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The Interplay between Digital Technologies, Supply Chain Resilience, Robustness and Sustainable Environmental Performance: Does Supply Chain Complexity Matter?

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Abstract: This study aims to investigate the mediating role of supply chain resilience and robustness on the relationship between the use of digital technologies and sustainable environmental performance. Additionally, it investigates the moderating role of supply chain complexity on the impact of digital technologies on supply chain resilience and robustness. Data were gathered from 292 supply chain managers at registered manufacturing companies in Egypt and analyzed using Smart-PLS 4 software. The findings reveal that supply chain resilience and robustness partially mediate the link between digital technologies and sustainable environmental performance. Moreover, supply chain complexity was found to positively moderate the effect of digital technologies on both resilience and robustness. The model explained 53.2% of the variance in supply chain robustness, 56.6% in supply chain resilience, and 72.3% in sustainable environmental performance. These results provide critical insights for corporate policymaking, helping to drive continuous improvements in supply chain management, environmental performance, and sustainable development.

Keywords: supply chain resilience; supply chain robustness; supply chain complexity; sustainable environmental performance; emerging economy; Egypt

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1. Introduction

The escalating issues of global warming, biodiversity decline, and health crises such as the COVID-19 pandemic [1] have had a profound impact on the planet's sustainability, specifically the economic and social aspects [2]. As a result, there is a growing emphasis among researchers and industry leaders on devising and applying strategies that enhance competitive advantage [3] while prioritizing sustainable environmental performance (SEP) [2,4]. Both the manufacturing and service industries are increasingly focused on achieving long-term sustainability goals by reducing pollution and improving their environmental stewardship through the integration of ecological considerations into every aspect of their business practices [5].

The COVID-19 pandemic and its associated disruptions have ignited a surge of interest among practitioners and researchers in developing innovative strategies to manage such abrupt changes [6,7]. The widespread effects of the pandemic, coupled with the shift to telework, have dramatically transformed the understanding of corporate social responsibility, reshaping societal and business landscapes globally [8,9]. This shift has fostered environments ripe for innovation and ambition while simultaneously causing significant turmoil within the business sector [3,10]. The pandemic has affected all business activities, including supply chains [1]. Repeated lockdowns and precautionary measures imposed by various countries have led to disruptions and breaks in supply chains [11,12], resulting in a decline in competitive value for many business organizations [13]. This drastic and sudden change in the global supply chain has pushed some countries to rely more on local manufacturers and service providers. In that sense, the pandemic has led to some development and growth in the local markets of some countries. This represents a new business paradigm imposed on companies by the pandemic that led to shortening supply chains and relying on local companies [11]. In that sense, one of the unintended consequences of the pandemic was the prosperity of some local companies and the economic development of some countries because of this increased local manufacturing [14,15].

The COVID-19 pandemic has profoundly impacted the managerial, governmental, and public policy spheres [8,16,17]. Decision-making processes, especially those involving supply chain sustainability and the balance of local and global market demands [18], have faced increased risks and uncertainties [17,19]. Amid these challenges, environmental concerns have gained prominence, shifting from previous neglect to becoming a critical focus [3]. This underscores the concept that the success of organizations is heavily influenced by their external environment, highlighting the importance of cleanliness and safety. The importance of both cleanliness and safety emanates from their multifaceted relationship with external environment, which, in turn, could impact public health, safety, the environment, the economy, and social well-being. Ensuring that environments are clean and safe requires a holistic approach involving policy, community engagement, and sustainable practices [3,13]. Moreover, environmental considerations have transitioned from optional to essential, becoming a strategic and competitive necessity for achieving and maintaining competitive advantages [3,20].

Egypt has emerged as a significant COVID-19 hotspot worldwide, experiencing severe impacts as one of the most affected countries in Africa [21]. The pandemic has posed unprecedented challenges for many companies, especially small and medium enterprises (which represent a key driver of the Egyptian economy [22]), leading to labor shortages, supply chain disruptions, market instability, price volatility, and changes in consumer purchasing habits. Despite the government's decision to lift restrictions, these businesses faced significant hurdles in resuming operations, resulting in further economic losses and threatening their survival [23]. Many studies in the literature discussed the importance of adopting DTs, and teleworking in the Egyptian companies and how it has a positive role in supply chain resilience and agility [8,24,25].

In recent supply chain and management accounting literature, the adoption of digital technologies (DTs) has emerged as a prominent topic. DTs encompass a range of smart chain tools, including digital twins, big data analytics, blockchain, cloud computing, and the Internet of Things, which enhance connectivity, produce better communications throughout the supply chain, and enable automation of processes and transactions [26–29]. In manufacturing systems driven by digital advancements, these technologies facilitate the implementation of strategies that utilize extensive data collection [30], enhancing integration within the manufacturing system [27].

The integration of DTs provides both benefits and hurdles for achieving sustainable growth in manufacturing enterprises. The extensive incorporation of DTs and the needed transformation holds the potential to enhance product development, boost production efficiency, enhance supply chain resilience (SCRE), increase supply chain robustness (SCRO), and improve customer service [28–34]. Additionally, these cutting-edge technologies enable the optimal distribution of resources, thereby unlocking significant potential for SEP [30,35]. However, embracing these new technologies can intensify competitive pressures and create financial and environmental challenges for manufacturing companies [36]. In that sense, DTs may have unintended consequences for SEP, which requires further investigation to understand more about how DTs impact SCRE, SCRO, and SEP in less developed countries (LDCs).

Resilience and robustness encompass a broad spectrum of perspectives across disciplines, spanning the ecological, psychological, economic, and organizational realms [29,37]. Within the field of supply chain management, there remains a lack of consensus regarding their definitions [38,39], with divergent views on whether resilience pertains solely to managing disruptions or also includes preparation before disruptions occur [40]. Commonly, concepts such as readiness, response, recovery, and growth are integral to understanding resilience [30].

The concept of SCRO is often conflated with SCRE, leading to some ambiguity [41]. However, sources such as [41–43] argue for a clear distinction between the two. According to [44], robustness refers to the ability to withstand disturbances without undergoing change, and it is typically related to managing recurring risk events [45]. Despite this, robustness is not a static attribute [41]; it involves the capacity to handle variability with minimal impact on performance, incorporating a level of flexibility [30,41,43]. In this study, SCRO is defined as the chain's ability to maintain effectiveness during disruptive events [30,41,43,45]. Essentially, while resilience involves reactive responses to disruptions, robustness represents a proactive capability.

Although many studies in the literature have studied the impact of DTs on SCRE, SCRO [31,34,40,46], and SEP [30,35,47–49], very little is known about the mediating role of SCRE and SCRO on the relationship between DTs and SEP, which is crucial to understand in this new industrial era. Moreover, little is known about the role of played by supply chain complexity (SCC) on this cycle, as SCRE and SCRO are proven to be affected directly by SCC. Having said this, this research seeks to address a notable empirical gap and add to the current body of knowledge by exploring how SCRE and SCRO mediate the relationship between DTs and SEP. Additionally, it investigates the moderating role of SCC on the impact of DTs on SCRE and SCRO. This investigation is particularly distinctive because it explores whether previous findings hold true or differ in the setting of a developing market in Africa. The study aims to answer the following research questions: (1) How do DTs impact SCRE and SCRO? (2) How do DTs impact SEP? (3) Does the presence of SCC moderate the relationship of DTs with SCRE and SCRO? (4) Do SCRE and SCRO mediate the relationship between DTs and SEP?

Theoretically, most supply chain studies predominantly utilize the resource-based view (RBV), the dynamic capabilities view, agency theory, actor network theory, transaction-cost theory, and game theory. Meanwhile, most environmental performance and CSR studies deploy agency, legitimacy, and stakeholder theories, and little reliance on information processing theory (IPT) is present. In this context, the current study will extend the debate in the literature by building upon information processing theory (IPT). This will enable us to grasp and explain the dynamics of the study variables.

Our research is grounded in information processing theory (IPT) as conceptualized by [50] and expanded by [51]. Both operations and environmental management are recognized as processes that demand extensive information handling [30]. According to IPT, organizations operate as open socio-economic systems, capable of attaining superior performance by improving their information processing capabilities and quality [50,51]. In this context, DTs form the core of a firm's internal information architecture, reflecting its capability to process information effectively. Additionally, supply chain platforms facilitate the communication of data between supply chain partners, providing crucial external data [30]. The synergy between enhanced internal and external information processing fosters sustainability and growth of organizations. Building on the principles of IPT, this study explores the application of DTs in supply chain relationships and their subsequent effects on SEP. IPT argues that an organization's ability to process information must align with its business environment to optimize performance. Prior research suggests that DTs' effectiveness and supply chains are influenced by the surrounding environment [30].

This study introduces a novel research framework that explores the determinants influencing SEP. Additionally, it investigates how SCRE and SCRO mediate the relationship between DTs and SEP. Further, it investigates the moderating role of SCC on the impact of

DTs on SCRE and SCRO. The research gains further significance by focusing on the validation of this framework within the crucial industrial sector of Egypt, a developing nation. The structure of the paper is as follows: Section 2 introduces the theoretical underpinnings that guide this study. Section 3 critically examines the current literature, identifies gaps, and develops hypotheses for investigation. Section 4 delineates the research methodology employed and details the methods utilized in this study. Section 5 unveils the empirical findings and engages in a thorough discussion of their implications. Section 6 presents a comprehensive conclusion, while the final section explores implications, acknowledges limitations, and suggests avenues for future research.

2. Theoretical Framework

Information processing theory (IPT), initially developed in the 1970s, was primarily aimed at addressing internal organizational design issues. Over time, its application has expanded to the inter-organizational context, elucidating the dynamic interactions between buyers and suppliers [50]. The core premise of IPT posits that a company operates akin to an information processing system, aimed fundamentally at alleviating uncertainty through the acquisition, analysis, and effective utilization of information [52]. Uncertainty refers to the disparity between the information required to accomplish a task and the information currently available within the organization [50–52].

According to IPT, ensuring that an organization's information needs align effectively with its operational capabilities is essential for maximizing performance outcomes [51]. Information needs are determined by the surrounding parties in the surrounding environment, while capabilities are defined by resource availability; DT architecture; and other mechanisms that facilitate the collection, processing, and dissemination of information [50,53]. To address environmental dynamism, organizations can employ two strategies to enhance their decisions and performance: (1) gather a larger volume of high-quality information to mitigate the effects of dynamism and (2) enhance processing capabilities to support effective decision making [54]. Recently, IPT is utilized in various domains including information systems, technology integration, production control systems, maintenance management, and supply chain management [30,54].

Previous research has often highlighted DTs as central to processing information [30]. In [51], it is argued, based on IPT, that information technology support enhances these capabilities. In our study, DTs are structured and interconnected to manage the necessary information volumes, thereby representing the organization's information processing capabilities. Additionally, digital supply chains facilitate the exchange of information, providing access to external data. Thus, DTs enable supply chains to meet information needs [30]. Moreover, IPT posits that uncertainty is a fundamental aspect of both the business environment and internal organizational activities [50]. In an open system, companies continuously encounter uncertainties in their supply chain management, including fluctuating customer demands, unpredictable actions of competitors, and disruptions due to natural disasters or catastrophes [39,52].

The fundamental principle of supply chain management is that coordinating value-creating activities across various organizations can yield more value than individual firms can achieve alone [25,55]. This collaboration is enhanced by the transparency and exchange of information among supply chain partners. Over the past few decades, significant advancements in information technology and systems research have propelled the rapid evolution of supply chain management [25,56]. However, environmental uncertainty, which arises from the business environment, can impede the sharing of information and transparency, ultimately hindering collaboration. This issue is a central concern addressed in IPT by concentrating on enhancing information processing capabilities [56]. Enhancing their information processing capabilities enables firms to effectively manage these uncertainties, thereby improving organizational performance [39,52]. Consequently, information processing becomes strategically crucial for developing SCRE and SCRO.

Finally, IPT suggests that supply chains rely not only on their internal capabilities but also on their trading partners. This dependency introduces a level of unpredictability and lack of control over factors such as product quality and delivery performance of suppliers [52,57,58]. The risks and uncertainties arise from the growing supply chain complexities, which can be attributed to variables such as suppliers' engineering skills, manufacturing lead times, performance, product quality, and pricing [51]. These uncertainties complicate decision-making processes and heighten the need for new and additional information [51,57]. Therefore, IPT is applicable in elucidating information processing importance for supply chain effectiveness, including SCRE, SCRO, and SCC [39,42,58]. However, the specific role of DTs in enhancing information capabilities and, in turn, impacting sustainable environmental performance (SEP) has not been directly addressed, which is the focus of this study.

3. Review of Literature and Hypothesis Formulation

3.1. Digital Technologies Impact on Supply Chain Resilience and Robustness

Since COVID-19 pandemic, there has been an increased concentration on how to increase SCRE, and SCRO. The concentration on SCRE and SCRO emanates from their crucial role in adjusting to, adapting to, and recovering from disruptions [11,38]. Studies have defined supply chain robustness as the ability of supply chains to resist or avoid change [29,41], while the literature has defined SCRE as the capacity to bounce back from disruptions, adjust to shifting conditions, and maintain operations amidst diverse challenges, closely linked with sustainability [31,34,40,46]. SCRE and SCRO were connected in the literature with improving efficiency and resource utilization, seeking to gain the maximum benefits from each resource a company employs [59]. The emergence of SCRE underscores the necessity for innovation and adaptation to advance sustainable technologies [32].

The existence of proper DTs is expected to enhance the processing, collection, and dissemination of information, resulting in increased visibility, immediate access to information within the supply chain, and enhanced transparency [11,29]. Recent studies in management accounting and supply chain literature explored the impact of DTs on both SCRE and SCRO. These studies indicate that there is a positive impact of DTs on both SCRE and SCRO, as these technologies were found to strengthen the reactions to and recovery from disasters [29,60]. Contrary to these results, there are some rising voices that warn of the dark side of heavy reliance on DTs, as including DTs in the supply chain may results in cybersecurity risks that may result in the theft of data on customers, suppliers, and the like, thereby disrupting business continuity or the reliability of the supply chain and the information produced [14,61–65].

Innovative technologies such as blockchain and digital twins provide supply chain participants with access to real-time data, bridging the gap between the cyber and tangible realms [66,67]. Furthermore, blockchain technology boosts operational transparency and trust between supply chain members, leading to refined responses before and after the disruption [68,69]. Min [66] added that these innovative technologies foster robustness and resilience in supply chain by reducing shipment loss or damage and decreasing errors in order fulfillment.

Innovative technologies in the literature were not limited to blockchain and digital twins as some studies extended those technologies through examining the impact of the internet of things and cloud computing on SCRE and SCRO. These studies explained that those technologies help supply chain members to collect, store, transmit, and sharing large amounts of data, which enhances flexibility and collaboration, and visibility [70–72]. Those studies concluded that the internet of things has a significant positive impact on supply chain risk management as internet of things was found to improve the detection of infrequent severe risks and elevating both reactive and proactive risk management strategies [72].

Finally, DTs studies concentrated on another dimension of innovative technologies through examining how big data analytics improve the data quality which enhances resilience by enabling faster reconfiguration and reducing unforeseen outcomes [71].

Big data analytics has been verified by many studies in the literature to enhance SCRE and SCRO [29,68]. Big data also plays an important role in handling data from various DT sources such as IoT and cloud computing [27]. Moreover, it enhances the engagement of customers, employees, stakeholder, and communities in promoting sustainable practices [37,73,74]. Based on this, the following hypotheses are proposed:

H1. *Digital technologies positively impact supply chain resilience.*

H2. *Digital technologies positively impact supply chain robustness.*

3.2. Digital Technologies and Sustainable Environmental Performance

Supply chain management and related operations and environmental issues are heavily reliant on the quality and availability of information to ensure their efficient execution and environmental stewardship [75,76]. According to IPT, DTs enhance a firm's ability to process information, thereby supporting environmental and operational decisions. With the advent of Industry 4.0, these DTs are expected to improve the economic and environmental performance of manufacturing firms through advanced information collection and processing. By facilitating efficient information handling, DTs aid in production planning and control, leading to enhanced operational efficiency, cost reduction, and increased profitability [47]. In advanced manufacturing systems, firms integrate the Internet of Things (IoT), cloud computing, big data, and analytics to more effectively gather and process information related to production and operations [30].

In the manufacturing system, the generation, collection, and integration of vast amounts of data can be leveraged by big data and analytics to uncover valuable insights, aiding firms in making effective decisions [48,49]. Enhanced information processing capabilities are crucial for improving production efficiency and gaining a competitive edge [77]. Additionally, DTs facilitate decisions related to demand forecasting, price optimization, and product development [78], thereby better meeting customer demands and boosting market share and sales. On the contrary, some studies explained that DT embeddedness is a heavy cost to be fully digitally transformed and to obtain the benefits of having DTs on board. Moreover, if this investment is not made and only partial digital transformation is reached, the benefits will not impact the supply chain and sustainability as expected [79–81]. Other studies concentrated on the managerial and workforce problems that are associated with the change in business model related to the digital transformation [8,30].

Manufacturing firms are ignoring the abovementioned warnings and are increasingly embedding DTs across the entire value chain, from design to after-sales service [82]. These technologies provide critical product and market information, enabling rapid response to customer requests through product optimization and demand forecasting. Moreover, DTs allow firms to reconfigure production lines and resources flexibly and efficiently to produce customized products [83]. A digitally enabled infrastructure and multiple data sources help firms tailor products to customer demands and explore new market opportunities [84]. Customized products, in turn, create a unique competitive advantage and increase their perceived value [30].

Furthermore, it has been found that DTs can greatly enhance environmental performance. To achieve this, it is essential to integrate environmental considerations into conventional product development and manufacturing processes, which complicates decision making and operations [85]. These technologies provide effective solutions for designing, producing, and servicing green products, which result in fewer hazardous pollutants and reduced consumption of natural resources throughout the product life cycle. The Internet of Things (IoT), cloud-based design, and big data analytics improve the management of information flow and facilitate the development and innovation of eco-friendly products [30,35]. Accordingly, we posit the following hypothesis:

H3. *Digital technologies positively impact sustainable environmental performance.*

3.3. The Impact of Supply Chain Complexity: SCC's Moderating Role

Supply chain complexity (SCC) refers to the problematic factors that face the management and coordination of supply chains owing to vulnerabilities and inherent risks [86]. Complexity arises from multiple suppliers and customers, a variety of services and products, widespread interconnection among supply chain partners, and a fluid business landscape. Academics have investigated SCC using different models [87] and assessed both its harmful and advantageous impacts [40,88]. Scholars have categorized the three main dimensions of SCC as upstream, internal manufacturing processes and downstream activities, which encompass both structural and dynamic aspects [89]. Others have detailed structural complexities into horizontal, vertical, and spatial dimensions [90].

On the one hand, structural complexity within a supply network arises from the existence of multiple buyers and suppliers for each product and catering to a wide range of customers. That is why a supply network is structurally complex—because it includes many buyers and suppliers for each product and caters to a broad spectrum of customers [89]. This complexity can manifest as either static or detailed complexity [91]. On the other hand, dynamic complexity arises from continual changes and uncertainties in the supply network, such as fluctuations in demand. Studies indicate that there is a lack of research on how structural and dynamic complexities influence the resilience and robustness of supply chains, as well as the processes that support these impacts [40,60,86,88,92].

The appearance of SCC generates deep interconnectedness and reliance between network members, which differ along the supply chain. At all levels of a supply chain, SCC ranges from the upstream stage to downstream stage [89,93]. The existing research emphasizes the positive impact of SCC on SCRE. These findings demonstrate that integrating diverse components within the SC enhances its ability to handle the unexpected disruptions. This capacity is derived from the inherent flexibility of SCC's structural framework [40,86]. Moreover, SCC offer managers a detailed view of risks related to products, information, and materials [11,41]. Therefore, detailed understanding of SCC is important for developing resilience and bolstering quick responses to disruptions [94]. Having said this, SCC enhances, and reinforces resilience [94,95]. Additionally, SCC awareness enhances resilience and enables improve responses to disruptions [94].

The interplay between SCC and robustness has gained has gained attention mainly in production research [96]. In the field of supply chains, two main types of complexities were discussed namely: structural, often called static, and operational, referred to as dynamic. The focus of operational research is based on the dynamic aspects of supply chains, while assuming the structure remains constant. Conversely, structural research examines the network's scale, the interaction among them, and its components [97]. Theories have proven that either the structural or operational features of supply chain can influence its robustness. Regardless of the structure itself, it is typically expected that any change in structural robustness will correspond to a change in structural complexity [98,99]. The major issues lie in finding the optimal balance between the required robustness and the minimal complexity [100].

Studies emphasis the important role that SCRO plays for enabling business to sustain operations during crises [42]. Due to the high level of vulnerability and uncertainty associated with SCC conditions, companies are enhancing their supply base and developing access capacity to maintain stable production [101]. Firms may prefer SCRO to maintain their competitive edge. To prepare for disruption, firms invest in real-time monitoring, control towers, and analytical tools [40]. These tools provide real-time on production and inventory levels, which aid companies in managing dynamic processes. The extent of SCC can contribute to developing firms' robustness and resilience, enabling continuity of operation in volatile environments [40,98,99]. Based on this, the following hypotheses are proposed:

H4. *Supply chain complexity moderates the relationship between digital technologies and supply chain resilience.*

H5. *Supply chain complexity moderates the relationship between digital technologies and supply chain robustness.*

3.4. The Mediating Role of Supply Chain Resilience and Robustness

Supply chains frequently face environments of high volatility and unpredictability, where disruptions are routine rather than rare [102]. In such climates, supply chain integration by itself is insufficient for improving performance [103]. Structural contingency theory [50,53] asserts that the effectiveness of strategies such as supply chain integration relies on the alignment of structural elements with external and internal conditions [104]. Consequently, the influence of supply chain integration on firm performance is dependent on various contingent factors that shape this relationship [105]. This viewpoint is corroborated by numerous empirical studies [105–107] and meta-analytical reviews [108,109].

Robustness and resilience are two critical factors that can significantly influence firm performance, especially during disruptive events [42]. Firms that are robust and resilient are better positioned to manage and respond to disruptions effectively [11,67]. Multiple theoretical and empirical studies underscore the importance of robustness and resilience in maintaining firm performance during periods of turbulence and disruption [42,110,111]. Russell and Saldanha [112] advise companies to adopt new supply chain principles, such as disaster management and contingency planning, to enhance supply chain performance. Shukla et al. [113] highlight that achieving long-term supply chain reliability involves a trade-off between efficiency and robustness. Wieland and Durach [114] found that SCRE positively impacts business performance. Chen et al. [115] stress the importance of incremental recovery strategies to address disruptions from unexpected disasters, thereby improving the operational performance of the supply chain.

Furthermore, an empirical study found that SCRE is a multi-dimensional dynamic capability that significantly affects vulnerability and performance among firms [111]. Another study revealed that SCRE is positively related to market and financial performance [39]. Similarly, research has shown that SCRO can positively influence various performance aspects, including customer value and business performance [116,117].

Regarding performance indicators, Jun and Rowley [118] noted that relying solely on financial metrics to assess firm performance may have limitations in capturing the complete spectrum of organizational performance. Therefore, sustainable environmental performance evaluation incorporates a wider range of criteria, such as greenhouse gas emissions, energy consumption, water use, waste generation, and hazardous-material usage [28]. Building on this1, the hypotheses proposed are as follows:

H6. *Supply chain resilience positively impacts sustainable environmental performance.*

H7. *Supply chain robustness positively impacts sustainable environmental performance.*

H8. *Supply chain resilience mediates the relationship between digital technologies and sustainable environmental performance.*

H9. *Supply chain robustness mediates the relationship between digital technologies and sustainable environmental performance.*

The relationship between the study variables is presented in Figure 1 below.

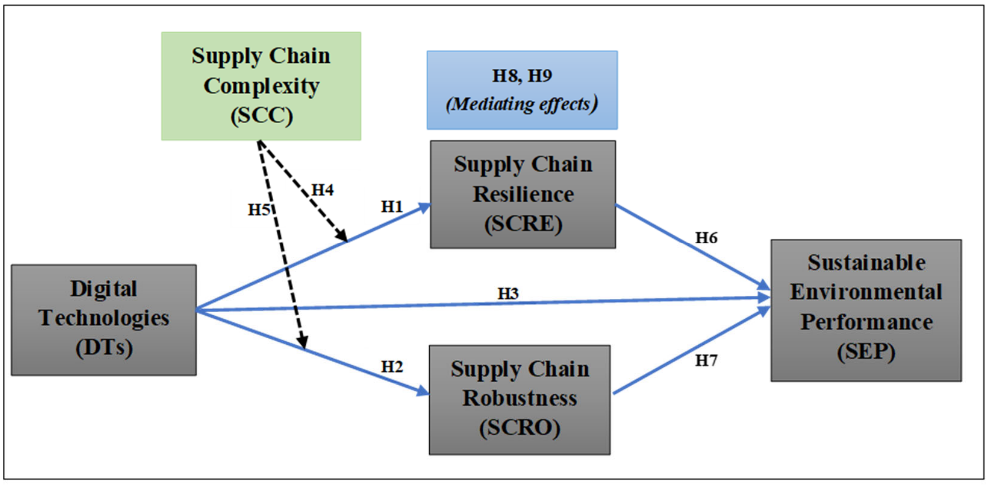

Figure 1. Study framework model.

4. Methodology

4.1. Data Collection and Sample Description

The study involved collecting data from Egypt's manufacturing supply chain, specifically targeting industrial companies registered on the Egyptian Stock Exchange (ESE). The researchers selected the manufacturing sector due to its considerable environmental impact and the significant environmental challenges it faces, particularly among companies utilizing DTs for supply chain management. The adoption of DTs in these sectors was a crucial factor in enhancing the resilience, robustness, and sustainability of the manufacturing supply chain. The list of manufacturing firms was obtained from the ESE. In order to obtain an objective method of data collecting, this study employs an objective method to data gathering by using a positivist paradigm that depends on observable and quantifiable measures [40]. The research approach is deductive and quantitative, the principal technique of data collecting for this research is a survey instrument. The survey questionnaire is structured according to generally known procedures and conducts the sampling. In other words, a simple random sampling method was used, which minimizes selection bias by guaranteeing that each participant has an equal chance of being chosen and that they are representative of the whole population.

Five hundred questionnaires were distributed to managers within these companies. managers of the supply chain were specifically targeted for their expertise and access to relevant information regarding the research topics. The questionnaire was administered using both manual and web-based methods, using a five-point Likert scale to measure respondents' levels from "strongly disagree" (1) to "strongly agree" (5), representing the degree of disagreement or agreement. Data collection began in December 2023 and continued for five months. The response rate was 58.4%, where 292 questionnaires were completed and returned out of the 500 distributed. Table 1 presents details about the demographic distribution of the respondents.

Table 1. Respondents' profile summary.

		Freq.	%
Gender	Male	237	81.2
	Female	55	18.8
Experience	1–5 years	30	10.2
	6–10 years	76	26
	11–15 years	88	30
	More than 15 years	98	33.8

Table 1. *Cont.*

		Freq.	%
Industry	Food and Beverages	69	23.6
	Textiles and Durables	36	12.3
	Industrial Goods, Services and Automobiles	44	15.1
	Energy and Support Services	14	4.8
	Paper and Packaging	28	9.6
	Basic Resources	57	19.5
	IT and Electronics	14	4.8
	Healthcare and Pharmaceuticals	30	10.3
Total		***292***	***100***

4.2. Scale Development and Metrics

The authors of this study deployed a survey methodology. The survey contains four sections, each section designed to meet the specific objectives of the study. The instrument underwent rigorous modifications to ensure its relevance to the current study context based on previous literature. Where these metrics have been extensively employed and shown effective in earlier research. As a result, their validity and dependability are high. Following that, the measurements were converted from English to Arabic, the native tongue of Egypt, and two specialists in supply chain management went over and made changes to the questions to improve their clarity and fluency. In order to verify that the translations were accurate and sufficiently similar to the originals, they were finally back-translated into English. The purpose of this was to improve content validity to ensure data quality and representativeness. To investigate response bias, the early and late respondents were compared, and no discernible differences were discovered between them.

To ensure voluntary consent to participate in this study, informed consent was obtained from participants in the first section. Then, each respondent's demographic data was collected. The questions related to digital technologies (DTs) is included in the second section, where the digital technology metrics—which include blockchain, digital twins, cloud computing, big data analytics, and the Internet of Things—were adapted from [27,29,30]. These cutting-edge technologies have been combined and connected to provide a more unified effect in the era of Industry 4.0. This suggests a strong correlation between the items for digital technology. Therefore, we measured digital technologies in our study using a reflecting model, where we asked the participants to rate the degree to which their company had integrated digital technology into its operations.

To gauge supply chain resilience, robustness, and complexity, the third section included 19 questions. Five items adapted from Ambulkar, Blackhurst, and Grawe [110]; Gölgeci and Kuivalainen [119]; Alvarenga, Oliveira, and Oliveira [29]; and Iftikhar, Ali, and Stevenson [40] were used to assess supply chain resilience (SCRE) and are related to the chain's ability to recover or move to a more desirable state after a disruption occurs. Further, five items derived from Wieland and Wallenburg [116]; Kwak, Seo, and Mason [43]; Alvarenga, Oliveira, and Oliveira [29]; and Iftikhar, Ali, and Stevenson [40] were used to evaluate supply chain robustness (SCRO) and pertain to preserving supply chain operations at a level acceptable or suitable for when disruptive occurrences occur. To assess supply chain complexity (SCC), we used nine items as a higher-order formative construct adapted from Chowdhury, Quaddus, and Agarwal [111]; Ateş and Memiş [87]; and Iftikhar, Ali, and Stevenson [40]. We employed structural and dynamic dimensions as lower order constructs within this construct. These two elements provided us with a comprehensive and all-encompassing grasp of SCC. Together, the two primary components of SCC were taken into consideration when developing the metrics. Sustainable environmental performance (SEP) was assessed in the final section, with six questions adapted from studies by Zaid et al. [120]; Junaid et al. [121]; and Ben Abdelaziz, Chen, and Dey [33]. These are ecologically linked items, such lowering air pollution, cutting wastewater, cutting down on solid waste, and improving the environmental status of the company. A brief synopsis of the primary constructs and their measurement methods is presented in Table 2.

Table 2. Measurement model.

Scale Variables and Items	Outer Loading	Alpha	CR	AVE
Digital Technologies (DTs)		0.877	0.881	0.672
DT-1: Internet of Things	0.824			
DT-2: Digital twins	0.822			
DT-3: Cloud computing	0.859			
DT-4: Big data analytics	0.849			
DT-5: Blockchain	0.738			
Supply Chain Resilience (SCRE)		0.810	0.831	0.547
SCRE-1: We can successfully respond to unanticipated disturbances by swiftly resuming the flow of our product.	0.717			
SCRE-2: We're ready to face the financial fallout from any disruptions in the supply chain.	0.726			
SCRE-3: We are able to respond promptly in the event that the supply chain is interrupted.	0.709			
SCRE-4: We can easily adjust to a disturbance in the supply chain.	0.778			
SCRE-5: We can adjust to the changes that an interruption in the supply chain brings about	0.765			
Supply Chain Robustness (SCRO)		0.810	0.857	0.547
SCRO-1: Our supply chain can continue to function effectively and sustain, even in the face of internal or external interruptions.	0.731			
SCRO-2: Our supply chain able to lessen or prevent risk occurrence by foreseeing and getting ready for them.	0.740			
SCRO-3: Our supply chain able to absorbed a sizable portion of the negative effects of recurring risks.	0.718			
SCRO-4: our supply chain gives us enough time to figure out a reasonable response when changes occur.	0.720			
SCRO-5: Our supply chain has enough time to consider the optimal course of effective reactions.	0.787			
Supply Chain Complexity (SCC)		0.921	0.928	0.616
SCC-1: We have several buyers for every product.	0.722			
SCC-2: For every material or part, we have several suppliers.	0.735			
SCC-3: Our suppliers are spread throughout a variety of geographic areas.	0.695			
SCC-4: Our company/plant serves a numerous client.	0.720			
SCC-5: We have several production and logistical facilities spread across various locations.	0.801			
SCC-6: In this supply chain, we can rely on suppliers to deliver goods on-time.	0.888			
SCC-7: In order to avoid inventory and stockouts, our company works to reduce supplier lead times.	0.863			
SCC-8: We frequently experience variation in our products demand.	0.821			
SCC-9: Our customers want different products with numerous characteristics.	0.793			

Table 2. *Cont.*

Scale Variables and Items	Outer Loading	Alpha	CR	AVE
Sustainable Environmental Performance (SEP)		0.892	0.904	0.651
SEP-1: Our company have substantially reduced energy consumption in production processes.	0.837			
SEP-2: Our company have reduced noxious chemicals into the air and water substantially	0.910			
SEP-3: Our company have substantially improved recycle of waste.	0.832			
SEP-4: The use of sustainable fuels and renewable energy has increased in our company.	0.735			
SEP-5: Our company do business with green suppliers and customers.	0.707			
SEP-6: Our company has improved its environmental status and decreased the number of environmental accidents.	0.804			

4.3. Methods for Data Analysis

To assess the hypotheses, the authors of this study used SmartPLS-4 through the Partial Least Squares Structural Equation Modeling (PLS-SEM) methodology, Where PLS-SEM allows for the efficient estimation of multiple interdependent regression equations, concurrently considering the relationships between the variables that are observed and their underlying constructs [122]. The bootstrapping method using five thousand resamples was employed to ascertain the statistical significance of these relationships. The collinearity between predictor constructs was examined using the variance inflation factor (VIF), where all VIF values were well below the threshold of five, indicating the absence of collinearity problems. PLS-SEM is particularly advantageous for smaller sample sizes, can manage complex models, and does not require assumptions about data distribution [123].

5. Results

5.1. Measurement Model Assessment

By identifying indicators for each latent construct, a measurement model was created to assess the validity and reliability of the latent constructs. The results of this measurement model are detailed in Table 2. First, in order to determine the convergent validity, we used standardized factor loading scores; the average variance extracted (AVE) was computed for each latent construct. All constructs' AVE values exceeded the 0.50 threshold, and the outer loadings for each latent variable were significantly higher than the cross-loadings, as seen in Table 3, Thereby, the scales' convergent validity is verified [123]. Second, to examined the discriminant validity, we used the Heterotrait–Monotrait (HTMT) ratio of correlations and the Fornell–Larcker criterion [124], both of which were below than the strict cutoff of 0.85, as presented in Table 4. Lastly, to evaluate the reliability of the measures, we calculated Cronbach's alpha (α) and composite reliability (CR), finding that both metrics exceeded the acceptable cut-off value of 0.70 [125]. These results indicate that the measures used exhibit high reliability.

Table 3. Cross-loading indicators.

	DTs	SCC	SCRE	SCRO	SEP
DT-1	0.824	0.547	0.469	0.572	0.595
DT-2	0.822	0.462	0.403	0.507	0.581
DT-3	0.859	0.593	0.593	0.562	0.549
DT-4	0.849	0.533	0.509	0.475	0.575
DT-5	0.738	0.516	0.462	0.586	0.561
SCC-1	0.387	0.722	0.462	0.385	0.534

Table 3. *Cont.*

	DTs	SCC	SCRE	SCRO	SEP
SCC-2	0.489	0.735	0.499	0.526	0.547
SCC-3	0.458	0.695	0.457	0.386	0.591
SCC-4	0.492	0.720	0.536	0.497	0.555
SCC-5	0.596	0.801	0.608	0.535	0.601
SCC-6	0.613	0.888	0.573	0.585	0.528
SCC-7	0.600	0.863	0.541	0.528	0.533
SCC-8	0.533	0.821	0.526	0.488	0.548
SCC-9	0.556	0.793	0.585	0.518	0.608
SCRE-1	0.266	0.320	0.717	0.543	0.314
SCRE-2	0.378	0.363	0.726	0.592	0.432
SCRE-3	0.357	0.321	0.709	0.561	0.375
SCRE-4	0.516	0.515	0.778	0.543	0.546
SCRE-5	0.563	0.536	0.765	0.576	0.583
SCRO-1	0.269	0.384	0.558	0.731	0.319
SCRO-2	0.299	0.401	0.584	0.740	0.351
SCRO-3	0.365	0.342	0.566	0.718	0.374
SCRO-4	0.532	0.404	0.459	0.720	0.493
SCRO-5	0.521	0.563	0.520	0.787	0.548
SEP-1	0.562	0.530	0.453	0.526	0.837
SEP-2	0.581	0.554	0.580	0.524	0.910
SEP-3	0.539	0.563	0.571	0.523	0.832
SEP-4	0.549	0.577	0.468	0.522	0.735
SEP-5	0.530	0.527	0.526	0.473	0.707
SEP-6	0.600	0.606	0.518	0.521	0.804

Table 4. Scales' discriminant validity measures.

	Fornell–Larcker					HTMT				
	DTs	SCC	SCRE	SCRO	SEP	DTs	SCC	SCRE	SCRO	SEP
1. DTs	0.827									
2. SCC	0.675	0.785				0.742				
3. SCRE	0.600	0.734	0.815			0.649	0.748			
4. SCRO	0.659	0.635	0.740	0.749		0.688	0.669	0.848		
5. SEP	0.807	0.770	0.642	0.682	0.825	0.820	0.862	0.703	0.711	

5.2. Hypotheses Testing

There are nine hypotheses that make up this study: five hypotheses target direct influences (H1, H2, H3, H6, and H7), two hypotheses (H4 and H5) aim to evaluate the moderating effect of SCC, and two hypotheses (H8 and H9) are intended to evaluate the mediating effect of SCRE and SCRO. The proposed model and the path estimation are shown in Figure 2. The t-statistics, *p*-value, and path estimates for the hypothesis are displayed in Table 5. Path coefficients (β) are used to validate hypotheses; statistical significance of these coefficients' values indicates acceptance of the hypothesis. A hypothesis is considered accepted in PLS-SEM if the t-value is higher than 1.96 and p is less than 5%.

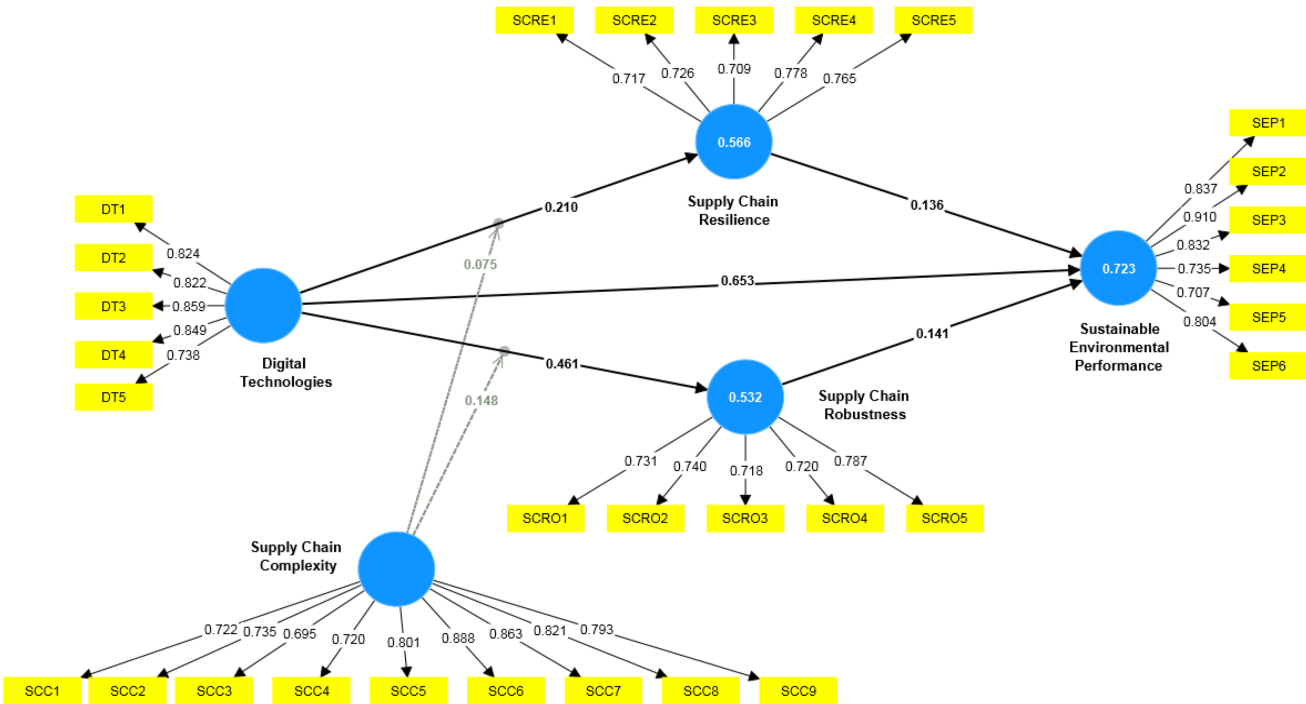

Figure 2. The final research model.

Table 5. Evaluations of structural parameters.

Hypotheses		Beta (β)	T-Statistics	Results
		Direct effects		
H-1	DTs -> SCRE	0.210 ***	3.842	Accepted
H-2	DTs -> SCRO	0.461 ***	5.733	Accepted
H-3	DTs -> SEP	0.653 ***	13.750	Accepted
H-6	SCRE -> SEP	0.136 *	2.380	Accepted
H-7	SCRO -> SEP	0.141 *	2.077	Accepted
		Moderating effects		
H-4	DTs × SCC -> SCRE	0.075 *	2.187	Accepted
H-5	DTs × SCC -> SCRO	0.148 ***	3.758	Accepted
		Mediating effects (partial mediation)		
H-8	DTs -> SCRE -> SEP	0.029 *	2.094	Accepted
H-9	DTs -> SCRO -> SEP	0.065 *	2.146	Accepted

Note: *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

The findings of the hypothesis test are presented in Table 5. The results show that the direct effects posited in H1, H2, H3, H6, and H7 as proposed in the study are supported; the findings demonstrate that DTs significantly and positively impact SCRE (β = 0.210; t-value = 3.842), Consequently, accepting hypothesis H1. Additionally, DTs positively and significantly impact SCRO (β = 0.461; t-value = 5.733); Thus, the research validates hypothesis H2. This result is consistent with earlier research [11,29,60,66,68–72], where it was discovered that DTs strengthened the resilience and robustness of supply chains by assisting members in gathering, storing, transmitting, and exchanging vast quantities of data, which improves flexibility, collaboration, and visibility. Furthermore, these findings corroborate the IPT's theoretical assertion that the development of novel deep learning techniques will augment information processing capacity necessary for efficient supply chain management strategies, hence enhancing resilience, robustness, and associated intricacies [39,42,58].

Similarly, DTs enhance sustainable environmental performance (SEP) (β = 0.653; t-value = 13.750), supporting hypothesis H3. Additionally, we examined the effects of SCRE and SCRO on SEP. It was found that SCRE positively and significantly impacts the SEP (β = 0.136; t-value = 2.380) and SCRO (β = 0.141; t-value = 2.077) significantly and positively impact SEP. As a result, the study accepts H6 and H7. These findings align with previous studies [30,35,47–49,75–77,85] that demonstrated the capability of digital technologies (DTs) to offer remote storage for real-time operational data and enable on-demand access to this data through cloud technology [126]. This facilitates seamless sharing, unhindered flow, instant utilization, and efficient distribution of manufacturing information, leading to a significant improvement in operational effectiveness. Furthermore, these findings validate the theoretical assertions of IPT that DTs can enhance a company's information processing ability, thus supporting decision making in operations and environmental management, ultimately enhancing economic and environmental performance. Consequently, DTs play a crucial role in production scheduling and control, resulting in improved operational efficiency, cost savings, higher profits, and sustainability [30,47].

Regarding the moderation analysis, the results confirmed that H4 and H5 are supported. Regarding H4, which investigates the moderating effect of SCC (DTs × SCC -> SCRE), the result revealed a statistically significant and positive pattern (β = 0.075; t-value = 2.187), as Figure 3 demonstrates that supply chain complexity was found to increase the relationship between DTs and SCRE. Figure 3 displays values for supply chain resilience on the *Y*-axis and low and high values for digital technologies on the *X*-axis. A line in the middle shows the influence of DTs on SCRE at high supply chain complexity levels, and another line (dashed) shows the effect at low supply chain complexity levels. Given that the line is steeper at high SCC than it is at low SCC, this indicates that the influence of DTs on SCRE is greater at higher SCC levels. Furthermore, the findings of H5, which investigated the moderating effect of SCC (DTs × SCC -> SCRO), were statistically significant and positive (β = 0.148; t-value = 3.758). Figure 4 shows that supply chain complexity enhanced the relationship between DTs and SCRO, The *X*-axis in Figure 4 displays values for low and high levels of digital technologies, while the *Y*-axis displays supply chain robustness levels. The effect of DTs on SCRO at high supply chain complexity levels is shown by a line in the middle, while the effect at low supply chain complexity levels is represented by a different line (dashed). where The line is steeper at high SCC than it is at low SCC, indicating that higher SCC levels have a stronger impact of DTs on SCRO. This demonstrates that the relationship between DTs and both SCRE and SCRO is stronger when SCC increases.

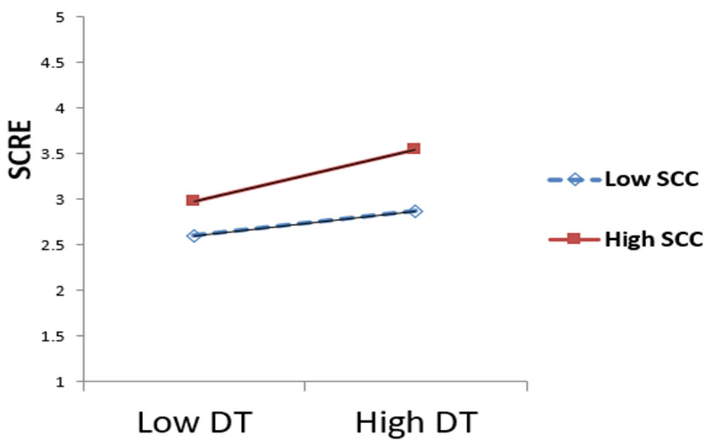

Figure 3. The relationship between DTs and SCRE is moderated by SCC.

Likewise, Table 5 illustrates the outcomes of the mediation. We created hypothesis H8 (DTs -> SCRE -> SEP), suggesting that SCRE partially mediates the relationship between DTs and SEP. Hypothesis H8 (β = 0.029; t-value = 2.094) confirms this. Moreover, the relationship between DTs and SEP is partially mediated by SCRO, according to hypothesis H9 (DTs -> SCRO -> SEP). The hypothesis result H9 (β = 0.065; t-value = 2.146) validates this.

These results are consistent with other research [42,111,116,117] showing that resilience and robustness may have a major impact on a firm's performance, particularly in the face of disruptive occurrences. Thus, using a wider variety of criteria, including greenhouse gas emissions, energy consumption, water use, waste production, and the use of hazardous materials, SCRE and SCRO may be utilized as additional alternative indicators that improve sustainable environmental performance [28,118].

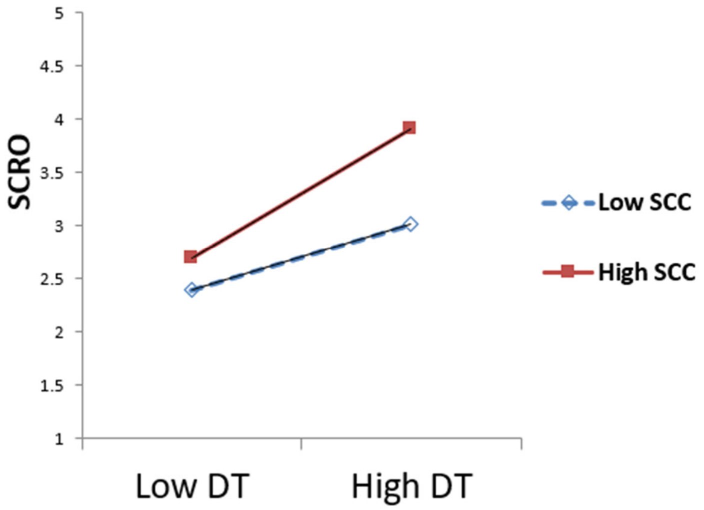

Figure 4. The relationship between DTs and SCRO is moderated by SCC.

The calculated R^2 values are 0.532, 0.566, and 0.723, demonstrating a strong degree of explanatory power. This indicates that the full model was able to explain 53.2% of supply chain robustness, 56.6% of supply chain resilience, and 72.3% of sustainable environmental performance.

6. Discussion and Conclusions

The current study investigated the impact of DTs on SCRE, SCRO, and SEP and the impact of SCRE and SCRO on SEP. The results revealed the following significant and positive relationships: between DTs and SCRE; between DTs and SCRO; between DTs and SEP; between SCRE and SEP; and finally, between SCRO and SEP. Hence, the first three hypotheses along with hypotheses six and seven were accepted. The findings also indicated that SCC had a positive impact on the relationship between DTs and SCRE and a positive impact on the relationship between DTs and SCRO, which confirmed the moderating role of SCC. Hence, hypotheses four and five were accepted. Finally, the findings also revealed that SCRE and SCRO mediated the relationship between DTs and SEP. The study model was able to explain 53.2% of the variance in supply chain robustness, 56.6% of the variance in supply chain resilience, and 72.3% of the variance in sustainable environmental performance.

Furthermore, our study demonstrated H1 and H2, affirming the favorable impact of DTs on SCRE and SCRO. In line with prior studies [11,29,60,66,68–72], DTs were found to positively impact resilience and robustness of supply chains as it was found to strengthen the resilience and robustness, through helping supply chain members to collect, store, transmit, and share large quantities of data, which enhances flexibility, collaboration, and visibility [11,29,60,70–72]. These results also support the theoretical claim by IPT that the existence of innovative DTs will add new capacities in information processing capabilities for effective supply chain management practices, including resilience, robustness, and related complexities [39,42,58].

H3, demonstrating a significant and positive relationship between DTs and SEP, was supported by our study. The presence of DTs notably augments sustainability and environmental performance. Consistent with prior research [30,35,47–49,75–77,85], our findings confirm early results that DTs enhance the level of SEP. Previous studies have illustrated that DTs offer remote storage for real-time operational data and provide on-demand access to this information via the cloud [126], facilitating the complete sharing, unrestricted flow, on-demand usage, and optimal distribution of manufacturing information [127], which significantly enhances operational efficiency. These results support the IPT-based theoretical claims that DTs enhance a firm's ability to process information, thereby supporting decision making in both operations and environmental management, which, in turn, improves economic and environmental performance. Hence, DTs aid in production planning and control, leading to enhanced operational efficiency, cost reduction, increased profitability, and sustainability [30,47].

The study results regarding the moderating effect of SCC on the relationship between DTs and SCRE and the relationship between DTs and SCRO are noteworthy, given that H4 and H5 were accepted and confirmed by the current study. The study concludes that SCC exhibited a moderating effect that was positive in the association between DTs and SCRE and another moderating effect that was positive in the association between DTs and SCRO. These results imply that the appearance of SCC generates deep interconnectedness and reliance between network members [89,93]. Moreover, these findings demonstrate that integrating diverse components within the SC enhances its ability to handle unexpected disruptions. This capacity is derived from the inherent flexibility of SCC [40,86]. Therefore, detailed understanding of SCC is important for developing resilience and bolstering quick responses to disruptions [94]. Having said this, SCC enhances and reinforces resilience [94,95]. Furthermore, SCC's positive moderating impact on the relationship between DTs and SCRO is a crucial result, as it is important to increase the levels of SCRO. SCRO has a crucial role in enabling business to sustain operations during crises [42]. Due to the high level of vulnerability and uncertainty associated with SCC conditions, companies are enhancing their supply base and developing access capacity to maintain stable production [101]. The extent of SCC can contribute to developing firms' robustness and resilience, enabling continuity of operation in volatile environments [40,98,99].

Our study further confirmed hypotheses six, seven, eight, and nine, affirming the favorable impact of SCRE and SCRO on SEP and affirming the mediating role of SCRE and SCRO in the relationship between DTs and SEP. These results are important, as supply chains frequently face environments of high volatility and unpredictability, where disruptions are routine rather than rare [102]. In such climates, improving performance and sustainability is a must [103]. Knowing the importance of robustness and resilience can significantly influence firm performance, especially during disruptive events [42,111,116,117]. Finally, the results of the current study may be helpful to determine a firm's performance out of the financial metrics that have limitations in capturing the complete spectrum of organizational performance. Therefore, SCRE and SCRO can be used as other alternative indicators that boost sustainable environmental performance through a wider range of criteria, such as greenhouse gas emissions, energy consumption, water use, waste generation, and hazardous-material usage [28,118].

7. Implications, Limitations, and Future Research

This study presents several theoretical implications, primarily by developing a conceptual model that explores the interplay between digital technologies (DTs), supply chain resilience (SCRE), supply chain robustness (SCRO), and sustainable environmental performance (SEP) within the Egyptian industrial sector. Unlike previous research, this study focuses on the complexities within supply chains and their influence on SCRE and SCRO. A key contribution of this research is its emphasis on the mediating role of SCRE and SCRO in the relationship between DTs and SEP, suggesting that SCRE and SCRO can serve as alternative indicators to enhance SEP.

Grounded in information processing theory (IPT), the study supports previous findings that efforts to strengthen robust and resilient supply chains contribute to sustainability by improving SEP. Additionally, this research sheds light on the connections among DTs, SCRE, SCRO, and SEP and their interaction with supply chain complexity (SCC), going beyond earlier studies that primarily confirmed direct relationships. The impact of SCRE and SCRO on environmental performance and sustainable development emerges as a promising area for future academic exploration.

This paper argues that information processing theory (IPT) provides a more comprehensive framework for understanding sustainable environmental performance (SEP) than other theories such as the resource-based view (RBV), the dynamic capabilities view, agency theory, actor network theory, transaction-cost theory, and game theory. The key assertion is that by focusing on supply chains and their associated contingencies, companies can mitigate the risks and uncertainties stemming from the increasing complexity of global supply networks. DTs play a crucial role in this context by offering real-time information that enhances SCRE and SCRO, subsequently improving SEP. The findings have significant implications for both practitioners and policymakers, suggesting that promoting SCRE and SCRO and advancing environmental performance can be achieved through the implementation and enhancement of technologies.

This study reveals the synergy between supply chain complexity and improved resilience and robustness, highlighting how advancements in technologies can bring both environmental and economic benefits to firms. The research underscores the vital roles of SCRE and SCRO in boosting SEP. Consequently, SCRO and SCRE are as critical as technologies in enhancing SEP. These insights suggest a multifaceted strategy for corporate performance improvement: (1) adopting cutting-edge digital technologies, (2) constructing complex supply chains to navigate uncertainties comprehensively, and (3) developing robust and resilient supply chains with a focus on environmental sustainability. This approach requires investing in new technologies and allocating resources to build complex, robust, and resilient supply chains. By doing so, firms can not only enhance their performance but also better align with stakeholders' sustainability expectations.

The findings of this study, while significant, come with several limitations that should be considered. The use of cross-sectional data limits the ability to make broad generalizations, and future research could benefit from employing longitudinal or panel data to better understand the dynamic relationships between the examined constructs. Additionally, expanding the study to include various contexts, countries, and cultures would provide a more comprehensive view of the DT–SEP relationship. Incorporating qualitative methods, such as interviews, alongside quantitative approaches could offer valuable insights and enrich future investigations. Moreover, the current study examined DTs as one variable; exploring each specific component of DTs and its impact on resilience, robustness, and sustainability would enhance our understanding regarding the strongest relationship and which of those technologies should receive more concentration in the Egyptian context. Lastly, exploring the potential mediating role of supply chain memory in the DT–SEP relationship would enhance our understanding of causal links and provide a more detailed picture by including insights that quantitative data alone may not fully capture.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the deanship of the scientific research ethical committee, King Faisal University (project number: A495; date of approval: 1 May 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are available upon request from researchers who meet the eligibility criteria. Kindly contact the corresponding author privately through e-mail.

Conflicts of Interest: The authors declare no conflicts of interest.

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