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Link between Digital Technologies Adoption and Sustainability Performance: Supply Chain Traceability/Resilience or Circular Economy Practices

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Abstract: Technological progress and digitalization have ushered in significant transformations in business strategies. At present, research is scarcely focused on the influence of the adoption of digital technologies (DTs) on establishing comprehensive relationships within the context of a circular economy (CE), and the supply chain (SC) framework to contribute to the Resource-Based View (RBV) theory. This study utilizes survey data collected from 235 manufacturing practitioners employed by Turkish manufacturing enterprises to explore a model elucidating the relationship between DTs adoption and sustainability performance (SP) through supply chain traceability (SCT), supply chain resilience (SCR), and circular economy practices (CEPs), based on 10R strategies. Through this linkage, this research accentuates that the exclusive integration of CEPs with digital technology solutions is insufficient for industrial enterprises to attain their long-term sustainability goals. It underscores the necessity of ensuring SCT and/or SCR in this context.

Keywords: circular economy; supply chain; traceability; resilience; digital technologies

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1. Introduction

Examining the interplay between DTs and SP assumes a core role in shaping the corporate sector's and society's endeavors toward attaining sustainability objectives. This investigative pursuit aids industrial entities in fortifying their sustainability strategies and equips them with a more productive response mechanism to foreseeable environmental and social challenges. A selective understanding of how DTs advance various sustainable practices, such as optimization of resource use, energy consumption and distribution, improvements in productivity and operational efficiency, extended product lifecycles, and waste reduction, ref. [1] contributes significantly to businesses achieving these goals skillfully. In contrast to these contributions, the phenomenon of digital transformation can paradoxically pose a potential threat to sustainability. This danger arises from the reduction of product life cycles due to rapid technological developments, thus accelerating the obsolescence of previous technologies and devices and the excessive waste of raw materials and natural resources [2]. Addressing sustainability challenges in this context requires conscious management of products and materials from a sustainable perspective throughout their life cycles. Therefore, the integration of CE strategies in digital transformation processes is inevitable for sustainability purposes. Only in this way, CE opportunities, such as refurbishing equipment for the manufacturing industry, increasing employee productivity and motivation, establishing a smart factory based on resource efficiency, and designing closed-loop production process chains, can be provided [3]. Digital CE strategies support data transparency and accessibility by capturing detailed information on resource flows, material origins, manufacturing processes, and end-of-life operations [4]. On the other hand, the integration of advanced technologies in SC processes is bring increasingly discussed to understand the real-time and proactive exchange of granular information to achieve traceability and visibility in the SC [5]. Monitoring the entire product lifecycle or value-added process is also critical to the successful operation of the CE system [6]. Therefore, it is essential to develop a framework that evaluates the concepts of CEPs, SC traceability, and resilience in an integrated manner, and explains the interrelationships between these concepts on the path from adapting DTs to sustainability. Current researchers link DTs to various concepts, such as SCT [7–9], SCR [10–14], CEPs [2,4,15–17], and sustainable development [15,17,18]. Nevertheless, there is a lack of literature on developing an integrated model to capture how the adoption of DTs affects a firm's SP through CEPs, SCT, and SCR, and to examine the relationships among these concepts. To address this gap, this study aims to adopt digital empowerment as a theoretical perspective to uncover how organizations utilize DTs to facilitate the SC and circularity process integration, thereby improving SP.

The current research advances a novel model to predict the key factors influencing the link between DTs and SP within the manufacturing industry in Turkey. The main objective of this study is to identify which of the following structures are the factors that play an active role on the path from DTs to sustainability:

(a) Supply chain traceability;
(b) Supply chain resilience;
(c) Circular economy practices.

The rest of the study is organized as follows: in Section 2, the conception foundation of the leading research theories and hypotheses of the proposed model was elucidated. In Section 3, the methodological approach was presented, while data analyses and research results were reported in Section 4. Finally, the synthesized findings and strategic implications were explained in Section 5.

2. Literature Review and Hypothesis Generation

2.1. Theoretical Background

This study derives its theoretical foundations from accepted theory, i.e., the resource-based view. RBV is theoretically appropriate for explaining how a firm can gain a competitive advantage by systematically integrating its resources into its organizational processes and routines, restructuring, and transforming its unique resources into capabilities [19]. Therefore, it has been well-accepted in disciplines such as operations management, SC management, sustainability, etc. According to the literature [20], when evaluated from the RBV perspective, DTs are valuable due to their contributions to cost, delivery, flexibility, and quality performance in SCs. Researchers have [21] extended the RBV theory with green logistics practices, to focus on using DTs to facilitate the adoption of CEPs. In another study using the RBV theoretical perspective, it was suggested that BC positively affects SC performance through the SC capabilities it enables [19]. Researchers have also [22] examined how Industry 4.0-focused CE applications affect sustainable business performance based on RBV. The study [23] used the RBV as a theoretical framework to show the relationships among Industry 4.0, SC integration, and SCP. The reviews highlight that despite the increasing number of studies on digital integration in manufacturing enterprises, there is scarce literature on the interactions of SC and CE processes, and raises the voice to conduct a systematic investigation based on theory to understand the impact of digital transformation on the larger picture. This study serves as a guide for practitioners, managers, and users to understand the relationships between complex production processes and strategies. Using RBV as the theoretical basis, this study explores how firms' digital adaptation affects their SP through SCR, SCT, and CEPs. The following sections explain how this led to the development of each hypothesis of the proposed model to examine these relationships.

2.2. The Path from Digital Technologies Adoption to Sustainability Performance

Adapting digital technology plays a critical role in achieving sustainability goals for businesses, but it also brings new risks. Innovative technologies will replace traditional production and consumption processes with more circular and sustainable models. Therefore, the transformation of existing business models and organizational structures in industrial enterprises is inevitable due to digital transformation. However, this transition may lead to workforce and organizational alignment challenges for businesses and industries. The only way to overcome this is to identify practical tools for transitioning from digital technology adaptation to sustainability. Monitoring these tools enables companies to make more informed and effective decisions regarding strategic management, efficiency, risk management, competitive advantage, and societal/environmental/economic impacts. That is why the interaction between the level of sustainability of organizations and the level of digital technology is attracting increasing attention. The advent of sustainability as a key concept has expanded firm performance evaluation beyond conventional financial metrics. The research conducted by [15] found that assessing SP requires consideration of three primary dimensions: ES, SS, and ENVS. Hence, this study aims to elucidate the core mediating relationships between DTs and SP, emphasizing their impacts across economic, social, and environmental domains.

Theoretical studies (Table 1) have been conducted to ascertain whether digital transformation triggers SC development through SCT [24] and SCR [25,26] thereby determining whether SP can be enhanced or not. Likewise, scholars have generally focused on the direct impact of CE adoption on sustainability aspects [27] or digitalization effects on CE applications [28–30]. While there may be theoretical studies on digital transformation, SC development, SCT, SCR, and SP individually, there is a gap in comprehensive conceptual clarity that integrates these concepts. Theoretical studies often lack a unified framework that clearly defines the relationships, mechanisms, and causal pathways, making it challenging to ascertain the impact of DTs on sustainability through SC and CE mechanisms. Furthermore, none have comprehensively assessed the complex relationship between these variables or provided a scale for the use of digital tools as comprehensively as this study. In line with these observations, we examine how DTs interact with existing SC strategies and CEPs to affect SP, and we provide the literature with the most comprehensive scale of digital tools. In addition, Turkey's manufacturing sector's current state or actual status remains insufficiently examined, highlighting the need for more in-depth research. This objective will help clarify the effects of a resource-based view on resources and capabilities by examining the mediating role of DTs on SP. In this context, understanding the effects of the adoption of DTs on organizational resources and capabilities and how these effects shape SP will shed light on the perspective of the RBV theory.

Table 1. Summary chart of literature.

Reference	DTs	CEPs	SCR	SCT	Other Constscusts	Performance Type
[15]	Big Data	✔	-	-	SC Flexibility	Sustainable SC (ENVS, SS, ES)
[24]	Transformation	-	-	✔	Information Sharing	Sustainable SC
[25]	Organizational	-	✔	-	Absoptive Capacity	SP
[26]	Digital Twin	-	✔		SC Performance	SP
[27]	-	✔	-	-	Green SC Management Resource Efficiency	ENVS, ES
[28]	Execution Forecasting Planning	✔	-	-	SC Capability	Operational Sustainability ES
[29]	Addictive Manufacturing	✔	-	-	Sustainable SC	-
[30]	RFID-Block Chain	✔	-	✔	SC Transparency	Profitability Market Share Lead Time

2.3. Digital Technologies and Supply Chain Traceability

SCT provides information to companies by enabling them to measure and monitor material flows, parts, components and products from suppliers to end customers [31]. For managers to weigh this basic information and make the best decision, the data produced, transmitted, stored, and analyzed must be seamlessly transmitted on the same backbone. For this reason, DTs are now indispensable tools for ensuring traceability [24]. Multiple researchers [24,32] advocate for the essential requirement of enhancing existing SCs through integrating DTs, emphasizing the impact on traceability.

For example, AI-based traceability of the product supply chain improves the quality and safety of a product by enabling the detection of weaknesses, defects, and counterfeits [8]. The infusion of digital solutions, such as Radio Frequency Identification (RFID), Internet of Things (IoT), Blockchain (BC), and AI, imparts a level of granularity and precision to the transparency through the traceability of goods and information [8]. Moreover, technologies such as QR codes and RFID tags enable the traceability of products throughout their life cycle [33]. Therefore,

H1. *Adoption of DTs positively influences SCT.*

2.4. Digital Technologies and Supply Chain Resilience

Various SC-related technologies are part of the digital transformation. DTs can be used for response tracking, especially in crises, and are important in building resilient SC models. The onset of the coronavirus pandemic highlighted that companies making extensive use of DTs exhibited increased resilience through improved visibility and coordination [12]. Adopting these technologies strengthens resilience capabilities by improving data quality, increasing the speed of reconstruction, and mitigating unexpected consequences [11]. For example, artificial intelligence and machine learning offer numerous advantages such as cost reduction, quality improvement, and accelerated responsiveness [17]. Investments in cyber security technologies and practices are known to protect digital assets, ensure data integrity, and mitigate cyber security risks that could jeopardize SCR. Another recent study showcases the contribution of Industry 4.0, including IoT, Cloud computing (CC), BD, digital twins (DT), and BC in achieving SCR [11].

Similarly, AM can reduce the need for risk mitigation stocks and capacity reservations, which involve identifying and maintaining alternative backup suppliers [12]. Early warning systems also enable the early detection of potential problems, thus enabling intervention and minimizing the impact of crises. It is foreseen that increasing SCR through early warning systems and AM will be one of the key issues of the future [34]. In short, the use of DTs has the potential to increase resilience within enterprises by enabling the creation of a synchronized SC through information exchange and collaborative decision-making processes [26]. Hence,

H2. *Adoption of DTs positively influences SCR.*

2.5. Digital Technologies and Circular Economy Practices

DTs play a vital role in effectively utilizing resources and reducing waste, which are fundamental strategies of the CE. I4.0 integration enables firms to leverage vast amounts of data from multiple sources to optimize resource utilization while improving current operations [35]. BD insights based on these data can be used to integrate processes and share resources, thereby reducing resource consumption throughout the entire SC, extending product life, and encouraging material reuse and recycling [15]. Previously, researchers [36] have explained that IoT (through monitoring, analysis, and control of product data), cyber–physical systems (through making data available for real-time decision-making, enabling optimization of production and maintenance), and cloud technologies (through sharing production capabilities and resources on a cloud platform and improving sustainable process manufacturing) have a role in designing business models for CE. Furthermore, blockchain-based tracking devices can effectively enhance tracking across the entire product lifecycle and improve circularity performance by also supporting the implementation of recycling initiatives [37,38].

Previous studies [17,29,39] suggest that the implementation of CEPs is more straightforward when a firm has DTs. Consequently,

H3. *Adoption of DTs positively influences CEPs.*

2.6. Basis of Mediating Effects

Acting as a catalyst for traceability, digital transformation helps SC to eliminate barriers and achieve consistent growth [24]. In this context, traceability serving as a key driver can help SC achieve superior performance by leveraging digital transformation [24]. Moreover, traceability in every sector and for every product catalyzes a smarter, safer, efficient, and fully interconnected global SC, which is a key element in realizing a smart SC and thus contributing to a more sustainable Earth [40]. The complete traceability provided in SC processes also allows the capability to swiftly respond to situations that may have adverse effects across the SC and promptly implement corrective and preventive actions [7]. This, in turn, signifies preventing potential harm to sustainability goals. Hence, adopting DTs, enabling more effective monitoring and evaluation of all processes from input sources to the final product, serves as a critical bridge for businesses to achieve their sustainability goals regarding traceability.

The linear economy is considered unsustainable as it results in damage to the ecosphere, depletion of resources, and causes issues in terms of ES, SS, and ENVS [41], whereas the circular SC continues to loop using the 10R strategies. The integration of DTs into activities such as predictive maintenance facilitates the extension of a product's lifespan in line with CE strategies, which is critical for manufacturing companies seeking to advance sustainability management [42]. Therefore, the interaction between DTs and CEPs presents a significant business model for enhancing SP in enterprises.

A study by [39] underscored that integrating CEPs within SCs significantly mitigates the adverse effects traditionally associated with conventional business operations on both environmental and social well-being. CEP and sustainable SC flexibility as mediating variables between BD and sustainable SC performance support the theory that sustainability is a key part of the upcoming business strategy [15]. The above discussions motivated us to analyze the combined effect of CEPs on the link between DTs and SP.

From the point of view of visibility and digital control, it is clear that enterprises that leverage digital production networks can strategically position themselves more effectively during periods of crisis and subsequent recovery phases [43]. Similarly, [44] shows that BD improves SCR by increasing visibility. CC and BC technologies promote SCR by improving visibility, foresight, and adaptability [45]. The imperative to conduct SC activities by legal regulations and industry standards directs businesses to focus on ethical, environmental, and social responsibilities, thereby enhancing SP [46].

The more traceable an SC is, the faster it can respond to crises, thus the greater its resilience. For example, the impact of IoT is equally evident in the implementation of mitigation strategies such as knowledge management, development of suppliers, adaptation of supply networks, and increasing flexibility or visibility [47]. According to [48], thanks to machine learning models, production systems gain the ability to adapt to unexpected events and predict production problems. Tracing systems enable identification and the analysis of SC deviations, providing warnings about interruptions that have occurred or may occur, and restoring SC operability [49], thus increasing resilience.

Digital CE strategies improve SC visibility and traceability by enabling data to be collected, analyzed, and shared in real-time throughout the lifecycle stages of materials, components, and products. For instance, AI technology improves SC management by enabling companies to accurately predict waste generation and optimize demand for products [2]. The digital platforms based on BC technology can help to reduce costs involved with traditional tracking methods and ensure better traceability levels in operations through real-time reporting of information changes based on push mechanisms, thereby enabling information synchronization among circular SC partners [7]. In line with smarter product usage strategies, with the use of IoT, BDA, and cloud computing, and other I4 technologies, independent products can be transformed into smart products, enabling real-time monitoring of their usage, operating conditions, and location [2].

Briefly,

H1a. *SCT positively mediates the relationship between adoption of DTs and SP.*

H2a. *CEPs positively mediate the relationship between adoption of DTs and SP.*

H3a. *SCR positively mediates the relationship between adoption of DTs and SP.*

H4a. *SCT positively mediates the relationship between adoption of DTs and SCR.*

H5a. *CEPs positively mediate the relationship between adoption of DTs and SCT.*

H4. *SCT positively influences SCR.*

H5. *CEPs positively influence SCT.*

H6. *SCT positively influences SP.*

H7. *CEPs positively influence SP.*

H8. *SCR positively influences SP.*

Figure 1 presents the model developed to contribute to the literature based on the aforementioned reasons for generating hypotheses.

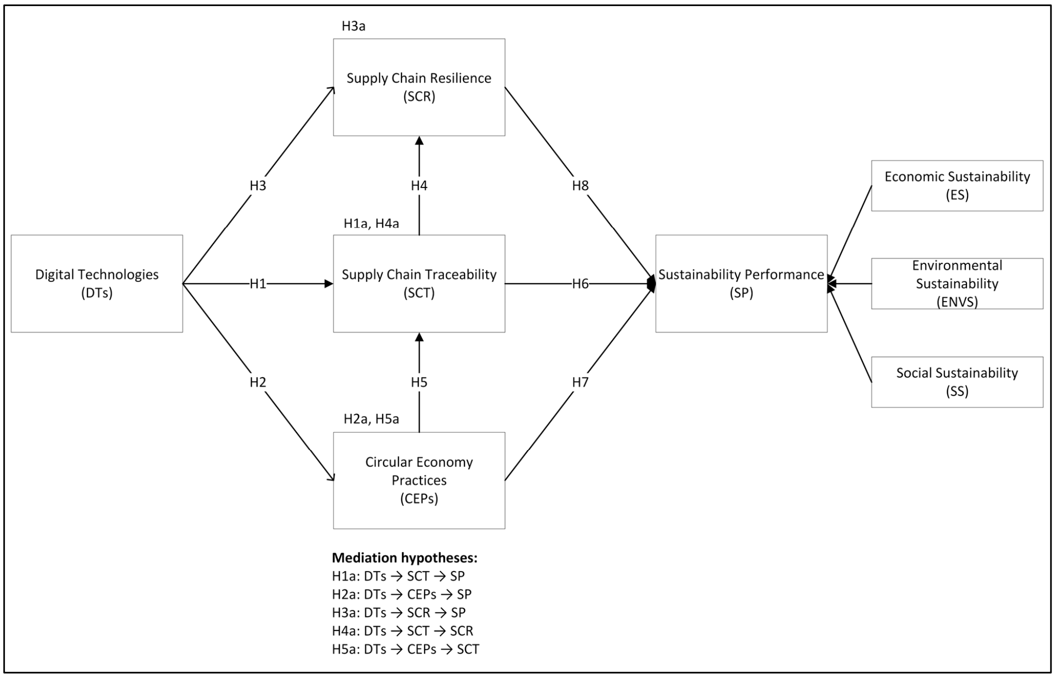

Figure 1. Measurement model.

3. Methodological Approach

3.1. Sampling and Data Gathering

To develop the scale, academic studies from the Web of Science and Scopus were examined. The draft survey structure was evaluated by a team of three academics and three production managers in the manufacturing sector. As a result from the feedback, explanations were added to the survey for each item in the digital technologies scale. In the context of this study, an online survey was developed for the target manufacturing companies in Turkey to examine the relationships between several variables under consideration. Data were collected between December and April 2023. It was gathered utilizing a simple random sampling methodology, whereby direct outreach was conducted mainly via LinkedIn to the pertinent managers of the respective firms. A total of 235 questionnaires were collected. Of the participants, 42% of the managers and experts in the study had a postgraduate degree, 55% had a bachelor's degree, and 3% had an associate degree. All of the associate degree graduates were managers with more than 15 years of work experience. All of the managers were selected from individuals who worked in SC processes and were knowledgeable about digital technologies. Since we reached out to the participants one-on-one through our personal accounts, those who did not have sufficient knowledge gave us feedback and did not participate in the survey. The participation rate in the survey was approximately 22%. No survey participant was excluded due to incomplete responses as all questions were mandatory. The demographics of the 235 valid samples are presented in Table 2. Considering the education of the respondents, the majority of the respondents had bachelor's degrees, representing 55%. A substantial number of respondents (42%) had a postgraduate education level.

Table 2. Sample characteristics.

Characteristic	Number of Firms	Percentage (%)
Position of the respondent		
Owner	8	0.03
Genel Manager	12	0.05
Departmant Head/Director	150	0.64
Professional expert	65	0.28
Total		100%
Number of employees		
<50	12	0.05
50–249	51	0.22
250–499	38	0.16
>500	134	0.57
Total	235	100%
Ownership Structure		
Local	149	0.63
Foreign Capital	49	0.21
Foreign Participated	37	0.16
Total	235	100%
Sector		
Textile	32	0.14
Automotive-Electronic and Machinery	80	0.34
Basic Metal	17	0.07
Food and beverage	23	0.10
Plastics	9	0.04
Fabricated Metal Products	11	0.05
Chemicals and pharmaceutical	36	0.15
Others	27	0.11
Total	235	100%

3.2. Measurement of Variables

The items (as presented in Appendix A) used to measure the core variables were adapted from existing literature. The CEPs scale was taken from [16]. The scales used by [50] and [51] were combined for SCR, consisting of 8 items. The SCT construct was measured using the scale developed by [52], which contained 5 items, while the scale for CEPs was adapted from [16] and contained 10 items. Also, the scale of SP was measured by three aspects: ENVS, ES, and SS, totaling 20 items: 6, 8, and 6 items for each element, respectively [2]. To determine the items of adoption of DTs, an evaluation was conducted from a perspective encompassing Industry 4.0 to 5.0. Consequently, a total of 14 items were used, including BD, CC, CPS, AM, H&VI, CS, AR, VR, Robots/Cobots, AI, DT, BC, MT, and IoT, which were based on previous studies [53,54]. The model consists of items measured on a five-point Likert scale.

4. Data Analyses and Results

PLS-SEM has been preferred due to its flexibility and robust results in predicting and validating complex models, as well as its ability to produce reliable outcomes even with small sample sizes and violations of normality assumptions [55].

4.1. Reliability and Validity Analyses

Before validating the structural model, multicollinearity between the constructs in the research framework was assessed through the application of the Variance Inflation Factor (VIF). Following the threshold set by [15], all VIF values were found to be below the critical limit of 10. VIF values ranging from 1.28 to 4.381, clearly indicate that multicollinearity is not a significant concern for the investigated constructs.

Factor loadings, Cronbach's alpha, Dijkstra-Henseler, and composite reliability were tested to confirm construct reliability and validity. As shown in Table 3, the factor loadings of all items were above the recommended value of 0.4 [53,56]. Cronbach's alpha values ranged from 0.832 to 0.921, within the acceptance level recommended by [56]. As shown in Table 4, the Dijkstra-Henseler (ρ_a) and composite reliability (ρ_c) values of all constructs were above 0.70, which is acceptable according to the recommendations of [57].

Table 3. Indicators of items and constructs.

Construct	Items	FL	ρ_a	ρ_c	AVE
DTs	DT1	0.709	0.915	0.923	0.501
	DT2	0.748			
	DT3	0.661			
	DT4	0.694			
	DT5	0.769			
	DT6	0.668			
	DT7	0.763			
	DT8	0.716			
	DT9	0.754			
	DT10	0.641			
	DT11	0.731			
	DT12	0.619			
CEPs	CE4	0.596	0.832	0.874	0.502
	CE5	0.648			
	CE6	0.726			
	CE7	0.790			
	CE8	0.799			
	CE9	0.769			
	CE10	0.596			

Table 3. *Cont.*

Construct	Items	FL	ρ_a	ρ_c	AVE
SCT	SCT1	0.728	0.859	0.896	0.633
	SCT2	0.763			
	SCT3	0.756			
	SCT4	0.869			
	SCT5	0.854			
SCR	SCR1	0.822	0.926	0.935	0.644
	SCR2	0.821			
	SCR3	0.797			
	SCR4	0.817			
	SCR5	0.836			
	SCR6	0.805			
	SCR7	0.732			
	SCR8	0.783			
SP					
ENVS	ENVS1	0.852	0.924	0.940	0.722
	ENVS2	0.920			
	ENVS3	0.866			
	ENVS4	0.866			
	ENVS5	0.827			
	ENVS6	0.758			
ES	ES1	0.738	0.867	0.894	0.513
	ES2	0.649			
	ES3	0.707			
	ES4	0.703			
	ES5	0.723			
	ES6	0.736			
	ES7	0.729			
	ES8	0.740			
SS	SS1	0.851	0.915	0.933	0.701
	SS2	0.871			
	SS3	0.904			
	SS4	0.870			
	SS5	0.738			
	SS6	0.777			

Table 4. Results of the Fornell-Larcker test.

Constructs	CEPs	DTs	SCR	SCT	SP
CEPs	0.708				
DTs	0.317	0.708			
SCR	0.263	0.414	0.802		
SCT	0.370	0.490	0.592	0.796	
SP	0.282	0.544	0.552	0.578	0.866

Furthermore, to verify the convergent and discriminant validity of the items, the average variance extracted (AVE), Fornell-Larcker criterion, and hetero–trait–mono–trait ratio (HTMT) were evaluated. As shown in Table 3, the AVE values of all constructs are above the recommended value of 0.5 [57]. To fulfill this rule, DT and VR items, and CE1-CE3 items were removed. Thus, the convergent validity of the model was ensured. Furthermore, discriminant validity was assessed using the Fornell-Larcker criterion. As seen in Table 4, it was observed that the square root of AVE was higher than the correlations between constructs [58]. According to [59], the HTMT for conceptually similar constructs should ideally be below 0.90. Since the maximum observed HTMT value was 0.682 (Table 5), the measurement model also fulfilled the HTMT criterion.

Table 5. Results of the HTMT test.

Constructs	CEPs	DTs	SCR	SCT
DTs	0.348			
SCR	0.289	0.435		
SCT	0.427	0.549	0.651	
SP	0.324	0.619	0.606	0.682

4.2. Testing of Hypotheses

A PLS-SEM bootstrap procedure with 5000 subsamples was used to verify the statistical significance of path coefficients between latent constructs. Hypotheses H1–H8 were determined to be statistically significant at a *p*-value less than 0.05. Furthermore, Cohen's f^2 values associated with significant pathways exceeded the threshold value of 0.02, and the effect sizes of these associations were found to be acceptable according to [60]. The only hypothesis not statistically supported based on *p*-values and Cohen's f^2 values was hypothesis H7.

According to the [60], if the value of f^2 is between 0.020 and 0.150, between 0.150 and 0.350, and greater than 0.350, the degree of influence on an endogenous latent variable is small, medium, and large, respectively. In this study, the f^2 values exceeded the thresholds of 0.020 and 0.350, as presented in Table 6. These results ensured the general validity of the constructs and the model.

Table 6. Summary of direct hypotheses results.

Hypotheses	Original Sample (O)	T Statistics	*p* Values	Cohen f^2	Decision	Effect Size
CEps → SCT	0.239	3.997	0.000	0.072	Supported	Small
CEPs → SP	0.063	1.212	0.226	0.006	Not Supported	-
DTs → CEPs	0.317	5.738	0.000	0.111	Supported	Close to Medium
DTs → SCR	0.164	2.520	0.012	0.032	Supported	Small
DTs → SCT	0.414	6.666	0.000	0.218	Supported	Medium
SCR → SP	0.320	4.935	0.000	0.111	Supported	Close to Medium
SCT → SCR	0.512	8.999	0.000	0.316	Supported	Substantial
SCT → SP	0.366	5.849	0.000	0.135	Supported	Close to Medium

The indirect (mediation) effects between the constructs are shown in Table 7. Based on the mediation procedure, we conclude that SCR and SCT fully mediate the DTs adoption to SP relationship, in contrast to CEPs.

Table 7. Summary of indirect (mediation) hypotheses results.

Hypotheses	Original Sample (O)	T Statistics	*p* Values	Decision
DTs → SCT → SP	0.152	3.891	0.001	Supported
DTs → CEPs → SP	0.020	1.073	0.284	Not Supported
DTs → SCR → SP	0.052	2.011	0.044	Supported
DTs → SCT → SCR	0.212	5.079	0.000	Supported
DTs → CEPs → SCT	0.076	3.101	0.002	Supported

In this study, the relationships among the constructs were assumed to be linear. To assess the model's robustness, it is essential to explore the potential for a nonlinear relationship between the dependent and independent constructs using Ramsey's [61] regression equation specification error test (RESET).

The first step to apply the RESET test in the variance-based structural equation model is to compute the construct scores. Next, both quadratic and cubic effects should be examined to determine if the inclusion of nonlinear effects yields significant results [62]. In this model, sustainability performance is used as a dependent construct. The independent constructs include SP, SCT, CEPs, SCR, and adoption of DTs. The results of Ramsey's RESET indicate that neither the quadratic (p (F (2228) > 0.446872) = 0.64) nor the cubic (p (F (1229) > 0.384007) = 0.536) effects, nor both combined (p (F (2228) > 0.446872) = 0.64), are significant. Consequently, it can be concluded that the linear model is robust.

5. Synthesizing Findings and Strategic Implications

5.1. Synthesizing Findings

Digital technology adaptation is a trigger for CEPs, SCT, and SCR in manufacturing enterprises. These results are consistent with the findings of DTs in terms of SCT accelerated by [8,18,63], CEP [2,16,28,38,39] and SCR [11,13,14,64,65]. This study meets the need to provide a better understanding of the predictors of how SCT and CEPs mediate the influence of DTs on SP. The current research results are also consistent with [24,66], which stated that the SC, to increase traceability, could be significantly effective on SP if it is equipped with DTs. Similarly, SCR as a mediating variable between DTs and SP corroborates the conclusions drawn by previous researchers [13,26,67] that sustainability will be a pivotal element in forthcoming business strategies.

We also obtained a result that runs counter to commonly accepted conclusions. Extant studies have mainly emphasized the mediating effect of CE on the road from DTs to sustainability. Ref. [68] investigated the role of BC on CE to enhance organizational performance for Chinese and Pakistani firms [69] and examined how DTs (IoT, CC, BD, AM, AR, AI) influence circular product design to enhance environmental performance in the electric–electronic and equipment sectors in Brazil. A study conducted by [2] demonstrated that CEPs serve as a complete mediator in the relationship between DTs and SP within Indian manufacturing organizations. The study's findings in the Chinese automobile sector [28] also supported the view of implementing DTs in CE processes to bolster economic and operational performance, and there was a focus on ecological practices and advancements in waste management. They also [2] discerned the mediating impact of CEPs on the association between DTs and SP, delineating three dimensions, specifically within the Indian manufacturing sector. Nonetheless, our results refuted previous studies directly supporting CEPs' influence on SP. This finding is in line with the study on Indian manufacturing firms which concluded that CEPs do not directly affect the sustainability of SC performance [15]. The reason for this conclusion may be that the elements of practice associated with the 3 R's of design in the 10R practices have been removed from the scale. These elements are based on strategies that aim to completely eliminate waste at the beginning of the value chain during the initial design and development of products. Hence, the remaining 7Rs elements may not have been able to exert a dominant influence on SP. Another reason for the lack of direct impact of CEPs on sustainability performance may be the lack of successful strategic integration of CEPs in achieving corporate sustainability goals. On the other hand, our findings suggest that DTs have a significant impact on the adoption of CE tools as well as on the enhancement of SCT and SCR capabilities.

This study has strikingly demonstrated that the implementation of CE strategies alone may not be sufficient to achieve sustainability goals on the path from digital technologies to sustainability. Instead, it is seen that a synergistic integration with SC management strategies is necessary, and only in this way can companies maintain their sustainability.

5.2. Managerial Implications

The findings of the study provide valuable insights to operational managers on the deployment of DTs in Turkish manufacturing firms, exploring their linkages with SCT, SCR, and CEPs in the sustainability framework. The affirmative mediating influence of SCT and SCR on SP underscores the practitioners' acknowledgment that digital SC management catalyzes attaining sustainability goals.

Although the DTs offer enormous promise, top management's lack of vision and leadership is a major barrier hindering the adoption of DTs [70,71]. Therefore, it is strategically important for practitioners in Turkish manufacturing organizations to analyze the obstacles to implementing DTs on the path to sustainability. This is only possible by exploring the relationships and interactions of complex processes with each other. The results based on the research model examined within the scope of this study can be used as a good decision-making and strategy development tool as they contain essential results that will add vision to managers.

The findings reveal the power of DTs to enable the CE. However, this power does not reflect the SP targets similarly. This result is instructive for managers in that it shows that the implementation of CE strategies is not sufficient to increase SP. Practitioners are advised that the implementation of DTs within CE strategies should align with the SP objectives that the organization aims to accomplish. To achieve SP objectives through CEPs, production organizations should select and adopt appropriate DTs that facilitate the achievement of these objectives. Therefore, managers should critically approach all available technologies and ensure the integration of appropriate technologies after assessing how relevant technologies can contribute to SP objectives.

CEPs are critical not only for the sustainability of businesses but also for economic development. These strategies, which can be a solution for the sustainability of natural capital, should be integrated by accounting for the complexity of production and should be correctly associated with existing resources.

This outcome provides a basis for governments to enhance awareness regarding implementing DTs in the manufacturing industry, specifically to support the development of programs financially aiding companies in investing in these technologies, particularly in emerging economies.

5.3. Theoretical Implications

The present study is one of the preliminary studies that has empirically investigated the impact of DTs (with a perspective that extends from Industry 4.0 to Industry 5.0 technologies) on SP, filling this gap in the literature.

Subsequently, existing literature indicates that the influence of technology initiatives on firm performance should be examined within the context of a mediating variable. To address this gap, we identified CEPs, SCT, and SCR as crucial mediating variables affecting the relationship between DTs and SP. We present a comprehensive and integrated network model of relationships to the literature. Moreover, we shed light on the expansion of the RBV theory with the results of our study regarding these relationships being presented. To examine these relationships, we developed the scale containing the most comprehensive tools in the literature. The hypotheses that CEPs directly influence the implementation of SP were not supported in this study. In addition, we add to the literature by concluding that the regulatory effect of CEP on the DTs-SP relationship can only be achieved by securing SCT or SCR.

5.4. Limitations and Future Areas of Research

This analysis focuses on the Turkish manufacturing industry. Hence, analogous studies in other countries are necessary to facilitate the extrapolation of our findings to diverse contexts. Indeed, studies scrutinizing a particular sector can also unveil details about sector-specific relationships.

The concept of DTs has been used as a generalized term that includes different technology applications, with a perspective extending to Industry 5.0. In the future, studies tailored to specific applications will be necessary depending on technological developments. The scale utilized in this study is not related to the success level of DT applications in the manufacturing sector but is solely concerned with usage intensity. However, considering that the digital transformation process has not yet been fully completed in developing countries such as Turkey, we recommend validating the study’s findings following the successful implementation of DTs in the Turkish manufacturing industry.

Furthermore, in future sustainability studies, sustainability practitioners should consider the impact of the CE's design, consumption, and recycling practices separately and determine the degree of effectiveness in achieving the goal.

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Appendix A

Table A1. Measurement of constructs.

Construct	Items	Source
Digital Technologies	Please indicate to what extent each of the following digital technologies has been used in your company (1 = "too low level"; 5 = "too high level"). DT1. Artificial intelligent DT2. Augmented reality DT3. Additive manufacturing DT4. Blockchain DT 5. Big data DT 6. Cloud computing DT 7. Cyber physical systems DT 8. Cybersecurity DT 9. Integration DT 10. IoT DT 11. Mobile technologies DT 12. Robots DT13. Digital twins * DT14. Virtual reality *	[53,54]
Supply Chain Traceability	Please indicate to what extent you agree or disagree with the following statement regarding your company. (1 = "strongly disagree" to 5 = "strongly agree"). SCT1. Identifying the sources of our green raw materials. SCT2. Tracking the processes distribution and transportation activities. SCT3. Tracing the origins of our purchases through the entire supply chain. SCT4. Tracking the environmental performance of our logistics activities. SCT5. Tracking the impact of warehousing and packaging on the environment.	[52]

Table A1. *Cont.*

Construct	Items	Source
Supply Chain Resilience	Please indicate to what extent you agree or disagree with the following statement regarding your company. (1 = "strongly disagree" to 5 = "strongly agree"). SCR1. We are able to cope with changes brought about by supply chain disruptions. SCR2. We are able to adapt to supply chain disruptions easily. SCR3. We are able to provide a quick response to supply chain disruption. SCR4. We are able to maintain high situational awareness at all times. SCR5. Our company's supply chain can move to a new, more desirable state after being disrupted. SCR6. Our company's supply chain is able to adequately respond to unexpected disruptions by quickly restoring its product flow. SCR7. We can reduce the occurrence of negative events. SCR8. We can reduce impact of loss with the least cost.	[50,51]
Circular Economy Practices	Please indicate to what extent you agree or disagree with the following statement regarding your company. (1 = "strongly disagree" to 5 = "strongly agree"). CE1. Refuse * CE2. Rethink * CE3. Reduce * CE4. Reuse CE5. Repair CE6. Refurbish CE7. Remanufacture CE8. Repurpose CE9. Recycle CE10. Recover	[16]
Sustainability Performance	Please rate your company's development in the following performance parameters over the last 3 years. (1 = "significantly worsened" to 5 = "significantly improved").	
Economic sustainability	ES1. Lower production costs ES2. Increased profit ES3. Decreased NPD costs ES4. Reduced energy usage ES5. Reduction in costs of inventory ES6. Reduced product rejection and rework costs ES7. Decreased purchasing costs for raw material ES8. Reduction in treatment costs for production waste	[2]
Enviromental sustainability	ENVS1. Reduction of air emissions ENVS2. Reduction of liquid waste ENVS3. Reduction of solid wastes ENVS4. Decrease in consumption for hazardous/harmful/toxic materials ENVS5. Decrease in frequency for environmental accidents/Improved environmental situation of the firm ENVS6. Improvement in an enterprise's environmental situation	[2]
Social sustainability	SS1. Better working condition SS2. Better workplace safety SS3. Healthier employees SS4. Improved labour relations SS5. Decrease in number of accidents SS6. Decrease in the number of customer complaints	[2]

Note: The marked (*) items are deleted and removed from further analysis.

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