantages. Digital transformation predicts the variation in supply chain sustainability by 51.5% and predicts the variations in green innovation by 44.6%. Also, the study highlighted some limitations, such as the reliance on self-reported data through questionnaires, which could introduce response bias or social desirability bias, limited sample size and specific context may restrict the broader applicability of the findings, thereby limiting their generalizability.*

Additionally, the study suggested future research directions such as exploring the impact of emerging digital technologies beyond those discussed, including augmented reality (AR) and virtual reality (VR), on supply chain and marketing effectiveness, focusing on industry-specific impacts of digital transformation, as different sectors may experience unique challenges and benefits, testing technologies like block chain and AI and how they could be beneficial, and how firms can make investments in these technologies.

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Practical Implications: *By implementing sustainable supply chain practices, the findings of this study will help the industrial enterprises under examination keep up with contemporary advancements in digital transformation and manufacturing. This includes adopting green innovation methods and introducing innovative processes, services, and products. The aim is to guarantee the uninterrupted operation and long-term viability of supply chains for these industrial enterprises. Moreover, it aligns with Egypt's sustainable development strategies.*

Originality/Value: *The research contributes to the field by highlighting the critical role of information systems and digital transformation in advancing sustainable supply chain management.*

Keywords: *Digital Transformation, Sustainable Supply Chain, Green Innovation.*

Introduction

The Fourth Industrial Revolution (4IR), which includes AI, 3D printing, IIoT, big data, and robotics, has transformed the global economy into a sustainable growth model. IR 4.0 technology offers efficient and flexible production setups for large-scale product customization, enhancing competitiveness and cost-effectiveness. The researchers expect this shift in manufacturing strategies and business models to boost market competitiveness, reshoring manufacturing, and promoting sustainability in operations (Fanoro et al., 2021; AUC, 2021).

The digital age is characterized by rapid development, growth, and innovation. Organizations must adapt to this environment by fostering innovation and green innovation. Digital transformation goes beyond implementing new technology, investing in tools, and enhancing systems. Companies must engage in proactive planning and actively shape their future, with a digital transformation plan being crucial (Nadkarni & Prügl, 2021; Jones et al., 2021; Konopik et al., 2022). A digital transformation strategy helps leaders address business inquiries, focusing on current digitization, future aspirations, and pathways. Organizations must develop operational awareness, informed decision-making, and rapid execution (Kraus et al., 2022; Saarikko et al., 2020).

Egypt's Vision 2030 encompasses three primary dimensions: (1) an economic dimension aimed at fostering inclusive development, enhancing transparency, and optimizing governmental efficiency; (2) a social dimension dedicated to investing in human capital through lifelong learning, health, culture, and social justice; and (3) an environmental dimension centered on environmental and urban development. The Give the name in full for the first time you mention the abbreviation (ICT) sector is a fundamental and pervasive component of this vision; it spans the three dimensions horizontally and may significantly aid in attaining the specified objectives (MPED, 2023).

Sustainable supply chains are efficient organizations that deliver raw materials from the source to consumption using efficient logistics. Companies must electronically link their supply chains to compete in global markets. Digitalization, particularly e-commerce, has profound impacts on supply chains, creating operational and policy-making challenges for companies. Despite the recognition of the impact of e-commerce, innovation and competition contribute to the sustainability of operations, ensuring efficient logistics and effective supply chain management (Heider et al., 2022; Wittmeir et al., 2023).

Green innovation is crucial for business decisions, strategy, management, manufacturing, and product development. It eliminates environmental obstacles and promotes cooperation between customers and suppliers. Green customer integration improves cost and environmental performance by facilitating the innovation of green processes within the organization, not just green products (Wong et al., 2020; Khan et al., 2022; Song et al., 2020).

Sustainability is crucial for companies to maintain a strong economy and corporate profitability. Companies that prioritize growth and environmental preservation are the longest-term growth gateways. They follow a sustainability policy in their operations, adhering to the Three Pillars: Society, Environment, and Economy. Advances in information technology and e-commerce supply chain integration improve the profitability and competitiveness of these companies by effectively managing large amounts of data and transactions (Díaz-Caro et al., 2023; Paulsy, 2024; de Carlos Fraile et al., 2024).

Digital transformation in supply chains improves sustainability, reduces waste, promotes green innovation, reduces theft, and enhances business efficiency. It streamlines transactions, enabling all parties in a sustainable procurement process to share trade-related information. This leads to innovation and efficiency in logistics and digital documentation, with 74% and 75% achieved, respectively. Green

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logistics could use blockchain technology to enhance environmental sustainability in e-commerce supply chains (B.Rawat et al., 2020; Bisht et al., 2024).

A review of the literature reveals a significant and growing interest in sustainability issues and their impact on electronic supply chain practices and digital transformation, which promotes green innovation in both products and operations to attain sustainability (Salim et al., 2021; Awain et al., 2023; Munir et al., 2022).

Industrial supply chains in small and developing countries face significant challenges in implementing digital transformation due to lack of capabilities, waste reduction, and sustainable performance. In order to remain competitive and penetrate new markets, industrial supply chains in small and developing countries must integrate all electronic operations and engage in innovation to develop new products and services. Digital transformation risks local companies failing to keep pace with global market developments, leading to new technologies and business models. (Brunetti et al., 2020).

Certain companies in the industrial and distribution sectors have exerted pressure to establish connections with retailers, which has resulted in significant time and financial waste due to inadequate utilization of modern technology. This has led to an unsustainable supply chain and a deficiency in green innovation (Pacheco & Clausen, 2024; Suchek and Franco, 2024).

Research in industrial sectors and distribution processes has lagged due to insufficient innovation, resulting in company collapse and the emergence of rival firms that dominate the market (Huang et al., 2022).

Globalization and the pursuit of sustainability in supply chains have evidently broadened opportunities for enterprises to adopt innovation and green technology while fostering consumer engagement (He et al., 2021).

Despite research, studies, and practices aimed at constructing more sustainable supply chains, the industrial sector in emerging nations reveals that their current configurations jeopardize their future development. Innovations will facilitate the emergence of novel technologies and methods for the production of products and services, hence enhancing the exploration of improved business models (Cristino, 2021).

The challenges of waste or loss within production and manufacturing processes, along with the desire to fulfill sustainability mandates and implement strategies that enhance efficiency and sustainable supply chains, encapsulate the research issue.

Limited knowledge exists regarding the role of sustainable digital transformation in developing and enhancing sustainable supply networks that adapt to contemporary environmental changes. The recent research aims at investigating the effect of digital transformation on sustainable supply chains in the industrial companies under study in Egypt and the mediation effect of green innovation practices between digital transformation and sustainable supply chains (Oubrahim et al., 2023; Mwendwa, 2023).

Digital transformation is the process that an organization applies to integrate digital technology in all areas of business. It is the application of modern technologies and smart software used by companies, such as customer relationship management programs, blockchain, artificial intelligence (AI), and the Internet of Things (IoT), in addition to management programs. Data analysis plays a crucial role in the digital transformation process, accelerating the digitization of systems like inventory management. The goal of achieving complete digital management and gradually eliminating paperwork not only enhances the customer's experience with the company but also provides comfort for both parties, thereby boosting productivity and ultimately increasing profit (Hai et al., 2021; Nguyen et al., 2022).

Green innovation is defined as the use of new methods in production, operations, or management aimed at reducing overall environmental risks and reducing environmental pollution and other negative impacts on resources, including energy use. The OECD defines green innovation as strategic planning aimed at implementing a new product, a new or innovatively improved process, a new marketing method, or a new organizational method (Rojas-Cabezas et al., 2024).

A sustainable supply chain fully incorporates ethical and environmentally responsible activities into an effective competitive framework. Comprehensive supply chain transparency is of utmost importance. Sustainability activities must encompass raw material procurement, last-mile logistics, and product returns and recycling. Sustainable supply networks enhance the equilibrium between operational efficiency and the attainment of long-term effectiveness and profitability. Technological advancements are crucial for optimizing the sustainability of the supply chain. A sustainable supply chain comprehensively incorporates ethical and ecologically responsible practices into a competitive and effective framework (Mina et al., 2021; Oubrahim et al., 2023).

Digital transformation directly impacts environmental

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sustainability, identifying the disruptions it causes. The results present the impact of digital transformation within a framework that identifies transformations in four main areas: pollution control, waste management, sustainable supply chain production, and green sustainability. It seeks to clarify the performance and digital transformation strategy with regard to environmental sustainability in the industrial field and the extent of its impact on the sustainability and profitability of industrial companies (Feroz et al., 2021; Cristino, 2021).

Digital transformation profoundly influences sustainable supply chain management by improving efficiency, transparency, and sustainability performance across diverse industries. The incorporation of digital technologies, including IoT, blockchain, AI, and advanced analytics, transforms supply chain dynamics, enhancing visibility, decision-making, and collaboration among partners, essential for sustainability (Holloway, 2024; Reynolds, 2024). These technologies allow organizations to refine inventory management, predict market trends, and provide tailored client experiences, therefore improving operational efficiency and customer satisfaction while fostering sustainability and ethical standards (Holloway, 2024). Blockchain is emphasized as a revolutionary technology for guaranteeing food product traceability, safety, and sustainability, meeting customer needs for immediate information regarding the environmental and social sustainability of food items (Leković et al., 2024).

De Sousa Jabbour et al. (2022) pointed out the potential benefits of integrating digital technologies and supply chain management, focusing on sustainable supply chains based on big data. Big data has benefits for both dimensions of the triple bottom line in supply chains. Applying big data for sustainability in supply chains presents some challenges for companies. There is a need to develop complementary organizational capabilities to overcome the challenges and facilitate the benefits of big data technology for sustainable supply chain management.

Companies are actively pursuing digital transformation to achieve sustainable development in a volatile and uncertain environment. Digital strategy and digital capability significantly improve environmental processes, environmental products, and environmental management innovation. Environmental processes, environmental products, and environmental management innovation also improve sustainable performance. Meanwhile, eco-innovation partially mediates the positive relationship between digital transformation and sustainable performance (Zhang et al., 2023).

With the many attempts made by governments and companies to reduce environmental risks, blockchain technology has become a crucial tool to achieve sustainable supply chains in small and medium enterprises (SMEs). Green information systems and sustainable supply chain practices have a significant positive association. Sustainable supply chain practices have a positive and significant relationship with sustainability. The results of this study provide valuable insights into blockchain technology and offer policy implications for manufacturers and regulators regarding implementing and promoting green supply chain practices (Khan et al., 2021).

Benzidia et al. (2021) confirm that environmental process integration and green supply chain cooperation have a significant impact on environmental performance. Their study highlights the significant impact of BDA-AI relationships and green supply chain cooperation, enabling them to mobilize BDA-AI technologies to support green supply operations and enhance environmental performance.

The Egyptian government has been actively utilizing digital technologies to achieve sustainable development goals, with initiatives led by the Ministry of Communication and Information Technology focusing on integrating ICT into various sectors (Elgohary, 2022). Moreover, digital transformation cultivates a collaborative culture and emphasizes trust and transparency, which are vital for realizing the complete advantages of digital cooperation and promoting sustainable growth in a linked world (Reynolds, 2024). The implementation of digital transfer technologies integrates business processes with sustainability concerns, enhancing sustainability performance by tackling social and environmental aspects (Hasani & Haseli, 2024). This alignment is essential for organizations seeking to develop flexible, robust, and competitive supply chains that can prosper in a digitalized landscape (Reynolds, 2024). Furthermore, digital transformation improves the efficiency of green supply chains by influencing green production, resources, and consumption, hence promoting environmental sustainability (Gholami, 2024).

The goods and logistics sector gains advantages from digital proficiency, strategic alignment, and the pursuit of innovation, which are critical elements influencing sustainability performance (Mutambik, 2024). Despite the revolutionary advantages, there are still constraints such as substantial investment demands, integration difficulties, and data security issues, which necessitate deliberate methodologies for technology adoption and robust cybersecurity protocols (Holloway, 2024; Reynolds, 2024). Furthermore, digital transformation facilitates the establishment of

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robust global supply chains by enhancing transparency, flexibility, and adaptability, which are essential for forecasting and alleviating probable failures and issues (Ning & Yao, 2023). The strategic amalgamation of digital transformation and sustainable policies within organizational frameworks is essential for improving company performance and attaining operational excellence, allowing enterprises to enhance their economic, social, and environmental impact (Stroumpoulis et al., 2024). Digital transformation offers exceptional prospects for supply chains to enhance agility, transparency, and customer focus while promoting innovation, encouraging sustainability, and bolstering resilience against global disruptions (Singh et al., 2024). Organizations can navigate competitive environments, satisfy changing consumer demands, and attain sustainable growth in the digital age by adopting digital technology and linking supply chain strategies with sustainability goals (Holloway, 2024). Drawing from prior research, the researchers can formulate the 1st hypothesis as follows:

H1: Digital transformation practices have a significant effect on the sustainable supply chain in the exporting sector in Egypt.

In the context of sustainable development, countries around the world highlight green innovation in their environmental policies, and the digital economy may play a vital role in improving it. The number of urban green patent applications serves as a measure of green innovation progress in the urban digital economy. This digital economy has a significant influence on green innovation. The development of the digital economy can improve the levels of green innovation in indirect ways, such as enhancing the degree of economic openness, improving the industrial structure, and expanding the market potential. As economic openness, industrial structure, and market potential continue to progress, the intensity of the digital economy promotion of green innovation diminishes. The development of green innovation has an obvious spatial impact. However, promoting green innovation in more developed regions may inhibit green innovation in less developed regions due to talent outflow and industry relocation (Luo, 2022).

According to Takalo and Tooranloo (2021), green innovation (GI) literature has developed and expanded over the past decades due to its wide-ranging fundamental applications coupled with environmental awareness and service delivery of green products and applications. Topics such as the benefits of implementing geographical indications received the highest share. The researchers divided the articles based on the study area. The industries sector had more than one industry, and the largest share was for manufacturing industries and digital transformation processes in factories.

Management and organization by providing a framework that identifies three levels of analysis (i.e., macro, meso, and micro) to organize current and future research on the topic, scholars have increasingly focused on the interconnection between digital transformation and green innovation management. Learn how industries and companies compete and organize for innovation in a digital world and how new product and service development processes change under the influence of digital technology. Appio et al. (2021) explore the impact of digital transformation on the management of individuals and teams participating in the innovation process through various technologies.

Digital transformation has a profound impact on green innovation across various sectors, as evidenced by multiple studies. It serves as a catalyst for green innovation by enhancing the technological capabilities of enterprises, thereby improving the quantity and quality of green innovation outputs. For instance, studies have shown that digital transformation in Chinese companies significantly boosts green innovation performance, with each standard deviation increase in digital transformation boosting green innovation by 2.924% in quantity and 2.124% in quality (Wang & Zhong, 2024). This transformation alleviates financing constraints and information asymmetries, which are critical barriers to innovation, and improves human capital, particularly in regions with high environmental investment and stringent regulations (Wang & Zhong, 2024). In the transportation sector, digital transformation not only promotes green innovation but also has a sustained impact, with lagged effects being more influential than immediate ones. This is partly due to the mediating role of financing constraints, which digital transformation helps to alleviate, thus facilitating green innovation (Xuqian, 2024). Similarly, in agriculture-related enterprises, digitalization fosters green transformation by promoting economies of scale, technological innovation, and structural adjustments, although a certain threshold of digitization is necessary to realize these benefits (Yue et al., 2024). These findings suggest that similar strategies could be effectively applied in Egypt's exporting sector to enhance green innovation, leveraging digital transformation to improve sustainability and competitiveness in the global market. The research provides a pathway for countries like Egypt to implement digital transformation strategies that align with green sustainable development goals ("Digital Transformation, Green Innovation and the Solow Productivity Paradox", 2022) (Sun & Guo, 2022). Drawing from the existing literature, the researchers can formulate the 2nd hypothesis as follows:

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H2: Digital transformation practices have a significant effect on green innovation in the exporting sector in Egypt.

In the Egyptian context, green intellectual capital significantly influences business sustainability, with green innovation acting as a partial mediator in this relationship. This suggests that investments in green intellectual capital can enhance green innovation, thereby improving sustainability outcomes for industrial companies (Mohamed, 2023).

Green innovation is crucial for improving sustainable supply chains by promoting environmental sustainability and competitive advantage in multiple industries. The use of green supply chain management (GSCM) methods, encompassing green innovation, is essential for enhancing environmental performance and attaining sustainable development objectives. In the healthcare sector, green innovation, which includes green technology and management innovations, mediates the relationship between GSCM practices and environmental performance, therefore fostering sustainability in Bangladesh's healthcare business (Karim et al., 2024). In the manufacturing sector, green innovation serves as a crucial catalyst for collaborative innovation, improving the sustainability of manufacturing businesses through the utilization of corporate social capital (Liu, 2024).

It is important to note that the level of complexity in a supply chain has a big effect on sustainability efforts (Issa et al., 2024) because it shows how impactful it is to combine green innovation methods with logistics management approaches. Moreover, green innovation serves as an intermediary in the correlation between internal and external green supply chain practices and competitive advantage, highlighting the necessity for a comprehensive strategy to address environmental degradation and attain sustainable development (Javed et al., 2024). In the realm of digital finance, green innovation augments firm performance inside supply chains by enhancing corporate reputation and competitive advantages, underscoring its vital importance in the sustainable development of enterprises (Li et al., 2024).

Green innovation supports the shift to a circular supply chain model by influencing the connection between green supply chain strategies and sustainable practices, highlighting its significance in promoting circularity and long-term sustainability in a business-to-business context (Singh et al., 2024). Another important thing is green innovation, which fits with cultural and social norms to lessen environmental impact, and it is needed to turn traditional supply chains into sustainable circular economy frameworks. This is especially true in developing countries that do not have a lot of money. The implementation of green supply chain methods, encompassing green innovation, pertains not merely to immediate benefits but also to securing long-term business sustainability by safeguarding against environmental difficulties and market volatility (Tsikada et al., 2024).

Additionally, organizational traits and regional variations affect the implementation of green supply chain innovations, with competitive pressure motivating smaller entities and perceived advantages shaping the adoption intentions of larger organizations, thereby underscoring the strategic significance of green innovation across various contexts (Chen & Panichakarn, 2024). Green innovation is an essential element of sustainable supply chain management, promoting environmental collaboration, improving operational performance, and fostering a balanced approach that reconciles economic and environmental issues, thus advancing the progress of economic globalization and free trade while addressing the demand for eco-friendly products (Li et al., 2024).

As consumers, governments, and society in general are increasingly concerned about the loss of natural resources, coupled with environmental pollution, there is currently a significant trend to recognize the value of green innovation in achieving sustainable development. The tourism industry largely contributes to environmental pollution through hotels. However, only a few studies have explored the potential impact of green innovations on sustainable performance within the hotel industry, which can significantly and positively influence green innovation actions. Because it demonstrates the importance and potential of green innovation in enhancing sustainable performance in the hotel industry (Asadi et al., 2020).

According to Jiang et al. (2020), as the Chinese economy transitions to a new normal, the energy industry is increasingly driven by innovation, which is particularly evident in renewable energy. Considering that green innovation transformation is crucial during China's new normal phase, it explains the energy consumption on energy innovation and innovation transformation and reveals the net impact of green innovation transformation on economic sustainability and energy consumption. It explains that in terms of the innovative activity behavior of energy enterprises, energy consumption can promote overall energy innovation, of which renewable energy innovation is one of the most important. Much more stimulating. The energy structure is increasingly shifting towards renewable energy sources as energy consumption rises. The transformation of green innovation has the potential to decrease energy consumption and enhance economic sustainability. Therefore, the innovation transformation structure plays a more important role

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than overall energy innovation in stimulating economic growth and alleviating the discrepancy in energy consumption during China's new normal phase.

Hu et al. (2021) reveal that their study aims to investigate the impact of green innovation and corporate sustainability behaviors on financial performance by comparing the ways in which two different external factors drive firms to green innovation: environmental regulation and market disruptions. By dividing green innovation into green process innovation and green product innovation, the researchers propose that environmental regulation increases financial performance mainly through green process innovation rather than green product innovation, and market disruptions affect financial performance through green product innovation.

Collectively, these insights underscore the transformative impact of green innovation on the sustainable supply chain in Egypt's exporting sector, emphasizing the need for strategic investments and organizational readiness to foster a culture of sustainability. Based on the previous literature, the 3rd hypothesis could be formulated as follows:

H3: Green innovation has a significant effect on the sustainable supply chain in the exporting sector in Egypt.

Due to the scarcity of studies investigating the mediation effect of green innovation, the current study covers this gap. So, the 4th hypothesis could be formulated as follows:

H4: Green innovation mediates the relationship between digital transformation & sustainable supply chain in the exporting sector in Egypt.

The conceptual framework of this research encompasses three main constructs as shown in figure 1.

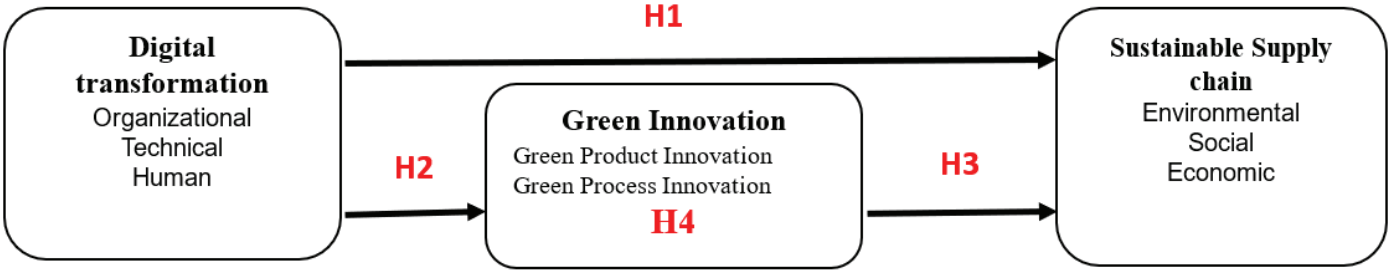

Figure 1 Research conceptual framework

Methods

A quantitative methodology was used. According to Cavaleri et al. (2018), quantitative research involves investigating research questions and/or hypotheses that aim to examine associations, assess discrepancies, clarify causal links between variables, and evaluate the effectiveness of interventions. The study population comprises companies operating in Egypt's industrial sector and exporting to other industries. Given the large size of the study population and the difficulty of accessing all of its subjects due to time and cost efforts, it was decided to rely on sampling methods and procedures to collect primary data for the study.

The study is restricted to large and medium-sized industrial companies that export overseas. Following a reconnaissance study of Egypt's industrial sector, the researchers carried out a technical study on exporting and registered companies. The Export Development Authority, the official website of the Ministry of Commerce and Industry in Egypt, provides the number of producing companies that export overseas.

The study sample consisted of participants working in 90 small and medium-sized enterprises (SMEs) in industrial areas in Egypt. The researchers distributed a total of 400 questionnaires online and received 290 responses. Ultimately, they used 266 questionnaires for the final data analysis. They conducted a pilot test on 30 people before collecting the research data. They subjected the obtained results to reliability analysis and decided to keep the scale expressions as they were.

The researchers individually sent self-administered online questionnaires to each participant to collect the data for this study. They chose a descriptive survey due to its ability to accurately describe or account for characteristics such as behavior, opinions, abilities, beliefs, and knowledge of a specific individual, situation, or group. They selected this design to align with the study's objectives, which aim to assess the influence of digital transformation on sustainable supply chains by examining the mediating role of green innovation. They tested the research hypotheses using the statistical packages of SPSS, version 29.

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Before filling out the questionnaire, the scale items were categorized as Likert types, with the midpoint being undecided (3), strongly disagree (1), and strongly agree (5). The Likert scale is a scale that aims to determine people's attitudes (Lee et al., 2023). The survey gauges their level of agreement or disagreement with the subject questions. The survey includes the demographic characteristics of the managers, such as gender, age, education, job level, and experience. At the same time, the 15-item scale developed by Martha et al. (2022), Benavides et al. (2020), Udovita (2020), and Purwanto et al. (2024) was used to measure digital transformation. The scale was developed by Olowoyin (2021) and Shahzad et al. (2024). Asadi et al. (2020) developed a 17-item scale to measure green innovation and Han and Huo (2020) developed a 12-item scale to measure sustainable supply chain variables.

Results

Validity and reliability analyses are conducted to make sure that the questionnaire statements are phrased in a good format. The two main factors that measure validity. First, the average variance extracted (AVE); it represents the average community for each latent factor. The AVE result should be greater than 0.5 to imply adequate validity. Second, to examine reliability, each factor is measured using a group of statements that indicate how stably and consistently the instrument taps the variable, which can be examined by Cronbach's alpha, the most commonly used test of reliability. The range of the Alpha coefficient comes between 0 and 1, and the higher the score, the higher the reliability. If Alpha coefficients are greater than or equal to 0.7, it implies adequate reliability.

The Kaiser-Meyer-Olkin (KMO) test is a measure of how suited one's data are for factor analysis. The test measures sampling adequacy for each variable in the model and for the complete model. The statistic measures the proportion of variance among variables that may be common. The lower the proportion, the more suited one's data are to factor analysis.

KMO returns values between 0 and 1. A rule of thumb for interpreting the statistic: KMO values between 0.8 and 1 indicate that the sampling is adequate; KMO values less than 0.6 indicate that the sampling is inadequate and that remedial action should be taken. Some authors put this value at 0.5; use one's own judgment for values between 0.5 and 0.6.

KMO values close to zero mean that there are large partial correlations compared to the sum of correlations. In other words, there are widespread correlations, which are a large problem for factor analysis.

Table.1 Validity and Reliability

Variables	KMO	AVE	Cron-bach's Alpha	Item	Factor Load-ing
Organizational practices	.768	54.914	.794	ORG1	.821
				ORG2	.822
				ORG3	.702
				ORG4	.548
				ORG5	.777
Technical	.841	53.041	.820	Tech1	.803
				Tech2	.780
				Tech3	.565
				Tech4	.556
				Tech5	.819
				Tech6	.794
Human Re-sources	.763	61.548	.763	HR1	.670
				HR2	.702
				HR3	.595
				HR4	.660
				HR5	.684
				HR6	.658
				HR7	.560
Green product innovation	.823	51.447	.810	Gp1	.697
				Gp2	.612
				Gp3	.649
				Gp4	.671
				Gp5	.627
				Gp6	.715
				Gp7	.629
				Gp8	.609
				Gp9	.490
Green process innovation	.794	65.648	.794	GPI1	.747
				GPI2	.687
				GPI3	.695
				GPI4	.617
				GPI5	.707
				GPI6	.619
				GPI7	.667
Environmental Sustainability	.716	65,982	.674	Env1	.663
				Env2	.697
				Env3	.728
				Env4	.777

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Economic Sustainability	.711	49.408	.636	Eco1	.722
				Eco2	.751
				Eco3	.595
				Eco4	.733
Social Sustainability	.743	65,982	.769	Soc1	.621
				Soc2	.771
				Soc3	.872
				Soc4	.828

Table 1 shows the results of the test. The values of KMO, AVE, and Cronbach's alpha, as observed, fall within the acceptable range.

Descriptive statistics is a tool that provides a clear understanding of the features of specific datasets by providing concise summaries of samples and demonstrating how to measure the data. The three major types of descriptive analysis are frequency, measures of central tendency such as averages, and measures of variability such as standard deviation. Measures of variability describe the degree to which the scores deviate from the mean. Measures of central tendency suggest a unique value that generally represents the entire score set.

Table (2) shows the respondent profile. In terms of gender, the sample consisted of approximately 65 males, accounting for 90%, and 34 females, making up 10%. The researchers observed that the age group between 40 and less than 50 constituted a higher percentage in the research sample, accounting for 30.50%, compared to other age groups. At the functional level, this group included 37% department heads, 29.6% managers, and 18.4% general managers. Additionally, 74.1% of the respondents reported having 12 or more years of experience.

Table (2): Respondent profile

Item	Frequency	Percent	Total
Gender			
Male	175	65,90%	266
Female	90	0,34	
Age			
less than 30 years	65	24,60%	266
from30to Less than 40	41	15,50%	
from 40 to less than 50	81	30,50%	
50years and more	78	29,40%	
Functional Level			
Head of Department	98	37,00%	266
Director	79	29,60%	
General Director	49	18,40%	
Chairman	40	15%	
Years of Experience			
Less than 6 years	6	2,20%	266
6-less than 10 years	28	10,40%	
11-less than 20years	197	74,10%	
20 and more	35	13,31%	
Industrial Sector			
Plastic &petrochemicals	104	39,00%	266
Fertilizers & Cement	99	37,20%	
Steel & Iron	43	16,00%	
Others	21	7,80%	

Testing research hypotheses

Regression analysis is a collection of statistical techniques that serve as a basis for drawing inferences about relationships among interrelated variables. Since these techniques are applicable in almost every field of study, including the social, physical, and biological sciences, business, and engineering, regression analysis is now perhaps the most used of all data analysis methods.

The analysis of the results revealed the following findings:

Hypothesis 1 (H1): Digital transformation practices have a significant effect on sustainable supply chains in the export sector in Egypt (accepted).

Table (3): Summary of Linear Regression for the Impact of Digital Transformation (DT) on Supply Chain Sustainability (N = 266)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	1.556	.122		12.774	<,05
ORG	1. 19	. 301	. 305	6.651	<,05
Tech	1. 32	. 373	. 488	9.848	<,05
HR	2.57	. 422	.665	13.807	<,05
R Square	51.5%				
F(263,3)	154.620				

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As mentioned in table (3), digital transformation (DT) has a direct positive and significant impact on the sustainable supply chain of organizations, organizational practices (B = 1.19*, p-value < 0.05), technical practices (B = 1.32*, p-value < 0.05), and human resources practices (B = 2.578*, p-value < 0.05), which reveals the acceptance of the first main hypothesis. On the other hand, the R square is 51.5, which means that digital transformation explains 51.5% of the variation in supply chain sustainability. It is possible to formulate the regression equation as follows:

Supply chain sustainability = 1.556 + 1.19 org + 1.32 tech + 2.57 HR

Hypothesis 2 (H2): Digital transformation practices have a significant effect on green innovation in the export sector in Egypt (accepted).

To test the second main hypothesis, it was tested by conducting multiple regression analysis, and the test results revealed the following:

Table (4): Summary of Linear Regression for the Impact of Digital Transformation (DT) on Green Innovation (N = 266)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	1,920	.124		15,515	<,05
ORG	.126	.030	.042	.847	<,05
Tech	.164	.038	.103	1,689	<,05
HR	.466	.043	.565	10,958	<,05
R Square	.446				
F(263,3)	116.960				

As mentioned in Table 4, digital transformation (DT) has a direct positive and significant impact on green product innovation, organizational practices (B = .126*, p-value < 0.05), technical practices (B = .164*, p-value < 0.05), and human resources practices (B = .466*, p-value < 0.05), which reveals the acceptance of the 2nd main hypothesis. On the other hand, the R square is .446, which means that digital transformation explains 44.6% of the variation in green innovation. The regression equation could be formulated as follows:

Hypothesis 3 (H3): Green innovation has a significant effect on supply chain sustainability in the export sector in Egypt (accepted).

To test the 3rd main hypothesis, it was tested by conducting multiple regression analysis, and the test results revealed the following:

Table (5): Summary of Linear Regression for the Impact of Digital Transformation (DT) on Green Innovation (N = 266)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	.715	.134		5,355	<,05
GProd	.539	.048	.534	11,136	<,05
GPI	.276	.047	.283	5,900	<,05
R Square	.60				
F(263,3)	327.803				

Table 5 shows that green innovation has a direct and positive effect on the sustainability of the supply chain. This effect is significant and positive for green product innovation (B = 539*, p-value < 0.05), green process innovation (B = 0.276*, p-value < 0.05), and human resources practices (B = 0.466*, p-value < 0.05). This supports the third main hypothesis. Conversely, the R square value stands at .60, indicating that green innovation accounts for 60% of the variation in supply chain sustainability. The researchers could formulate the regression equation as follows:

Hypothesis 4 (H4): Green innovation mediates the relationship between digital transformation practices and the green supply chains in the export sector in Egypt (Partially accepted).

The 4th main hypothesis was tested by conducting multiple regression analysis, and the test results revealed the following:

Table (6): Summary of green innovation mediation analysis (N = 266)

	L.C.I	U.C.I	p-value	Regression weight
Direct effect	0.441	0.590	0.04	0.521
Indirect effect	0.334	0.499	0.02	0.442

As mentioned in Table 6, the direct effect of digital transformation on the green supply chain is significant (R2 = 0.521, L.C.I. = 0.441, U.C.I. = 0.590) and the indirect effect of digital transformation on the green supply chain through green innovation is also significant (R2 = 0.442, L.C.I. = 0.334, U.C.I. = 0.334). This indicates a partial acceptance of the mediation hypothesis.

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Discussion

From the statistical results hypothesis one is supported, which means digital transformation has a profound effect on supply chain sustainability, enhancing operational efficiency, transparency, and resilience while promoting environmental and social responsibility. In other words, by integrating advanced digital technologies, supply chains can achieve significant improvements in sustainability practices, aligning with economic, social, and environmental goals. This result agrees with Holloway (2024), who point out that digital transformation is significantly reshaping supply chain management, which in turn enhances marketing effectiveness. Technologies like IoT, blockchain, AI, and advanced analytics are pivotal in this transformation. Also, it agrees with Stroumpoulis et al. (2024) who reveal that digital transformation plays a crucial role in enhancing sustainable supply chains by integrating sustainable practices with information systems. Also in this line, Nuševa et al. (2024) point out that digital transformation, particularly through technologies like block chains, plays a significant role in enhancing sustainable supply chains in the food industry. It enables improved traceability, safety, and sustainability practices throughout the food supply chain. By leveraging digitalization, actors in the supply chain can address environmental and social concerns, meet consumer demands for transparency, and effectively manage risks. The integration of digital solutions facilitates real-time information sharing, efficient problem-solving, and proactive responses to challenges, ultimately contributing to a more sustainable food supply chain management system. Also, Reynolds (2024) indicates that digital transformation positively impacts sustainable supply chains by enhancing collaboration, connectivity, and agility through digital platforms. The study highlights how digital technologies enable greater visibility and innovation within supply chains, fostering value creation. However, challenges like data security and trust issues can impede collaborative potential. Embracing digital tools, cultivating a collaborative culture, and prioritizing trust and transparency are crucial for unlocking the full benefits of digital collaboration. By leveraging digital transformation, organizations can strengthen their supply chain capabilities, boost competitiveness, and drive sustainable growth in an interconnected, digitalized world.

The statistical results support hypothesis two, indicating that the integration of digital technologies into business processes not only enhances operational efficiency but also fosters sustainable practices by promoting green innovation. Wang & Zhong (2024) concur with this result, asserting that digital transformation has a positive impact on both the quantity and quality of green innovation. For instance, a study on Chinese firms reveals that a standard deviation increase in digital transformation correlates with a 2.924% increase in quantity and a 2.124% increase in the quality of green innovation, and Zhu (2024) reveals that digital transformation in enterprises plays a crucial role in promoting green innovation. Moreover, two recently identified mechanisms—the technical imprint of senior executives and media attention—further enhance the enabling impact of digital transformation on green innovation. This study not only sheds light on driving enterprise green innovation in the digital era but also provides valuable insights for policymakers and firms aiming to implement sustainable development practices, particularly in developing countries. Xuqian (2024) points out that the effect of digital transformation on green innovation in transportation companies is significant. Research on listed companies in China from 2011 to 2021 shows that digital transformation positively influences green innovation. Moreover, the impact persists over time, with past digital transformation efforts having a greater impact on green innovation than current ones. Additionally, financing constraints play a mediating role between digital transformation and green innovation.

From the statistical results, hypothesis three was supported, which means green innovation plays a pivotal role in enhancing sustainable supply chains by integrating eco-friendly practices, improving resilience, and fostering competitive advantages. The adoption of green innovation strategies within supply chains not only addresses environmental concerns but also contributes to operational efficiency and long-term viability. This result is in line with Issa et al. (2024) who state that green innovation significantly enhances supply chain resilience by improving green logistics management practices. This is particularly effective in less structurally complex supply chains, where the impact of green logistics practices on resilience is more pronounced. According to Purnomo (2024), the integration of green innovation with green ambidexterity contributes to a green resilient supply chain, which in turn enhances a firm competitive advantage. This approach aligns with regulatory and social expectations, bolstering firms market positioning. Also, Chen and Panichakarn (2024) confirm that the relative advantage plays a crucial role in influencing the adoption intentions of larger organizations towards green supply chain innovations, highlighting the importance of organizational size in shaping sustainability practices. Singh (2024) points out that green innovation plays a significant role in enhancing sustainable supply chains by moderating the relationship between green supply chain strategies and the achievement of a circular supply chain. Green innovation positively impacts sustainable supply chains by fostering green resilient supply chain practices

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(Purnomo, 2024).

From the statistical results, hypothesis 4 is supported, which means that the relationship between digital transformation practices and green supply chain management is significantly mediated by green innovation. This mediation occurs as digital transformation facilitates the adoption of green innovation, which in turn enhances the effectiveness and efficiency of green supply chain practices. The integration of digital technologies with green innovation strategies not only improves supply chain resilience and performance but also contributes to sustainable development goals.

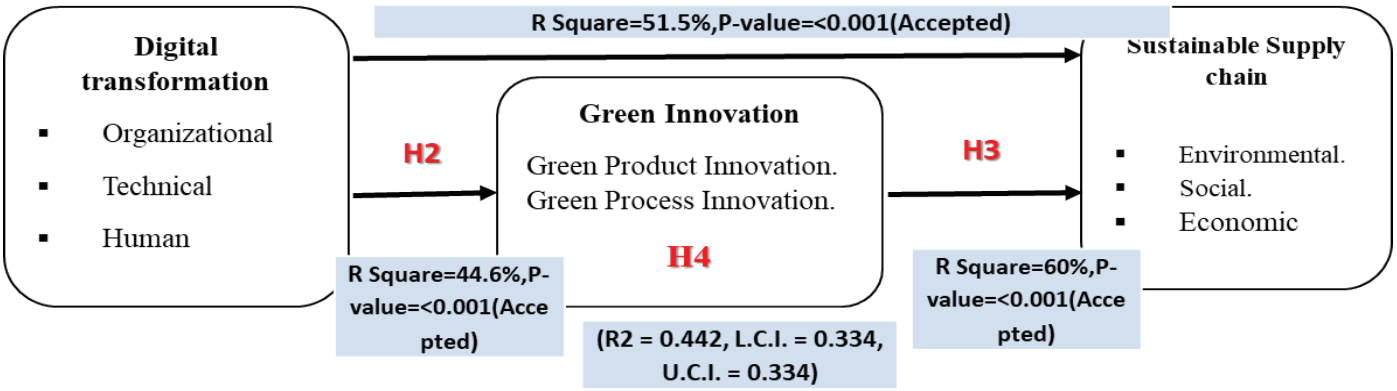

Figure 2 Research conceptual framework

Conclusion

The purpose of the research was to explore the effect of digital transformation practices on sustainable supply chains through testing the mediation effect of green innovation. The research aims to fill a theoretical gap in digital transformation research in sustainable supply chain tracks in Egypt, where it is under-researched. The study results revealed the existence of a significant effect of digital transformation on sustainable supply chains; green innovation mediates the relationship between digital transformation and sustainable supply chains.

There are some academic and practical implications that can be deduced from the current study.

- The research contributes by highlighting the critical role of information systems and digital transformation in advancing sustainable supply chain management.
- It emphasizes the importance of the strategic integration of digital transformation and sustainable policies within organizational contexts for enhancing business performance and achieving operational excellence.
- By implementing sustainable supply chain practices, the findings of this study will help the industrial enterprises under examination keep up with contemporary advancements in digital transformation and manufacturing. This includes adopting green innovation methods and introducing innovative processes, services, and products. The aim is to guarantee the uninterrupted operation and long-term viability of supply chains for these industrial enterprises. Moreover, it aligns with Egypt's sustainable development strategies.

Given these findings, the current study recommends the following actions:

- To effectively manage the intricacies and hazards in the supply chain, enterprises should embrace digital technology through employing digital technologies to facilitate immediate data exchange and communication to improve transparency and effectiveness.
- Companies should grow while considering environmental and social impacts. This involves integrating sustainable practices into their operations to meet consumer demands for environmentally and socially responsible products.
- Organizations should actively adopt digital platforms and ecosystems to improve connectivity, visibility, and agility within their supply chains. This adoption can lead to enhanced innovation and value creation.
- Implement robust data security measures to protect sensitive information and build trust among supply chain partners. This is essential for mitigating risks

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associated with digital transformation.

- Encourage continuous learning and adaptation to keep pace with evolving digital technologies and market dynamics. This approach will help organizations maintain competitiveness and drive sustainable growth.
- Make sure to closely link the deployment of digital technologies to the overall digital transformation strategy. This linkage is vital for achieving long-term sustainability goals and ensuring that technology investments align with strategic objectives.
- Effective change management is crucial for a successful digital transformation. Companies need to focus on managing the transition to digital processes to overcome resistance and ensure smooth integration.
- Cultivating a supportive organizational culture is essential. Encouraging a culture that embraces digital change can help mitigate challenges related to integration complexity and data security.
- Building agile and resilient supply chains is vital in a digitalized world. Companies should focus on creating flexible processes that can quickly adapt to changes and disruptions.
- Digital technologies can create significant value across supply chain networks. Businesses should explore innovative ways to utilize these technologies for competitive advantage.

Here is a summary of the primary limitations of the current study and some recommendations for future research:

- The limitations of the study may include reliance on self-reported data through questionnaires, which could introduce response bias or social desirability bias.
- The study limited sample size and specific context may restrict the findings broader applicability, thereby limiting their generalizability.
- The focus on organizational culture as a challenge indicates the need for additional research to understand how various cultural contexts affect digital transformation initiatives.
- There may be limited exploration of the wide range of digital technologies available, focusing on a few key technologies without delving into emerging or niche technologies that could also impact sustainability.
- The study is across-sectional which will limits the study generalization.

Future research might focus on the following areas:

- Future research could explore the impact of emerging digital technologies beyond those discussed, such as augmented reality (AR) and virtual reality (VR), on supply chain and marketing effectiveness.
- Further studies could focus on industry-specific impacts of digital transformation, as different sectors may experience unique challenges and benefits.
- ▪ Implementing longitudinal studies to assess the long-term effects of digital transformation on supply chain dynamics and marketing effectiveness.
- Examining the effects of digital transformation on supply chains across various regions, considering the differences in technological adoption rates and regulatory frameworks.
- Researching effective strategies for employee adaptation and training to maximize the benefits of digital technologies in supply chains.
- Future research should focus on identifying best practices and developing frameworks for effective digital transformation implementation. This will help organizations navigate the complexities of digital collaboration in diverse contexts.
- Future research directions should be directed towards technologies like block chain and AI , which could be beneficial, and how firms can make investments in these technologies.
- Conducting a longitudinal study to see the long-term changes or how investments in digital transformation and green innovation impact long term goals.

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