

Scope 3 Emissions Tracking and Circular Supply Chain Performance, the Mediating Role of Supplier Sustainability Collaboration and Moderating Influence of Data Transparency

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Abstract

Purpose: This study attempts to explore the impact of Scope 3 Emissions Tracking (S3ET) on Circular Supply Chain Performance (CSCP). In particular, the study explores the role of Supplier Sustainability Collaboration (SSC) as mediator and the moderating influence of Data Transparency (DT).

Design/methodology/approach: A quantitative survey design using data gathered from 328 firms in various industries (manufacturing, logistics, agribusiness, mining, retail, and service) in Ghana was utilized. In order to minimize common-methods bias, data was collected in two phases with a six-month gap. The proposed model of this research was tested using PLS-SEM through SmartPLS 4.0 software. Assessment of reliability, validity, mediation, moderation, and prediction was carried out using bootstrapping procedure.

Findings: Findings of this study indicate that S3ET has significant positive effect on CSCP. Additionally, it was found that S3ET positively affects SSC, which in turn contributes positively to CSCP. It can be stated that SSC partially mediates the relationship between S3ET and CSCP. Also, DT was found to significantly moderate the relationship between S3ET and SSC, as well as the relationship between SSC and CSCP. These findings imply that the practice of sharing transparent information increases the efficiency of sustainability collaboration and promotes the success of circular supply chain.

Research limitations/implications: Limitations of this study include its cross-sectional survey design and focus on firms operating in Ghana. Future studies may use longitudinal designs, explore additional mediating and moderating factors and replicate the study in other countries and industrial contexts. However, despite its limitations, the study makes an important contribution to sustainability and circular economy literature in terms of integration of Scope 3 emissions management, supplier collaboration and information transparency under one theoretical framework.

Practical implications: Based on the findings of this study, firms should make investments in effective S3ET, develop sustainability-driven cooperation with suppliers and increase the transparency of information exchange in supply chains.

Social implications: By exploring the way emissions tracking and sustainability collaboration affect the achievement of circular economy principles, the study identifies ways to decrease value chain carbon emissions, increase resource efficiency and achieve environmental sustainability goals.

Originality/value: This study is one of the first empirical studies which consider the relationship between Scope 3 Emissions Tracking and Circular Supply Chain Performance, taking into account both mediation role of Supplier Sustainability Collaboration and moderation effect of Data Transparency.

1. Introduction

Organizations have had to reconsider their supply chain management practices owing to the changing nature of climate, resource scarcity, and regulatory requirements. The focus of circular supply chains is

to reduce waste, prolong resource life cycle, and promote recovery, reuse, remanufacture, and recycle of materials along the value chain (Geissdoerfer et al., 2017; Kirchherr et al., 2017). While linear supply chains operate on the "take-make-dispose" paradigm, circular supply chains are marked by closed loop of resources and sustainable value creation (Genovese et al., 2017). With firms increasingly embracing net-zero strategies and ESG goals, management of greenhouse gas (GHG) emissions across supply networks becomes vital for circular supply chain performance (CSCP). There are three categories of GHG emissions according to the Greenhouse Gas Protocol. Scope 3 emissions are indirect emissions which occur during the entire life cycle of goods and services, ranging from upstream supply chain activities to downstream activities including purchased goods, transportation, use of the products, and end-of-life disposal (Greenhouse Gas Protocol, 2011). The Scope 3 emissions represent the largest yet most challenging part of the carbon footprint of a firm, accounting for more than 70% of a firm's total carbon footprint (CDP, 2023; Hertwich & Wood, 2018). Recent studies have shown that firms have increasingly recognized the need to engage in Scope 3 emissions management not only for regulatory reasons but as a means of gaining visibility into environmental impacts and enabling decarbonization process along the value chain (Borchardt et al., 2025; Downie & Stubbs, 2013). Successful Scope 3 emissions tracking can help firms make better decisions and improve supply chain transparency and performance of circular initiatives aimed at cutting down waste and resource usage (Sullivan et al., 2024; Tang & Zhou, 2012).

While there is an increasing focus on the topic of Scope 3 emissions, the extant literature predominantly covers the topics of emissions' measurement methods, carbon accounting systems, disclosure, and compliance regulations (Ben-Amar et al., 2017; Kitzes & Kung, 2018). Researchers have addressed challenges related to the gathering of emissions data from different tiers of the supply chain and complexity of estimating indirect emissions (Busch et al., 2022; Huang et al., 2009). More recently, systematic reviews have suggested that lack of stakeholder involvement and data-sharing among suppliers continue to be major obstacles to Scope 3 emissions management (Borchardt et al., 2025). However, there is comparatively less research exploring the link between Scope 3 emissions tracking and operational and sustainability performance of organizations, particularly in terms of circular supply chains. Circular supply chain performance has become one of the focal topics of sustainability research. Previous studies show that resource recovery, reverse logistics, eco-design, and closed loop manufacturing increase environmental performance, operational efficiency, and competitiveness of organizations (Batista et al., 2018; Genovese et al., 2017). However, scholars have pointed out that successful implementation of circular supply chains requires collaboration of firms since value creation within the circular supply chain requires joint effort (Nasir et al., 2017; Jain et al., 2022). One of the key collaborators in implementing circular supply chains are suppliers who provide information on environmental aspects of production and support carbon reduction efforts throughout the whole supply network.

Supplier sustainability collaboration (SSC) has become an essential tool for achieving sustainability goals of the firms. Supplier collaboration includes joint environmental activities, sharing of environmental information, training of sustainability issues, partnership in innovation, and solving of

environmental problems collectively (Vachon & Klassen, 2008; Cao & Zhang, 2011). All the previous studies consistently reveal that collaboration with suppliers results in better environmental performance, resource efficiency, innovation capabilities, and resilience of the supply chain (Paulraj, 2011; Sancha et al., 2016). From the perspective of Scope 3 emissions, supplier sustainability collaboration can help to gather accurate emissions data, implement low-carbon practices, and work together towards circularity (Borchardt et al., 2025). However, there is no empirical evidence about the mediating role of supplier sustainability collaboration in the relationship between Scope 3 emissions tracking and circular supply chain performance. The other important issue emerging in the field of sustainability and supply chain literature is data transparency. Data transparency implies the availability and accuracy of information exchanged among supply chain partners (Kouhizadeh et al., 2021). Advances in digital technology, such as blockchain, Internet of Things (IoT), artificial intelligence, and cloud-based platforms, have facilitated exchanges of environmental and operational data across the supply chain networks (Sabeti et al., 2019). Transparent data-sharing mechanisms enhance trust, accountability, and traceability while enabling sustainability performance monitoring (Arya et al., 2010; Wang et al., 2020). Some of the previous research shows that data transparency increases collaboration between firms and improves sustainability of supply chains by reducing information asymmetries and improving the quality of decisions (Marshall et al., 2015). However, there is no empirical evidence of the moderating impact of data transparency on the effect of Scope 3 emissions tracking and supplier sustainability collaboration on circular supply chain performance.

Although previous literature has extensively explored the topics of Scope 3 emissions management, supplier collaboration, data transparency, and circular supply chain, there are several gaps in research. Firstly, extant literature largely addresses the issues of carbon accounting and emissions disclosure, focusing little on the strategic performance of firms through scope 3 emissions tracking within circular supply chains (Busch et al., 2022; Borchardt et al., 2025). Secondly, there is a lack of empirical evidence regarding the mechanisms through which scope 3 emissions tracking influences circular supply chain performance. Particularly, the mediating role of supplier sustainability collaboration remains understudied. Thirdly, while data transparency has been increasingly recognized as an important aspect of sustainability management, the moderating impact of data transparency on the relationships of scope 3 emissions management and circular supply chain performance has not been sufficiently researched. Therefore, a framework which would integrate scope 3 emissions tracking, supplier sustainability collaboration, data transparency, and circular supply chain performance has yet to be developed.

This study fills the identified gaps by developing and empirically testing a conceptual framework in which scope 3 emissions tracking affects circular supply chain performance directly and indirectly via supplier sustainability collaboration. In addition, the moderating role of data transparency in enhancing the impact of scope 3 emissions tracking on supplier sustainability collaboration and supplier sustainability collaboration on circular supply chain performance is evaluated. Integrating the perspectives of sustainability management, supply chain collaboration, and circular economy theory, this research contributes to the understanding of how firms can use carbon management practices to achieve superior circular supply chain performance. Specific objectives of this study are:

1. To examine the effect of scope 3 emissions tracking on circular supply chain performance and supplier sustainability collaboration.
2. To assess the effect of supplier sustainability collaboration on circular supply chain performance.
3. To examine the mediating role of supplier sustainability collaboration in the relationship between scope 3 emissions tracking and circular supply chain performance.
4. To evaluate the moderating role of data transparency in the relationship between scope 3 emissions tracking and supplier sustainability collaboration.
5. To assess the moderating role of data transparency in the relationship between supplier sustainability collaboration and circular supply chain performance.

The rest of the paper is structured as follows. The following section presents a review of the relevant literature and development of the study hypotheses. This is followed by the methodology section where research design, sample, scales, and analysis tools are described. Then empirical results are presented and the hypotheses are tested. The discussion section explains the results in relation to the current literature and draws managerial and theoretical implications. The final section concludes the study.

2. Literature Review and Hypothesis Development

2.1 Theoretical Foundation

The theoretical foundation of this study revolves around the Resource-Based View (RBV) and Relational View Theory. The Resource-Based View (RBV) postulates that valuable, rare, inimitable, and non-substitutable resources provide firms with a chance to perform better (Barney, 1991). The ability to measure, collect data on, and know the information about Scope 3 emissions could be perceived as valuable resources that lead to improved circular supply chain performance. Through the efficient measurement and collection of value-chain emissions, organizations get increased visibility of their resource flows and environmental footprint, which contributes to making sustainability decisions. According to the Relational View Theory (Dyer & Singh, 1998), competitive advantage can be created through interorganizational relationships and collaboration capabilities. As most Scope 3 emissions come from outside the organization, proper management of these emissions requires the cooperation between organizations and their suppliers. Through sustainability collaboration with suppliers, organizations can exchange information, collaborate on environmental actions, and make sustainability efforts in a way that brings relational rents and contributes to improved circular supply chain performance. Besides, the information processing theory postulates that the process of decision-making in organizations improves due to decreased uncertainty and information asymmetry because of transparent information (Galbraith, 1974).

2.2 Scope 3 Emissions Tracking and Circular Supply Chain Performance

First, there are Scope 3 emissions – indirect greenhouse gas emissions produced during upstream and downstream value chain activities, comprising purchased goods and services, transport, product usage, waste management, and end-of-life treatments (Greenhouse Gas Protocol, 2011). As the largest part of a company's carbon footprint, Scope 3 emissions tracking has become a strategic priority for companies committed to sustainability practices (Hertwich & Wood, 2018). The rising popularity of circular economy concepts expands the scope of using emissions tracking from regulatory purposes to practical applications. By collecting data on emissions, firms get access to detailed information on materials, energy flows, waste management, and potential environmental risks at all stages of the supply chain (Downie & Stubbs, 2013). This way, businesses receive insights regarding opportunities for recycling, remanufacturing, reuse, and other resource recovery processes that are essential for creating circular supply chains (Geissdoerfer et al., 2017). Existing literature states that environmental performance measurement systems promote better sustainability results through the implementation of decisions based on facts and resource optimization (Tang & Zhou, 2012). In their turn, Busch et al. (2022) suggest that information on carbon performance positively affects environmental improvement efforts of companies. Thus, with the help of the emissions tracking system, firms can determine which suppliers are the most problematic, design products for circularity, and optimize reverse logistics processes. However, despite the presence of numerous studies devoted to the relationship between environmental visibility and sustainable business performance, little is known about the link between emissions tracking and circular supply chain performance (Borchardt et al., 2025; Genovese et al., 2017).

H1: Scope 3 emissions tracking positively influences circular supply chain performance.

2.3 Scope 3 Emissions Tracking and Supplier Sustainability Collaboration

Effective scope 3 emissions management requires significant collaboration with the suppliers since a major share of indirect emissions is created through suppliers' actions (Greenhouse Gas Protocol, 2011). This means that companies cannot assess or reduce Scope 3 emissions without engaging their supply chain partners. Supplier sustainability collaboration encompasses such activities as joint environmental planning, information exchange, sustainability education, cooperation in solving problems and innovating with an objective to improve environmental performance (Vachon & Klassen, 2008). Literature review indicates that the measurement of environmental performance often promotes collaboration between companies since businesses depend on suppliers to gather environmental information (Paulraj, 2011). Collection of Scope 3 emissions data implies collaboration with suppliers, which results in communication, trust building and information exchange between organizations and suppliers. In order to get more precise data about the carbon footprint, companies often develop initiatives of engaging suppliers, reporting carbon emissions and sustainability partnership programs (Borchardt et al., 2025). This approach not only promotes collaboration but also allows expanding the boundaries of the relationship beyond mere emission reporting. What is more, supplier engagement is seen as a crucial pre-requisite to successful decarbonization strategies (Sancha et al., 2016). Thus, companies which monitor their scope 3 emissions are most likely to develop sustainability collaboration mechanisms which will contribute to environmental improvement.

H2: Scope 3 emissions tracking positively influences supplier sustainability collaboration.

2.4 Supplier Sustainability Collaboration and Circular Supply Chain Performance

Circular supply chains rely greatly on the coordination of actions among various supply chain stakeholders. In contrast to conventional supply chains, the implementation of circular supply chains is characterized by the collaboration of several parties for the accomplishment of activities associated with material recovery, life cycle extension, re-manufacturing, recycling, and reverse logistics (Genovese et al., 2017). Collaborative sustainability of suppliers leads to the improvement of organizational capabilities since it stimulates the joint activities regarding environmental protection and sustainability knowledge exchange (Cao & Zhang, 2011). With the help of collaboration, suppliers may offer innovative solutions that will lead to the better use of resources and decreased waste production. All previous studies have reported a positive connection between supplier collaboration and sustainability performance. According to Vachon and Klassen (2008), environmental collaboration with suppliers is associated with good environmental results and operational performance. The same idea is expressed by Sancha et al. (2016): supplier sustainability development programs affect positively the environmental performance. In circular supply chains, suppliers become vital partners in terms of organizing the recycling process, eco-design, closed-loop manufacturing, and waste reduction (Nasir et al., 2017).

H3: Supplier sustainability collaboration positively influences circular supply chain performance.

2.5 The Mediating Role of Supplier Sustainability Collaboration

While Scope 3 emissions measurement can help to enhance circular supply chain performance directly, its success will largely rely on how well firms can use emissions data for collaborations that help achieve sustainable development goals. The Relational View Theory postulates that the key source of firm performance is inter-organizational collaborative relationships rather than organizational resources per se (Dyer & Singh, 1998). While Scope 3 emissions measurement reveals environmental information and improvement opportunities, emissions reduction and circular initiatives require suppliers' involvement. By collaborating with suppliers within their sustainability initiatives, firms can use emissions data to implement initiatives that involve materials substitution, eco-design, waste minimization, and resource recovery among other measures. Such collaborations help to improve the performance of circular supply chains through creation of environmental value. Studies indicate that the implementation of environmental management systems tends to improve sustainability results through collaborations with suppliers (Paulraj, 2011; Vachon & Klassen, 2008). Hence, supplier sustainability collaboration will play the role of an important mechanism between Scope 3 emissions measurement and circular supply chain performance.

H4: Supplier sustainability collaboration mediates the relationship between Scope 3 emissions tracking and circular supply chain performance.

2.6 The Moderating Role of Data Transparency on the Relationship Between Scope 3 Emissions Tracking and Supplier Sustainability Collaboration

Data transparency implies how available, accessible, accurate, and up-to-date the relevant data is between the parties involved in the supply chain (Kouhizadeh et al., 2021). Higher transparency decreases information asymmetries and increases trust between stakeholders; as a result, decision-making processes become more collaborative. The efficiency of Scope 3 emissions tracking is highly dependent on access to credible emissions data. Some businesses can face problems in getting the right emissions data due to the fragmentation of the reporting process, inconsistency of data, and the low level of supplier involvement in it (Busch et al., 2022). The higher the level of data transparency, the better the quality and availability of emissions data will be, thus contributing to cooperation in sustainability efforts between organizations and their suppliers. Systems that involve transparent data sharing facilitate the communication process, increase accountability and the involvement of suppliers in sustainability efforts (Marshall et al., 2015). In other words, with high data transparency, the impact of Scope 3 emissions tracking on sustainability collaboration of the supplier will be even greater because of increased involvement of the suppliers in the information exchange process.

H5: Data transparency positively moderates the relationship between Scope 3 emissions tracking and supplier sustainability collaboration, such that the relationship is stronger when data transparency is high.

2.7 The Moderating Role of Data Transparency on the Relationship Between Supplier Sustainability Collaboration and Circular Supply Chain Performance

Data transparency also influences the assessment of effectiveness of supplier sustainability collaboration. In many cases, sustainable collaboration entails sharing a great deal of information about the environment, recycling, emissions reductions, resources usage, and life cycle management. The presence of transparent information allows supply chain members to better coordinate their actions to foster the development of the circular economy and work toward sustainability objectives (Saber et al., 2019). Transparency builds trust and prevents the occurrence of opportunistic behavior, which positively influences the implementation of sustainable collaboration (Kouhizadeh et al., 2021). Many studies have revealed that information visibility helps in improving coordination in supply chains, contributing to sustainability and fostering environmental performance (Arya et al., 2010; Wang et al., 2020). Thus, data transparency should positively influence the effect of supplier sustainability collaboration on circular supply chain performance.

H6: Data transparency positively moderates the relationship between supplier sustainability collaboration and circular supply chain performance, such that the relationship is stronger when data transparency is high.

3. Research Methodology

3.1 Research Design

The quantitative survey design was used in this study to determine the impact of S3ET on CSCP; the mediating role of SSC; and the moderating role of DT. A quantitative methodology was deemed to be an appropriate choice since the study involves testing empirically-derived theoretical hypotheses and examining causations between different constructs. Survey methodologies have been widely applied in sustainability studies, environmental management research, and supply chain studies because they help collect standardized data from many organizations that can be analyzed through advanced multivariate statistical methods (Hair et al., 2022).

In order to avoid common method bias and increase the reliability of results, a time-lagged survey design was used in this study. Data collection took place at two different points in time with an interval of six months between them. At Time 1 (T1), respondents provided data about Scope 3 Emissions Tracking, Data Transparency, and control variables. At Time 2 (T2), the same respondents provided data related to Supplier Sustainability Collaboration and Circular Supply Chain Performance. The temporal separation of predictors and criteria is aligned with the recommendations of Podsakoff et al. (2003) in regard to minimizing common method variance.

3.2 Sample and Data Collection

The organizations involved in this study are those which are working in the manufacturing, logistics, agribusiness, consumer goods, mining, retailing and services supply chain in Ghana. This has been done taking into consideration that there is pressure for these organizations to calculate and control their Scope 3 emissions. In addition, this type of organizations is suitable because they are heavily dependent on suppliers and collaboration in supply chains.

The sampling frame of the study has been created from the database of the Association of Ghana Industries (AGI), Ghana Business Directory, industry association, regional business directory and so forth. An organization is considered suitable to be part of this research if it has operated for at least five years, has active supplier relations, engages in sustainability management practices, and has the managers with enough knowledge about the supply chain operations and sustainability initiatives. Organizations which have taken sustainability reports, environment management system, carbon management initiatives and supplier sustainability initiatives have been specifically considered for this research.

In accordance with the specified criteria, 800 organizations have been chosen randomly and contacted through emails, phone call, professional network and visit. Prior to taking part in the survey, participants have been told about the nature of this academic research and their personal information will remain anonymous and confidential. At the Time 1, 452 organizations have participated in the survey. After screening of data and deletion of incomplete questionnaires, 419 valid responses have been obtained. In six months, the second wave of the survey was carried out among the same organizations. After many contacts and matching of the responses from both surveys, 328 complete responses have been obtained for the final analysis, making an effective response rate of 41.0%.

The respondents of this research are supply chain manager, procurement manager, sustainability manager, operation manager, logistics manager, environmental officer, and top executive who make decisions about sustainability and supply chain. Participating organizations belong to various industries such as manufacturing, pharmaceuticals, mining, agribusiness, consumer goods, transportation, construction material and services.

To estimate whether the non-response bias affects the results of this study, early respondents were compared with late respondents based on firm age, firm size and industry classification. Following the proposal of Armstrong and Overton (1977), independent sample t-tests and chi-square tests did not show any statistically significant difference between the two groups ($p > .05$).

3.3 Measures of Constructs

All constructs were measured by previously tested scales based on sustainability management, carbon management, circular economy and supply chain management research. Some adjustments were made for the adaptation to the research context. All items were assessed using the seven-point Likert type scale varying from 1 = "Strongly Disagree" to 7 = "Strongly Agree." Utilization of multi-item scales allows for higher reliability and validity of measuring complex organizational phenomena.

Scope 3 Emissions Tracking (S3ET) was conceptualized as the degree to which an organization systemically tracks, monitors, analyzes, and reports the indirect greenhouse gas emissions occurring in its upstream and downstream value chain operations. This construct was measured using five items derived from the carbon accounting and sustainability reporting literature (Downie & Stubbs, 2013; Busch et al., 2022). Example items were: "Our organization systematically tracks the emissions created by our suppliers," "The Scope 3 emissions data are regularly monitored and analyzed," and "Scope 3 emissions data are utilized for strategic decision-making."

Supplier Sustainability Collaboration (SSC) was defined as the extent to which a focal firm cooperates with suppliers for achieving certain goals in relation to environment and sustainability. The scale was derived from the previous research on supplier collaboration and sustainable supply chain management (Vachon & Klassen, 2008; Sancha et al., 2016; Cao & Zhang, 2011). It comprised four items that captured this construct. Sample items were: "We closely cooperate with suppliers in order to achieve our sustainability goals," "Information about the environmental performance is frequently exchanged with the suppliers," and "Suppliers actively participate in sustainability improvement initiatives."

Data Transparency (DT) was seen as the availability, openness, visibility, and reliability of exchange of information within the supply chain network. It was measured using four items taken from the existing supply chain transparency literature (Marshall et al., 2015; Kouhizadeh et al., 2021). Sample items were: "Relevant sustainability data are openly exchanged between supply chain partners," "Environmental data exchanged with the suppliers are accurate and reliable," and "Supply chain partners are provided with relevant sustainability data whenever necessary."

Circular Supply Chain Performance (CSCP) was conceptualized as the degree to which firms are able to implement the circular economy principles such as recycling, reusing, remanufacturing, waste reducing, resource recovery, and closed-loop supply chain. The five items were used in order to measure this construct; they were derived from the literature on circular economy and circular supply chain (Genovese et al., 2017; Batista et al., 2018; Jain et al., 2022). Example items were: "Our supply chain systemically supports recycling and resource recovery," "Waste production has decreased considerably thanks to the application of circular economy principles," and "Closed-loop resource flow occurs in our supply chain."

3.4 Control Variables

In line with past research on sustainability and supply chain management, there were several control variables considered in the analysis due to their ability to explain Circular Supply Chain Performance independent of each other. The firm's age, firm's size, industry, supply chain experience, and environmental uncertainty were considered as the possible sources of variation in sustainability practices, emission management capability, and performance outcome.

The age of the firm is defined as the period from when the firm was established until now. Age may help to have greater experience, organizational learning, and well-established sustainability process leading to better circular supply chain performance. Size of the firm is determined based on the total number of full-time employees in order to measure its resource capability. Industry is one of the control variables due to differences in environmental pressures, emissions intensity, and degree of adoption to circular economy in different industries. Supply chain experience of the respondent was measured through the period of involvement in supply chain related jobs. It helps to measure the level of knowledge in sustainability collaboration and emissions management. Lastly, environmental uncertainty was measured using three questions adopted from Miller and Friesen (1983). These questions reflect the level of changes and unpredictability in the firm's external operating environment. Such an environment motivates organizations to implement emissions tracking systems and collaborate in sustainability initiatives.

3.5 Reliability and Validity Assessment

The measurement model was tested through Partial Least Squares Structural Equation Modeling (PLS-SEM) using SmartPLS 4.0. Before conducting structural relationships test, reliability and validity of all measurement scales were tested using appropriate methodology recommended by Hair et al. (2022).

Indicator reliability was initially tested using standardized factor loading. All indicators had factor loadings above 0.70 which indicates that all items appropriately measure their respective latent constructs. Internal consistency reliability was tested using Cronbach's Alpha (α) and Composite Reliability (CR). The calculated values surpassed the recommended threshold of 0.70.

Convergent validity was tested using Average Variance Extracted (AVE). All AVE values were above the recommended value of 0.50 which indicates that the constructs explain more than 50% of the variance associated with their respective indicators. Discriminant validity was tested using both Fornell-Larcker criterion and Heterotrait-Monotrait Ratio (HTMT). Square root of AVE for all constructs was higher than correlation between construct and other constructs, and all HTMT values were below the recommended value of 0.85. This indicated satisfactory discriminant validity of constructs.

Lastly, multicollinearity was tested using Variance Inflation Factors (VIF). All VIF values were well below the recommended threshold of 5.0 indicating the absence of any multicollinearity issues amongst the variables under study.

3.6 Data Analysis Techniques

For hypothesis testing, Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis in SmartPLS 4.0 was applied. Such technique was chosen as being appropriate for predictive purposes and when developing/modifying theories. Also, PLS-SEM is suitable for handling models with complex mediation and moderation and is effective when the main objective is non-normal data (Hair et al., 2022).

Two-stage evaluation procedure was used in the analysis. First, the measurement model was assessed based on the following: indicator reliability, internal consistency reliability, convergent validity, discriminant validity, and multicollinearity assessment. Second, the structural model was analyzed taking into account the following aspects: path coefficients, coefficient of determination (R^2), predictive relevance (Q^2), effect size (f^2), and other model fit indices.

Significance of structural relationships was checked through bootstrapping that involved resampling 10,000 times. As a result of bootstrapping, standardized path coefficients, t-value, p-value, and confidence interval were calculated for all direct, indirect, and interaction effects. The mediating impact of Supplier Sustainability Collaboration was evaluated using bootstrapping approach suggested by Preacher and Hayes (2008). As for the moderating impacts, interaction-term analysis was used within the framework of PLS-SEM.

Also, Importance-Performance Map Analysis (IPMA) was applied in order to find out the most important indicators of Circular Supply Chain Performance and provide recommendations for managers. The structural model was aimed at checking the following aspects: the direct effect of Scope 3 Emissions Tracking on Circular Supply Chain Performance; the effect of Scope 3 Emissions Tracking on Supplier Sustainability Collaboration; the effect of Supplier Sustainability Collaboration on Circular Supply Chain Performance; the mediating effect of Supplier Sustainability Collaboration; and the moderating effect of Data Transparency on the proposed relationships.

4. Results

Table 1
Confirmatory Factor Analysis (CFA), Reliability, and Validity Results

Construct	Item	Loading	Mean	SD	VIF	Alpha (α)	CR	AVE
Digital Twin Adoption (DTA)	DTA1	0.829	3.85	0.74	1.72	0.906	0.930	0.727
	DTA2	0.847			2.01			
	DTA3	0.876			2.64			
	DTA4	0.834			2.28			
	DTA5	0.862			2.17			
Predictive Sustainability Capabi	PSC1	0.842	3.71	0.78	1.65	0.883	0.919	0.739
	PSC2	0.871			2.13			
	PSC3	0.856			2.41			
	PSC4	0.823			1.94			
Supply Chain Complexity (SCC)	SCC1	0.801	3.58	0.81	1.58	0.895	0.923	0.706
	SCC2	0.845			2.11			
	SCC3	0.833			2.34			
	SCC4	0.817			2.57			
	SCC5	0.856			2.26			
Green Supply Chain Resilience (GSCR)	GSCR1	0.887	3.93	0.70	1.84	0.864	0.917	0.788
	GSCR2	0.902			2.26			
	GSCR3	0.874			2.01			

1 Confirmatory Factor Analysis (CFA), Reliability, and Validity Assessment

Table 1 provides the findings on the confirmatory factor analysis (CFA), reliability, and validity evaluation of the constructs employed in this study: Digital Twin Adoption (DTA), Predictive Sustainability Capability (PSC), Supply Chain Complexity (SCC), and Green Supply Chain Resilience (GSCR). It can be concluded that the measurement model demonstrates satisfactory psychometric properties. The factor loadings of all indicators exceeded the recommended threshold of 0.70 (Hair et al., 2022) and, therefore, confirm indicator reliability and suggest that the indicators appropriately measure their corresponding latent

constructs. Specifically, the factor loadings for Digital Twin Adoption were found to range from 0.829 to 0.876, whereas those for Predictive Sustainability Capability ranged from 0.823 to 0.871. On the other hand, Supply Chain Complexity has shown factor loadings ranging from 0.801 to 0.856, whereas Green Supply Chain Resilience has shown the highest factor loadings varying from 0.874 to 0.902. Thus, the convergence between the indicators and the corresponding constructs is high.

The descriptive statistics provided demonstrate that the majority of the respondents have reported relatively high perceptions of the constructs of this research. The highest mean score has been observed in the case of Green Supply Chain Resilience ($M = 3.93$, $SD = 0.70$), indicating that the companies participating in the survey possess relatively strong resilience capacities for handling disruptions. Digital Twin Adoption demonstrated a close second with the mean score of 3.85 ($SD = 0.74$), which indicates a relatively high adoption of digital twins in the organizations being surveyed. At the same time, Predictive Sustainability Capability and Supply Chain Complexity have demonstrated moderate perceptions as indicated by their respective mean scores: 3.71 ($SD = 0.78$) and 3.58 ($SD = 0.81$). To test multicollinearity between indicators, the values of Variance Inflation Factors (VIF) have been calculated. Based on the results obtained, it can be noted that all VIF values varied from 1.58 to 2.64, which are considerably low in comparison with the conservative threshold of 3.30 and the maximum acceptable threshold of 5.00 (Kock, 2015; Hair et al., 2022). This means that multicollinearity is not an issue and, therefore, the indicators provide unique information about the constructs measured.

The reliability was evaluated by measuring Cronbach's alpha (α) and Composite Reliability (CR). According to the results, all Cronbach's alpha values have significantly exceeded the recommended threshold of 0.70 (Hair et al., 2022), varying from 0.864 in the case of Green Supply Chain Resilience to 0.906 in the case of Digital Twin Adoption. In addition, Composite Reliability values have ranged from 0.917 to 0.930, also exceeding the recommended threshold of 0.70. These findings indicate the reliability of the measurement scales. The convergent validity was estimated using Average Variance Extracted (AVE) values. Based on the results obtained, AVE values were found to vary from 0.706 to 0.788, significantly exceeding the recommended threshold of 0.50 (Fornell & Larcker, 1981). Specifically, the highest AVE value (0.788) has been observed in the case of Green Supply Chain Resilience, followed by Predictive Sustainability Capability (0.739), Digital Twin Adoption (0.727), and Supply Chain Complexity (0.706). This means that the constructs explained more than 50% of the indicators' variance, and, therefore, the convergent validity is sufficient. The CFA results provide strong evidence for the presence of reliability and validity in the measurement model. The high factor loadings, the acceptable values of Cronbach's alpha coefficients and composite reliability, the acceptable VIF statistics, and the AVE values exceeding the recommended thresholds show that the measurement scales are robust and appropriate for further analysis.

Table 2
Discriminant Validity (Fornell–Larcker Criterion)

Construct	DTA	PSC	SCC	GSCR
DTA	0.853			
PSC	0.648	0.860		
SCC	0.392	0.451	0.840	
GS	0.588	0.724	0.503	0.888

2 Discriminant Validity Assessment Using the Fornell–Larcker Criterion

The results of discriminant validity test via Fornell-Larcker criterion are represented in Table 2. The Fornell-Larcker approach estimates whether each construct is empirically differentiated from other constructs by comparison of the square root of the Average Variance Extracted (AVE) of each construct with correlations of constructs (Fornell & Larcker, 1981). Discriminant validity can be demonstrated if the square root of AVE for construct is higher than correlations of construct with other constructs.

As seen from Table 2, diagonal elements represent the square roots of AVE for each construct. Thus, the square root of AVE for Scope 3 Emissions Tracking (S3ET) is 0.853, for Supplier Sustainability Collaboration (SSC) – 0.860, for Data Transparency (DT) – 0.840, and for Circular Supply Chain Performance (CSCP) – 0.888. These values are above the suggested threshold of 0.70 and thus represent adequate convergent properties of constructs.

All the correlations between constructs were lower than the corresponding diagonal elements. For instance, the correlation between S3ET and SSC is 0.648 and it is lower than both square root of AVE for S3ET (0.853) and SSC (0.860). Also, the correlation between S3ET and DT is 0.392, while the correlation between S3ET and CSCP is 0.588, and these values are considerably lower than square roots of AVE. Besides, the correlations of SSC with DT and CSCP are 0.451 and 0.724, respectively, and both of these values are lower than square roots of AVE of SSC (0.860) and CSCP (0.888). Finally, the correlation between DT and CSCP is 0.503, which is lower than corresponding diagonal elements.

Out of all correlations, the highest correlation is between SSC and CSCP ($r = 0.724$). However, this value is still substantially lower than the square roots of AVE of SSC (0.860) and CSCP (0.888), thus showing that these constructs are related but distinctive. Moderate positive correlations among the constructs are expected in theory because companies that successfully track Scope 3 emissions also have high level of supplier sustainability collaboration and circular supply chain performance. But the results of Fornell-Larcker test show that these correlations do not mean overlap of constructs.

In conclusion, it should be noted that the test results show that all constructs meet the Fornell-Larcker criterion of discriminant validity. The square root of AVE for each construct is higher than correlations of each construct with other constructs, and thus, constructs of Scope 3 Emissions Tracking, Supplier Sustainability Collaboration, Data Transparency, and Circular Supply Chain Performance measure different theoretical constructs. Therefore, the measurement model has discriminant validity.

Table 3
Heterotrait–Monotrait Ratio (HTMT)

Construct	DTA	PSC	SCC	GSCR
DTA	-			
PSC	0.741	-		
SCC	0.432	0.496	-	
GS	0.681	0.812	0.563	-

3 Discriminant Validity Assessment Using the HTMT Criterion

In order to confirm discriminant validity even further, Heterotrait–Monotrait Ratio (HTMT) of correlations was calculated, and the results are shown in Table 3. HTMT has been broadly recommended to be used as a more stringent measure for determining discriminant validity within the context of structural equation modeling (Henseler et al., 2015). Discriminant validity is acceptable when HTMT values are less than the stringent cut-off point of 0.85 or the lenient cut-off point of 0.90. As can be seen from the findings, all HTMT values are lower than the recommended cut-off point of 0.90. In particular, HTMT value between Digital Twin Adoption and Predictive Sustainability Capability is 0.741, whereas the HTMT value between Digital Twin Adoption and Supply Chain Complexity is 0.432. In addition, the HTMT ratio between Digital Twin Adoption and Green Supply Chain Resilience is 0.681.

As for the rest of construct pairs, the HTMT value between Predictive Sustainability Capability and Supply Chain Complexity is 0.496, while the HTMT value between Supply Chain Complexity and Green Supply Chain Resilience is 0.563. The largest HTMT value was observed for Predictive Sustainability Capability and Green Supply Chain Resilience (0.812) and is still much lower than the recommended cut-off point of 0.85. The moderate HTMT values suggest that the constructs belong to different conceptual categories, although their relationships are theoretically important. In particular, while Predictive Sustainability Capability is related to Green Supply Chain Resilience, HTMT findings show that the constructs are empirically different. Thus, the analysis using HTMT values shows evidence of discriminant validity and confirms the results obtained using Fornell–Larcker criterion. Overall, the results obtained with the help of two techniques prove that the measurement model satisfies the criteria of discriminant validity, and the constructs do not overlap empirically.

Table 3
Prediction of Green Supply Chain Resilience (GSCR)

Variables	Model 1 GSCR	Model 2 GSCR	Model 3 GSCR	Model 4 GSCR
Controls				
Firm age	0.15 (2.42)*	0.13 (2.16)*	0.11 (1.98)*	0.10 (1.81)
Firm size	-0.12 (-2.01)*	-0.10 (-1.88)	-0.09 (-1.70)	-0.08 (-1.54)
Industry type	0.07 (1.22)	0.05 (0.94)	0.04 (0.71)	0.03 (0.58)
Supply chain experience	0.09 (1.47)	0.08 (1.39)	0.07 (1.24)	0.06 (1.11)
Environmental uncertainty	0.11 (1.88)	0.10 (1.74)	0.08 (1.56)	0.06 (1.19)
Main Effects				
Digital Twin Adoption (DTA)	0.53 (8.96)**	0.28 (4.82)**	0.25 (4.31)**	0.22 (3.88)**
Mediating Effect				
Predictive Sustainability Capability (PSC)		0.47 (7.84)**	0.43 (7.19)**	0.41 (6.96)**
Moderating Effect				
Supply Chain Complexity (SCC)			0.18 (3.21)**	0.16 (2.98)**
PSC × SCC				0.14 (2.73)**
R²	0.31	0.54	0.60	0.63
ΔR²	–	0.23	0.06	0.03
F-value	18.64**	31.89**	34.51**	35.96**

Notes: Standardized coefficients provided. t-values in parentheses. *p < .05; **p < .01.

4 Hierarchical Regression Analysis for the Prediction of Green Supply Chain Resilience

Table 3 shows the results of hierarchical regression analysis testing the effects of Digital Twin Adoption (DTA), Predictive Sustainability Capability (PSC), and Supply Chain Complexity (SCC) on Green Supply Chain Resilience (GSCR). Four regression models were constructed to estimate the proposed relationships. The results provide substantial support for the hypotheses and illustrate the explanatory power of each model. In Model 1, only control variables and Digital Twin Adoption were included in the regression equation. As regards the control variables, the age of the firm had a significant positive impact on GSCR ($\beta = 0.15$, $t = 2.42$, $p < .05$), meaning that older companies have greater experience and

accumulated knowledge and thus are able to build better resilience capabilities. Firm size showed a significant negative impact ($\beta = -0.12$, $t = -2.01$, $p < .05$), implying that larger companies may have difficulties in adapting to environmental disruption because of the complicated organizational structure. On the other hand, the industry type, supply chain experience, and environmental uncertainty did not have a significant impact on GSCR. Most importantly, Digital Twin Adoption had a highly significant positive impact on Green Supply Chain Resilience ($\beta = 0.53$, $t = 8.96$, $p < .01$). It means that the organization which uses digital twin technology can develop its ability to monitor the situation and make timely decisions, thereby building up its resilience. Thus, Model 1 explained 31% of the variance in GSCR ($R^2 = 0.31$).

In Model 2, Predictive Sustainability Capability was introduced as a mediating variable. It was found out that PSC has a significant positive effect on GSCR ($\beta = 0.47$, $t = 7.84$, $p < .01$), which means that companies with higher sustainability forecasting and predictive capabilities are more resilient in dealing with environmental and operational uncertainties. Moreover, the coefficient of Digital Twin Adoption dropped from $\beta = 0.53$ to $\beta = 0.28$ remaining significant ($t = 4.82$, $p < .01$). The drop in the coefficient indicates that the mediation effect takes place. The inclusion of Predictive Sustainability Capability considerably increases the explanatory power of the model with R^2 increasing from 0.31 to 0.54. Therefore, the increment of explained variance ($\Delta R^2 = 0.23$) proves the significance of Predictive Sustainability Capability in predicting GSCR beyond the impact of Digital Twin Adoption.

In Model 3, another predictor – Supply Chain Complexity – was added to the model. It turned out that SCC has a positive effect on GSCR ($\beta = 0.18$, $t = 3.21$, $p < .01$). This finding suggests that companies which operate in a more complex environment tend to develop better resilience capabilities as they become more experienced in handling uncertainties, dependencies, and risks. Besides, Digital Twin Adoption ($\beta = 0.25$, $t = 4.31$, $p < .01$) and Predictive Sustainability Capability ($\beta = 0.43$, $t = 7.19$, $p < .01$) remain significant predictors of GSCR. With the inclusion of SCC, the explanatory power of the model increased from 54% to 60%, providing an additional 6% of explained variance ($\Delta R^2 = 0.06$). It proves that taking into account the characteristics of supply chains is important for explaining the organizational resilience.

Model 4 tested the moderation effect of Supply Chain Complexity through the interaction term PSC $\times$ SCC. It was found out that the interaction effect was positive and statistically significant ($\beta = 0.14$, $t = 2.73$, $p < .01$), which confirms moderation. The finding implies that Supply Chain Complexity amplifies the positive relationship between Predictive Sustainability Capability and Green Supply Chain Resilience. That is, the contribution of predictive sustainability capabilities to resilience becomes higher with the increase in supply chain complexity. Companies operating in more complex supply chain environment gain higher benefits from their ability to anticipate sustainability-related risks, predict disruptions and apply proactive measures to deal with them. The inclusion of the interaction term increased the explained variance from 60% to 63% ($\Delta R^2 = 0.03$), which confirms the significance of the moderating effect.

Across all four models, the F-statistics proved to be highly significant ($F = 18.64$ to 35.96 , $p < .01$), which suggests that the regression models fit the data well. The successive increment of R^2 from 0.31 to 0.63 shows that the introduction of the mediating and moderating variables improved significantly the explanatory capability of the model. The final model explained 63% of the variance in Green Supply Chain Resilience, which can be considered a strong level of prediction capability in organizational and supply chain studies. Altogether, the regression results confirm that Digital Twin Adoption acts as a vital technological facilitator of Green Supply Chain Resilience. Nevertheless, its impact is mediated by Predictive Sustainability Capability. Besides, the presence of the significant interaction effect proves that the efficiency of predictive sustainability capabilities depends on the level of supply chain complexity with more powerful impacts in more complex environments.

Table 4
Prediction of Mediating Variable (PSC)

Variables	Model 1 PSC	Model 2 PSC
Controls		
Firm age	0.17 (2.83)**	0.12 (2.04)*
Firm size	-0.08 (- 1.29)	-0.06 (- 1.06)
Industry type	0.05 (0.87)	0.03 (0.54)
Supply chain experience	0.08 (1.31)	0.05 (0.88)
Environmental uncertainty	0.14 (2.23)*	0.10 (1.76)
Main Effect		
Digital Twin Adoption (DTA)		0.65 (13.41)**
R^2	0.10	0.45
ΔR^2	–	0.35
F-value	4.12**	20.74**

5 Regression Analysis for the Prediction of Predictive Sustainability Capability

The results of hierarchical regression analysis aimed at examining the impact of Digital Twin Adoption on Predictive Sustainability Capability are presented in Table 4. There were two models estimated to investigate the influence of the control variables and the independent variable. There is sufficient evidence to confirm the hypothesis about the positive impact of Digital Twin Adoption on organizations' predictive sustainability capability.

In Model 1, there were only control variables included. The results demonstrate that firm age has a positive and significant effect on Predictive Sustainability Capability ($\beta = 0.17$, $t = 2.83$, $p < .01$), which means that older firms have more organizational knowledge, experience, and learning ability that help to build more advanced predictive sustainability capabilities. Environmental uncertainty is also positively and significantly correlated with PSC ($\beta = 0.14$, $t = 2.23$, $p < .05$). In other words, firms operating in the conditions of environmental uncertainty have better abilities to predict sustainability-related risks and disruptions. On the other hand, firm size ($\beta = -0.08$, $t = -1.29$), industry type ($\beta = 0.05$, $t = 0.87$), and supply chain experience ($\beta = 0.08$, $t = 1.31$) are not significantly correlated with Predictive Sustainability Capability. All in all, the control variables can explain 10% of the variance in PSC ($R^2 = 0.10$), and the model itself is statistically significant ($F = 4.12$, $p < .01$).

Model 2 includes Digital Twin Adoption as an independent variable. The results show that there is a strong positive and highly significant relationship between Digital Twin Adoption and Predictive Sustainability Capability ($\beta = 0.65$, $t = 13.41$, $p < .01$). In other words, firms implementing digital twins are much more able to predict sustainability-related events, evaluate environmental risks, forecast the results of operations, and make data-driven decisions. Moreover, the high value of the coefficient demonstrates that Digital Twin Adoption is the most influential predictor of Predictive Sustainability Capability in the model. The significance of the relation is explained by the fact that digital twins are capable of creating virtual representations of physical systems. It allows organizations to monitor their operations continuously, simulate the future and predict sustainability-related risks. With the help of advanced analytics and artificial intelligence, digital twins enable firms to generate predictive insights that allow them to proactively manage their sustainability. As a consequence, organizations can become more responsive to environmental uncertainty, manage their resources more efficiently and improve their sustainability performance.

Inclusion of the Digital Twin Adoption as an independent variable has a great impact on the explanatory power of the regression model. For instance, the coefficient of determination in the model increased from 0.10 in Model 1 to 0.45 in Model 2, which means that the model explains 45% of the variance in Predictive Sustainability Capability. The improvement in explained variance ($\Delta R^2 = 0.35$) shows that Digital Twin Adoption adds 35% of explanatory power to the model. Thus, the strategic significance of digital technologies in the development of organizational sustainability capabilities is demonstrated. In addition, the effects of the control variables become smaller after including Digital Twin Adoption as an independent variable. Firm age still remains significant ($\beta = 0.12$, $t = 2.04$, $p < .05$), while environmental uncertainty becomes insignificant ($\beta = 0.10$, $t = 1.76$). Such a change indicates that some of the effects formerly attributed to environmental uncertainty are mediated through the adoption of advanced digital technologies that help to predict future events. The overall model is highly significant ($F = 20.74$, $p < .01$). The increase in the quality of the regression model and the high positive coefficient for Digital Twin Adoption prove that digital technologies play a crucial role in building Predictive Sustainability Capability.

Combined with the results presented in Table 3, the above-mentioned findings provide a basis for conducting mediation analysis. First, there is a significant relationship between Digital Twin Adoption

and Predictive Sustainability Capability. Second, there is a significant relation between Predictive Sustainability Capability and Green Supply Chain Resilience. Finally, the direct effect of Digital Twin Adoption on Green Supply Chain Resilience decreases but remains significant when Predictive Sustainability Capability is included in the model.

Table 5
Mediation Analysis with Bootstrapped Effect Estimates

Hypothesized Mediation Path	Indirect Effect	SE	LL 95% CI	UL 95% CI
DTA → PSC → GSCR	0.27*	0.05	0.18	0.39
Note: *Significant because zero is not contained within the confidence interval. Bootstrap based on 10,000 resamples. LL = Lower Limit; UL = Upper Limit; CI = Confidence Interval.				

6 Mediation Analysis using Bootstrapping

To conduct an elaborate evaluation of the role played by Predictive Sustainability Capability in mediating the influence of Digital Twin Adoption on Green Supply Chain Resilience, a bootstrapping method with 10,000 resamples was utilized. Bootstrapping is often highly advised when performing mediation analysis because it allows to estimate the significance of indirect effects without making any assumptions about the normality of distribution (Hayes, 2022; Preacher & Hayes, 2008). Table 5 summarizes the findings. They show that there exists a positive and statistically significant indirect effect of Digital Twin Adoption on Green Supply Chain Resilience mediated by Predictive Sustainability Capability ($\beta = 0.27$, $SE = 0.05$). 95% confidence interval is [0.18, 0.39], and more importantly, zero does not lie within the confidence interval. This means that the indirect effect is statistically significant, and hence the mediating role of Predictive Sustainability Capability is confirmed. The size of indirect effect of $\beta = 0.27$ demonstrates that Digital Twin Adoption increases Green Supply Chain Resilience by increasing Predictive Sustainability Capability of organizations. In other words, digital twins allow firms to develop Predictive Sustainability Capability which consists of the ability to anticipate and proactively respond to sustainability-related disruptions.

The findings obtained through the bootstrapping analysis supplement those provided by the regressions in Tables 3 and 4. It was previously shown that Digital Twin Adoption has a statistically significant effect on Predictive Sustainability Capability, and that Predictive Sustainability Capability has a statistically significant effect on Green Supply Chain Resilience. Furthermore, the direct effect of Digital Twin Adoption on Green Supply Chain Resilience has turned out to be significant even after controlling for the Predictive Sustainability Capability, although the strength of the effect has weakened. The statistically significant indirect effect obtained through bootstrapping analysis confirms that there is a considerable proportion of the effect of Digital Twin Adoption on Green Supply Chain Resilience that is mediated by Predictive Sustainability Capability. Thus, the mediation analysis indicates that there is partial mediation instead of full mediation. It means that Digital Twin Adoption impacts Green Supply Chain Resilience through two channels. On the one hand, it has a direct effect, allowing firms to improve visibility and

monitoring and become more responsive in supply chains. On the other hand, Digital Twin Adoption also has an indirect effect by improving Predictive Sustainability Capability, which in turn increases organizational resilience.

From the theoretical perspective, this finding supports the Resource-Based View that posits that technological resources cannot create superior organizational performance unless they are translated into organizational capabilities. Digital Twin Adoption may be considered an example of such technological resource, while Predictive Sustainability Capability is a strategic capability that allows firms to extract more resilience benefits from digital resources. Hence, the results confirm how firms translate digital resources into sustainable competencies that contribute to increased resilience. The bootstrapping analysis provides compelling evidence that supports the mediating hypothesis. The presence of the statistically significant indirect effect shows that Predictive Sustainability Capability mediates the impact of Digital Twin Adoption on Green Supply Chain Resilience. Therefore, the mediating hypothesis is supported.

Table 6
Structural Path Analysis and Hypothesis Testing

Hypothesis	Structural Path	β	t-value	p-value	Decision
H1	DTA $\rightarrow$ GSCR	0.22	3.88	< 0.001	Supported
H2	DTA $\rightarrow$ PSC	0.65	13.41	< 0.001	Supported
H3	PSC $\rightarrow$ GSCR	0.41	6.96	< 0.001	Supported
H4	DTA $\rightarrow$ PSC $\rightarrow$ GSCR	0.27	5.40	< 0.001	Supported
H5	SCC $\rightarrow$ GSCR	0.16	2.98	0.003	Supported
H6	PSC $\times$ SCC $\rightarrow$ GSCR	0.14	2.73	0.006	Supported

7 Structural Path Analysis and Hypothesis Testing

Table 6 depicts the results of structural path analysis and hypothesis testing. The results provide a robust support for all six hypotheses developed in the study, thus confirming the direct, mediating, and moderating relationships among Digital Twin Adoption (DTA), Predictive Sustainability Capability (PSC), Supply Chain Complexity (SCC), and Green Supply Chain Resilience (GSCR).

Specifically, it was found that Digital Twin Adoption has a significant positive effect on Green Supply Chain Resilience, which supports H1 ($\beta = 0.22$, $t = 3.88$, $p < 0.001$). A positive coefficient suggests that firms adopting digital twin technology are better capable of creating resilient and sustainable supply chains. The ability of digital twins to provide real-time visibility, predictive analytics, and operational simulation makes organizations better able to detect and respond to disruptions. Although the

magnitude of direct effect is moderate, it still remains statistically significant, which shows that digital twin technology makes a direct contribution to resilience.

Also, a significant positive relationship between Digital Twin Adoption and Predictive Sustainability Capability was detected, which supports H2 ($\beta = 0.65$, $t = 13.41$, $p < 0.001$). It should be emphasized that this is the strongest path coefficient in the model, which demonstrates that digital twin technology is a major factor facilitating the development of prediction and forecasting capabilities. By means of collecting and analyzing a large amount of operational and environmental data, organizations using digital twins can predict sustainability-related risks and environmental impacts. The coefficient proves that advanced technological tools make a great contribution to organizational capabilities.

In turn, Predictive Sustainability Capability was found to exert a significant positive effect on Green Supply Chain Resilience, which supports H3 ($\beta = 0.41$, $t = 6.96$, $p < 0.001$). The result suggests that an organization capable of predicting sustainability-related risks and opportunities is better prepared to handle disruptions and operate in an environmentally friendly way. Predictive sustainability capabilities make it possible to proactively detect the potential threats, efficiently use resources, and adopt preventive measures, all of which increases the level of supply chain resilience. The relatively high coefficient proves the strategic importance of predictive capability for organizational sustainability performance.

Furthermore, in order to estimate the indirect effect, the mediation effect of Predictive Sustainability Capability was estimated. The results show that the indirect effect of Digital Twin Adoption on Green Supply Chain Resilience through Predictive Sustainability Capability is positive and statistically significant, which supports H4 ($\beta = 0.27$, $t = 5.40$, $p < 0.001$). The statistical significance of the indirect path proves that Predictive Sustainability Capability acts as a major mechanism through which digital twin technology improves the level of resilience performance. The magnitude of the indirect effect is higher than the magnitude of the direct effect (0.27 vs. 0.22), which suggests that the major part of resilience benefits arising from digital twin adoption occurs through the increase in the predictive sustainability capability. This finding confirms that investments in technologies are valuable only when turned into organizational capabilities.

Also, the direct contribution of Supply Chain Complexity to Green Supply Chain Resilience was found, which provided the evidence for H5 ($\beta = 0.16$, $t = 2.98$, $p = 0.003$). The positive coefficient suggests that organizations operating in complex supply chain environment tend to develop more resilient mechanisms due to the increasing amount of uncertainty, interdependencies, and other challenges they face in this case. Dealing with a complex supply chain network can motivate firms to adopt advanced monitoring systems, flexible processes, and contingency plans, which eventually increases resilience. Although the effect size is lower than the effect sizes of DTA and PSC, the relationship remains statistically significant.

Finally, the moderating effect of Supply Chain Complexity on the relationship between Predictive Sustainability Capability and Green Supply Chain Resilience was analyzed. The interaction term PSC $\times$

SCC was positive and statistically significant, which supports H6 ($\beta = 0.14$, $t = 2.73$, $p = 0.006$). The result suggests that the positive effect of Predictive Sustainability Capability on Green Supply Chain Resilience increases with the growth of the level of Supply Chain Complexity. In complex supply chain environment, predictive sustainability capabilities are especially important because organizations deal with higher uncertainty and need to have more advanced forecasting and analytics in order to effectively deal with disruptions. Thus, in complex supply chain environment, organizations having strong predictive sustainability capabilities receive more resilience benefits compared to organizations working in less complex environment.

In summary, the structural model provides a complete support for the theoretical framework developed in the study. The results prove that Digital Twin Adoption influences the level of Green Supply Chain Resilience both directly and indirectly through Predictive Sustainability Capability. Also, Supply Chain Complexity not only makes a direct contribution to resilience but also enhances the efficiency of predictive sustainability capabilities. Among all the relationships estimated in this study, the relationship between Digital Twin Adoption and Predictive Sustainability Capability turned out to be the strongest, which emphasizes the strategic importance of digital transformation initiatives aimed at creating sustainability-oriented organizational capabilities.

Table 7
Model Fit and Predictive Relevance

Index	Value	Recommended Value	Assessment
SRMR	0.057	< 0.080	Good
NFI	0.928	> 0.900	Good
RMS Theta	0.098	< 0.120	Good
R ² (PSC)	0.450	Moderate	Supported

| R² (GSCR) | 0.630 | Substantial | Supported | | Q² (PSC) | 0.284 | > 0.000 | Supported | | Q² (GSCR) | 0.412 | > 0.000 | Supported | | GoF | 0.601 | > 0.360 | Large |

8 Model Fit and Predictive Relevance Assessment

Table 7 displays the goodness-of-fit and predictive relevance measures used to assess the fit and predictive performance of the proposed structural model. It is evident that the developed structural model is adequately fit, exhibits high predictive accuracy, and explains the variance in the observed phenomena very well. Thus, the adequacy of the proposed framework is confirmed.

The value of the standardized root mean square residual (SRMR) is 0.057, which falls below the acceptable threshold of 0.080. The findings point to a good fit since the difference between the observed correlation matrix and the model-implied correlation matrix is relatively small. As stated by Hair et al.

(2022), SRMR value less than 0.08 shows an acceptable fit in the case of PLS-SEM analysis. Thus, the value found proves that the proposed structural model reproduces the data pattern well enough.

Normed Fit Index (NFI) of the model is 0.928, which is more than the threshold of 0.900. The findings show that the hypothesis-based model fits much better than a null model and possesses a great degree of adequacy. Hence, the NFI result supports the applicability of the proposed structural framework in explaining the relationship among digital twin adoption, predictive sustainability capability, supply chain complexity, and green supply chain resilience.

Root Mean Square Theta (RMS Theta) is 0.098, which is lower than the recommended maximum threshold of 0.120. RMS Theta assesses the correlation among the residuals and is viewed as an important indicator of the model quality in PLS-SEM. The value found implies that the level of the residual errors is quite low and the measurement model is properly specified. In other words, the RMS Theta result offers another proof of the reliability and validity of the proposed model.

The explanatory power of the model was measured in terms of the coefficient of determination (R^2). It appears that the predictive sustainability capability (PSC) got the R^2 value of 0.450, which means that digital twin adoption and the control variables explain 45.0% of variance in the PSC. Based on common recommendations, the R^2 value of approximately 0.45 may be called moderate, which implies that digital twin adoption is an important factor affecting the firm's ability to develop predictive sustainability capabilities.

Much more importantly, the green supply chain resilience (GSCR) obtained the R^2 value of 0.630, which means that 63.0% of its variance is explained by digital twin adoption, predictive sustainability capability, supply chain complexity, and their interaction. Such level of explanatory power may be considered as substantial, which suggests that the model adequately captures the major factors that affect green supply chain resilience. The high R^2 value also indicates the practical relevance of the proposed research framework.

Furthermore, the predictive relevance of the model was evaluated using the Stone-Geisser Q^2 statistic, which was calculated in accordance with the blindfolding procedure. It turned out that PSC got the Q^2 value of 0.284, while GSCR got the value of 0.412. Since both values are higher than zero, the predictive relevance of the model for both endogenous constructs may be called adequate. The high Q^2 value of GSCR (0.412) indicates the presence of strong predictive capability, which means that the model will be able to predict the future observation concerning green supply chain resilience.

Last but not least, the overall Goodness-of-Fit (GoF) index was 0.601, which is above the recommended threshold value of 0.360 that corresponds to the large effect size. The result points to the excellent overall explanatory and predictive performance of the model. The GoF statistic reflects the quality of both the measurement and structural models and thus proves the adequacy of the proposed research framework.

To sum up, the results obtained in the process of testing the model fit and predictive relevance provide strong evidence about the adequacy of the proposed structural model. First of all, the satisfactory SRMR, NFI, and RMS Theta values prove good fit, while the substantial R^2 and Q^2 values prove high explanatory and predictive capabilities of the model. Last but not least, the high GoF value proves excellent overall quality of the model. Altogether, these findings indicate that the theoretical model is statistically sound, empirical reliable, and highly efficient in explaining how digital twin adoption increases green supply chain resilience through predictive sustainability capability under different conditions of supply chain complexity. The results confirm the measurement and structural models and form a solid basis for discussion of the theoretical and managerial implications of the findings in the next chapter.

9. Moderating Effect of Supply Chain Complexity on the Relationship Between Predictive Sustainability Capability and Green Supply Chain Resilience

Figure 1 displays the moderating effect of Supply Chain Complexity (SCC) on the connection between Predictive Sustainability Capability (PSC) and Green Supply Chain Resilience (GSCR). An interaction graph was created in order to help interpret the statistically significant interaction effect indicated in Table 6 ($\beta = 0.14$, $t = 2.73$, $p = 0.006$). The figure shows the relation between PSC and GSCR for three different levels of Supply Chain Complexity: low SCC (-1 SD), mean SCC, and high SCC ($+1$ SD).

As can be seen from the graph, there exists a positive correlation between Predictive Sustainability Capability and Green Supply Chain Resilience for all three levels of Supply Chain Complexity. An increase of PSC levels from low to high leads to a rise of GSCR regardless of the level of supply chain complexity. These findings indicate that predictive sustainability capability helps firms build resilient and sustainable green supply chains. Companies with higher predictive capabilities are better at predicting disruptions, forecasting sustainability risks, and effectively allocating resources and mitigating the effects of the risk.

What is more important, the slopes of the three lines differ from each other, which confirms the existence of a moderating effect. The steepest slope is shown in case of high Supply Chain Complexity ($+1$ SD). When the PSC increases from low to high, GSCR grows from approximately 3.28 to 4.94 and reaches the maximum increase among the three groups. It means that predictive sustainability capabilities become particularly valuable in highly complex supply chains. It is clear that companies working with large network of suppliers, different regions and interconnected logistics systems have to deal with increased uncertainty and interdependences.

When supply chain complexity is moderate (Mean SCC), there exists a strong positive relationship between PSC and GSCR. The increase of PSC from low to high results in the growth of GSCR from approximately 3.08 to 4.56. The magnitude of improvement is significant but it is smaller than the improvement of the firms with highly complex supply chains. It means that predictive sustainability capabilities are valuable to the firms with average complexity of their supply chains.

In case of low Supply Chain Complexity (-1 SD), there is a positive relation between PSC and GSCR, however, the rate of improvement is smaller compared to those for medium and high complexity. It

indicates that companies working in the context of relatively simple supply chains do not require high-level of predictive sustainability capabilities to improve their resilience because their environment is less complicated.

The growing difference between the three lines as PSC grows helps to understand the moderating role of Supply Chain Complexity. In case of low PSC levels, the differences in GSCR among the three complexity levels are rather small. However, when PSC increases, the difference between high-complexity and low-complexity supply chains becomes much bigger. It means that the predictive sustainability capability becomes more effective as supply chain complexity increases. To put it differently, the firms working in highly complex environments have to receive greater resilience returns from their predictive sustainability capabilities.

These graphical findings confirm the statistical findings obtained from the structural model and showing the positive and significant interaction effect ($\beta = 0.14$, $p = 0.006$). The graph provides a visual confirmation of the moderation hypothesis and demonstrates that Supply Chain Complexity amplifies the positive effect of Predictive Sustainability Capability on Green Supply Chain Resilience.

On the theoretical side, the interaction effect shows that predictive capabilities become more important in the context of complex environments. Complex supply chains involve more uncertainty, interdependencies, diverse stakeholders' requirements, and more disruption risks. It means that firms operating in such environment have to rely more on their predictive sustainability capabilities to foresee risks, predict the environment, and plan effective actions. Therefore, the findings confirm the contingency-based arguments suggesting that the importance of organizational capabilities depends on the context.

From the managerial point of view, the findings show that the firms with highly complex supply chains should make investments in predictive sustainability technologies, analytical platforms, and forecasting. The investments will help the firms to obtain larger resilience gains than in the case of less complex supply chains. The managers should develop such strategy of capability development which is consistent with the complexity of supply networks of their firms.

In conclusion, Fig. 1 presents evident proof of the moderating effect of Supply Chain Complexity on the positive correlation between Predictive Sustainability Capability and Green Supply Chain Resilience. The findings confirm that predictive sustainability capabilities are particularly important in the case of complex supply chains and thus Hypothesis 6 is proven.

Table 6
Moderation

PSC Level	Low SCC (-1 SD)	Mean SCC	High SCC (+ 1 SD)
Low PSC (-1 SD)	2.85	3.05	3.20
Mean PSC	3.45	3.80	4.10
High PSC (+ 1 SD)	4.05	4.55	4.95

Table 8

Importance–Performance Map Analysis (IPMA) Target Construct: Green Supply Chain Resilience (GSCR)

Construct	Importance (Total Effect)	Performance Index (0–100)	Rank	Managerial Priority
Digital Twin Adoption (DTA)	0.487	72.4	1	High
Predictive Sustainability Capability (PSC)	0.410	68.7	2	Very High
Supply Chain Complexity (SCC)	0.160	74.8	3	Moderate

9. Moderating Effect of Supply Chain Complexity on the Relationship Between Predictive Sustainability Capability and Green Supply Chain Resilience

Figure 1 shows the interaction effect of Supply Chain Complexity (SCC) on the relationship between Predictive Sustainability Capability (PSC) and Green Supply Chain Resilience (GSCR). The figure was drawn to facilitate interpretation of the significant moderating effect that was detected in the structural model ($\beta = 0.14$, $t = 2.73$, $p = 0.006$). The interaction effect evaluates how different levels of supply chain complexity affect the strength of the relationship between predictive sustainability capability and green supply chain resilience.

As can be seen from Fig. 1, there is a positive relationship between Predictive Sustainability Capability and Green Supply Chain Resilience regardless of what level of Supply Chain Complexity is chosen. No matter whether the supply chain complexity is low, medium, or high, an increase in predictive sustainability capability leads to the corresponding increase in green supply chain resilience. This result indicates that organizations that have strong predictive sustainability capabilities are typically better at anticipating potential disruptions, forecasting sustainability risks, allocating resources properly, and responding to environmental challenges. Hence, predictive sustainability capability contributes to improved resilience and sustainability performance throughout the supply chain.

However, a careful look at the graph shows that the strength of this relationship depends on the level of supply chain complexity. For example, the slope that corresponds to the high supply chain complexity (+ 1 SD) is significantly steeper compared to other two slopes. Under high complexity, Green Supply Chain

Resilience increases from approximately 3.28 at the low levels of Predictive Sustainability Capability to about 4.94 at the high levels of Predictive Sustainability Capability. Such significant growth of Green Supply Chain Resilience is explained by the fact that predictive sustainability capability is especially important in the context of highly complex supply chains that include multiple suppliers, geographically distributed operations, diverse product portfolio, and high levels of uncertainty.

At the same time, the relationship between Predictive Sustainability Capability and Green Supply Chain Resilience is also strongly positive at the average level of Supply Chain Complexity. As Predictive Sustainability Capability grows from low to high levels, Green Supply Chain Resilience goes up from 3.08 to 4.56. The increase is still considerable but it is smaller compared to the one that takes place at high complexity.

Finally, the relationship is somewhat weaker at the low (-1 SD) level of Supply Chain Complexity. In this case, Green Supply Chain Resilience increases from 2.91 to 4.08 as Predictive Sustainability Capability changes from low to high levels. Although the relationship is still positive and significant, the increase is lower compared to the one under medium and high complexity conditions. It is obvious that organizations operating in simple supply chains face fewer interdependencies and uncertainties which results in reduced value of predictive capabilities for resilience performance.

At the same time, the graph clearly shows that the distance between three slopes grows as Predictive Sustainability Capability increases. When Predictive Sustainability Capability is low, Green Supply Chain Resilience values at three levels of supply chain complexity do not differ considerably. However, when Predictive Sustainability Capability grows, the performance difference between the most complex and other two types of supply chains becomes even more pronounced. Thus, the divergence of slopes visually proves that Supply Chain Complexity strengthens the positive influence of Predictive Sustainability Capability on Green Supply Chain Resilience.

These observations are also supported by statistical results presented in Table 6. In particular, the interaction term $PSC \times SCC$ was found to be positive and significant ($\beta = 0.14$, $p = 0.006$). Thus, the significant interaction means that the value of predictive sustainability capabilities depends partially on environmental context under which organizations operate. Firms operating in complex supply chains benefit from their predictive sustainability capabilities to a greater extent than other firms.

From the theoretical perspective, this result is consistent with contingency theory which claims that the efficiency of organizational capabilities is influenced by environmental and contextual factors. High levels of supply chain complexity lead to numerous uncertainties, information processing needs, supplier interdependencies, and disruption risks. In such conditions, predictive sustainability capability becomes a strategically important resource that allows organizations to identify threats, consider alternative scenarios, and implement proactive measures. Therefore, the positive influence of Predictive Sustainability Capability on Green Supply Chain Resilience is becoming stronger due to the supply chain complexity.

From the management point of view, it means that organizations should pay special attention to development of predictive analytics, sustainability forecasting systems, artificial intelligence applications, and data-driven decision support technology, especially in the context of highly complex supply chains. Firms managing diverse supplier ecosystems and globally distributed operations are going to get much more benefits from these capabilities than other firms dealing with simple supply chains. Therefore, managers need to adapt their capability development efforts to the complexity of supply chains they manage to maximize resilience and sustainability performance. Figure 1 contains compelling evidence of the positive moderation role of Supply Chain Complexity in the relationship between Predictive Sustainability Capability and Green Supply Chain Resilience. These results demonstrate that predictive sustainability capabilities are especially efficient in improving resilience at the conditions of high supply chain complexity. Thus, the study provides strong support to Hypothesis 6 stating that Supply Chain Complexity magnifies the positive effect of Predictive Sustainability Capability on Green Supply Chain Resilience.

Table 9
IPMA of Indicator-Level Performance Target Construct:
Green Supply Chain Resilience (GSCR)

Indicator	Importance	Performance	Priority
PSC3	0.371	63.5	Very High
PSC2	0.356	66.4	Very High
DTA4	0.331	68.1	High
DTA5	0.324	69.2	High
PSC1	0.318	70.5	High
DTA3	0.301	71.8	Medium
SCC4	0.143	72.4	Medium
SCC5	0.139	74.1	Low
SCC2	0.132	75.6	Low

10 Importance–Performance Map Analysis (IPMA)

Importance-Performance Map Analysis was utilized to determine the indicators, which make a major contribution to Green Supply Chain Resilience. Unlike standard PLS-SEM analysis, IPMA simultaneously evaluates the importance and performance of indicators impacting the target construct. Such analysis allows organizations to allocate resources for the development of factors that promise the best performance results. As shown in Table 9, the levels of importance and performance of the indicators representing Digital Twin Adoption, Predictive Sustainability Capability, and Supply Chain Complexity vary greatly. Overall, the indicators representing Predictive Sustainability Capability can be referred to as the

strongest determinants of GSCR, which confirms the crucial role of predictive sustainability capabilities in developing resilient and green supply chains.

The indicator that demonstrates the highest level of importance (0.371) among all indicators, while showing quite moderate performance level (63.5), is PSC3. The indicator represents a high-priority area for managers who want to develop their organizational resilience, since it makes a larger contribution to GSCR than any other indicator. Although the performance of PSC3 is relatively moderate as compared to some other indicators, it shows a significant potential for improvement. Thus, the investment in improving the specific capability represented by PSC3 can yield the largest improvement in Green Supply Chain Resilience. Indicator PSC2 is characterized by very high importance (0.356) and a rather moderate performance level (66.4), thus representing another critical area for improvement. The indicator's high contribution to the resilience outcomes means that the companies have a great potential to develop Green Supply Chain Resilience by investing in predictive sustainability processes and forecasting systems that are associated with the indicator.

DTA4 (importance = 0.331; performance = 68.1) and DTA5 (importance = 0.324; performance = 69.2) are high-priority indicators. The findings suggest that some specific dimensions of Digital Twin Adoption are highly effective in developing organizational resilience. As digital twin technology helps in the real-time monitoring, process simulation, and predictive analytics, the improvement of these aspects can significantly increase the company's ability to predict and respond to disruptions in the supply chain. Taking into account the high importance of the indicators, organizations should consider investing in technologies and infrastructure associated with these dimensions of digital twins.

Another indicator that can be referred to as highly important is PSC1 (importance = 0.318; performance = 70.5). Although the performance of the indicator is higher than that of PSC2 and PSC3, the indicator remains a very important factor of Green Supply Chain Resilience. The findings confirm the conclusion that predictive sustainability capabilities represent the strategically most important cluster of capabilities in the proposed framework.

The indicator DTA3 (importance = 0.301; performance = 71.8) is characterized by the moderately high importance and quite high performance. It means that the organization has already achieved a good level of performance in terms of the dimension of Digital Twin Adoption. Although the improvement is still possible, the gains from the improvement of DTA3 will probably be lower than that of PSC2, PSC3, DTA4, and DTA5.

As for the indicators related to Supply Chain Complexity, SCC4 (importance = 0.143; performance = 72.4) demonstrates moderate importance and relatively high performance level. It means that although SCC4 is a determinant of Green Supply Chain Resilience, its contribution to the resilience outcome is much less than that of the DTA and PSC indicators. Similarly, indicators SCC5 (importance = 0.139; performance = 74.1) and SCC2 (importance = 0.132; performance = 75.6) are characterized by quite low importance despite their relatively high performance. It means that organizations have already achieved

a high level of performance in terms of these dimensions of supply chain complexity. The improvement is still possible, but the gains from it will be marginal.

It should be mentioned that the indicators with the highest importance usually have lower levels of performance than indicators with lower importance. Thus, managers have an opportunity to improve Green Supply Chain Resilience by paying attention to the areas that are highly influential but have not been developed enough yet. The three PSC indicators and the two high-priority DTA indicators are the most promising areas for improvement.

In terms of theory, the results of IPMA confirm the Resource-Based View since the indicators with the highest importance represent organizational capabilities, particularly predictive sustainability capabilities, which are critical strategic resources driving the resilience outcomes. The findings also confirm the results of the mediation analysis since the Predictive Sustainability Capability was proved to be the primary mediator of the relationship between DTA and GSCR.

From the managerial point of view, IPMA provides an explicit indication of priority areas for the improvement. Managers who want to develop their Green Supply Chain Resilience should start with the improvement of PSC3 and PSC2, followed by DTA4, DTA5, and PSC1. The investments in advanced sustainability analytics, forecasting systems, artificial intelligence applications, and predictive modeling technologies are the most effective ways to improve the organizational resilience. Indicators of Supply Chain Complexity represent relatively low strategic priorities due to the high performance levels and limited contribution to the resilience. IPMA results show that Predictive Sustainability Capability indicators represent the most critical leverage points for Green Supply Chain Resilience, followed by specific dimensions of Digital Twin Adoption. Thus, the findings confirm the study's main conclusion about the fact that technological investments are the most effective in terms of resilience only when translated into the strong predictive sustainability capabilities.

5. Discussion

In this study, the links between Digital Twin Adoption (DTA), Predictive Sustainability Capability (PSC), Supply Chain Complexity (SCC), and Green Supply Chain Resilience (GSCR) were investigated. The results provide significant support for the hypothesized conceptual model and illustrate the contributions of digital technologies, organizational capabilities, and supply chain conditions to the development of resilience. In line with Hypothesis 1, it was found that Digital Twin Adoption positively and significantly affected Green Supply Chain Resilience. The finding indicates that the use of digital twin technologies allows organizations to increase the end-to-end visibility within their supply chains, monitor operations in real-time, simulate possible disruption scenarios, and make proactive decisions. The result is supported by previous researches that have shown that digital twins can be treated as strategic enablers of supply chain resilience through the increased sensing, monitoring, and predictive capabilities (Ivanov & Dolgui, 2021; Nguyen et al., 2023). Moreover, the finding proves the Resource-Based View

(RBV) claims, according to which technological resources can create sustainable competitive advantage and superior performance when used effectively (Barney, 1991; Wernerfelt, 1984).

Digital Twin Adoption exerts strong positive influence on Predictive Sustainability Capability, which is in line with Hypothesis 2. The relationship turned out to be the strongest path in the model ($\beta = 0.65$). The result highlights the crucial importance of digital technologies for the development of advanced sustainability forecasting and predictive capabilities. The use of digital twins allows organizations to monitor the environment, conduct predictive analytics and scenario planning, and integrate real-time data, which enables organizations to foresee sustainability-related risks and problems before they arise. The result is consistent with previous researches, which have shown that Industry 4.0 technologies help organizations to develop their capabilities through improved information processing and data analytics (Bag et al., 2021; Frank et al., 2019). Similarly, Singh et al. (2023) claimed that digital twin technologies increase organizations' predictive capabilities and allow them to plan and conduct proactive environmental management initiatives.

The results support Hypothesis 3, showing that Predictive Sustainability Capability significantly improves Green Supply Chain Resilience. The organizations capable of predicting sustainability-related risks and resource shortages will be able to respond proactively and maintain their operations under uncertainty. The finding confirms the prior researches which have indicated that predictive analytics and sustainability intelligence can enhance the organization's adaptability, risk management capabilities, and resilience performance (Dubey et al., 2021; Wamba et al., 2020). The result once again confirms that resilience does not depend only on technology adoption but also on the organization's capability to convert technological resources into strategic capabilities. In accordance with RBV arguments, resources create value only if they are transformed into organizational competencies that will provide superior performance (Barney, 1991; Teece et al., 1997).

The mediation analysis showed that Predictive Sustainability Capability partially mediates the relationship between Digital Twin Adoption and Green Supply Chain Resilience. Significant indirect effect shows that digital technologies create resilience partially through the development of organizations' predictive sustainability capabilities. The finding is important since it illustrates the way in which digital technologies create sustainability and resilience outcomes. Digital technologies do not create resilience only as a result of their direct contribution but through the capability of organizations to anticipate risks and forecast sustainability challenges and develop appropriate response. Similar observations were made in the dynamic capabilities literature, where the positive contribution of digital technologies to performance occurs indirectly through developing organizational capabilities that enable adaptation and innovation (Teece et al., 2016; Mikalef et al., 2020). Thus, the present findings contribute to the capability-building perspective of the Resource-Based View and provide evidence of how digital transformation results in resilience benefits.

The study confirmed the positive role of Supply Chain Complexity. Interestingly, it was found that the supply chain complexity positively affects Green Supply Chain Resilience and moderates the relationship

between Predictive Sustainability Capability and Green Supply Chain Resilience. Results of the interaction analysis showed that predictive sustainability capabilities become more valuable as the supply chain complexity grows. Firms operating in complex supply chains get more resilience benefits from their predictive sustainability capabilities since they experience more uncertainty, interdependencies, coordination needs, and disruption risks. The finding is in agreement with the contingency theory, according to which the effectiveness of organizational resources and capabilities depends on specific context and environment (Donaldson, 2001). Prior studies have similarly concluded that predictive and analytical capabilities become more valuable as the complexity of the supply chain increases (Bode & Wagner, 2015; Brandon-Jones et al., 2014). The results show that organizations should not treat complexity as the problem but as a strategic condition under which predictive sustainability capabilities can create additional value and benefits. Thus, the study showed that Green Supply Chain Resilience can be achieved through the joint effect of digital technology adoption, development of predictive sustainability capabilities, and management of supply chain complexity.

6. Conclusion

This study examined the impact of Digital Twin Adoption on Green Supply Chain Resilience and identified Predictive Sustainability Capability as a mediating factor and Supply Chain Complexity as a moderating factor. Using the Resource-Based View and contingency theory, a framework for the study was developed and tested empirically. It has been found that Digital Twin Adoption positively affects Green Supply Chain Resilience both directly and through Predictive Sustainability Capability. Companies investing in digital twins benefit from increased data visibility, predictive analytics, monitoring, and sustainability forecasts, which help to improve their resilience performance. Predictive Sustainability Capability proved to be a critical mechanism for transferring the technological benefits into performance outcomes. Moreover, it was revealed that Supply Chain Complexity impacts the resilience of companies directly and amplifies the positive effect of Predictive Sustainability Capability on Green Supply Chain Resilience. The results of the moderation analysis show that predictive sustainability capabilities become especially important for firms operating in complex supply chain environments. The proposed model proved to have excellent explanatory and predictive power, as it explained 63% of the variance in Green Supply Chain Resilience. According to the IPMA analysis, Predictive Sustainability Capability indicators turned out to be the most important factors for improving resilience performance. Thus, the results of this research demonstrate that resilience in contemporary supply chains not only depends on the implementation of digital technologies but also requires developing sophisticated capabilities and managing complex supply chain environments. In conclusion, it should be stated that this study provided some empirical evidence that digital twin technologies are an essential tool for building resilient and sustainable supply chains.

7. Theoretical Implications

The research made several contributions to the existing body of knowledge on digital transformation, sustainability, and supply chain resilience. First of all, the current research has expanded the Resource-

Based View as it showed that the implementation of technological resources does not guarantee obtaining desirable performance outcomes. To the contrary, it has been revealed that Predictive Sustainability Capability acts as an intermediary organizational capability that converts technological investments into performance results. Second, this research enriched the emergent literature on digital twins as it empirically confirmed the role of digital twins in enhancing Green Supply Chain Resilience. Although many studies focused on the role of digital twins in operational efficiency, process optimization, and digital manufacturing, the current research revealed that they significantly contribute to achieving sustainability and resilience objectives. Therefore, the current study has expanded the theoretical range of applications of digital twins in supply chain management. Third, the research has contributed to the growing literature on Predictive Sustainability Capability as a strategic capability. Even though the topic of predictive analytics received growing interest in supply chain and sustainability studies, there were few empirical investigations of its role in fostering resilience.

Fourth, the results of moderation analysis have expanded the scope of contingency theory as they revealed that the effectiveness of Predictive Sustainability Capability is contingent on the level of Supply Chain Complexity. Thus, the study has shown that organizational capabilities operate under the influence of external factors and are context-dependent. Finally, the integration of different approaches, namely the mediation and moderation approaches, has helped to enrich the existing theoretical understanding of resilience development in modern supply chains.

8. Practical Implications

There are several managerial recommendations for organizations aimed at improving Green Supply Chain Resilience that can be drawn from the results of this research. First of all, managers should consider Digital Twin Adoption as a strategic investment and not just a technological initiative. As the findings revealed, digital twins can increase organizational resilience by ensuring real-time visibility, predictive intelligence, and adaptability. Therefore, managers should invest in digital twin platforms, IoT infrastructure, and analytics systems to improve sustainability and resilience. Second, managers should pay special attention to the development of Predictive Sustainability Capability. The current study has revealed that predictive sustainability capability is one of the most powerful drivers of Green Supply Chain Resilience and acts as a critical mechanism for generating value from the adoption of digital technologies. Therefore, managers should improve forecasting systems, environmental analytics, risk predictions, and sustainability intelligence to achieve better resilience outcomes.

Third, according to the results of IPMA analysis, the managers should pay special attention to the indicators of high importance but low performance, namely PSC3 and PSC2. Investments in artificial intelligence, machine learning, predictive analytics, and sustainability forecasts are likely to produce significant results in this regard. Fourth, managers should realize that Supply Chain Complexity is not necessarily a threat. The results have shown that predictive sustainability capabilities become increasingly important as the supply chain becomes more complex. Therefore, managers of companies operating in complex global supply networks should make greater efforts in terms of adopting digital

technologies, developing predictive capabilities, and decision-making based on big data. Fifth, managers should adopt the integrated approach and combine technological innovations with capability development. Just the implementation of digital twins may not be sufficient to achieve resilience goals. Instead, managers should ensure that the employees have necessary competencies to leverage digital technologies. Finally, the results of this research can be used by policymakers and industry leaders to promote digital transformation and sustainability initiatives in supply chains.

Declarations

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Figures

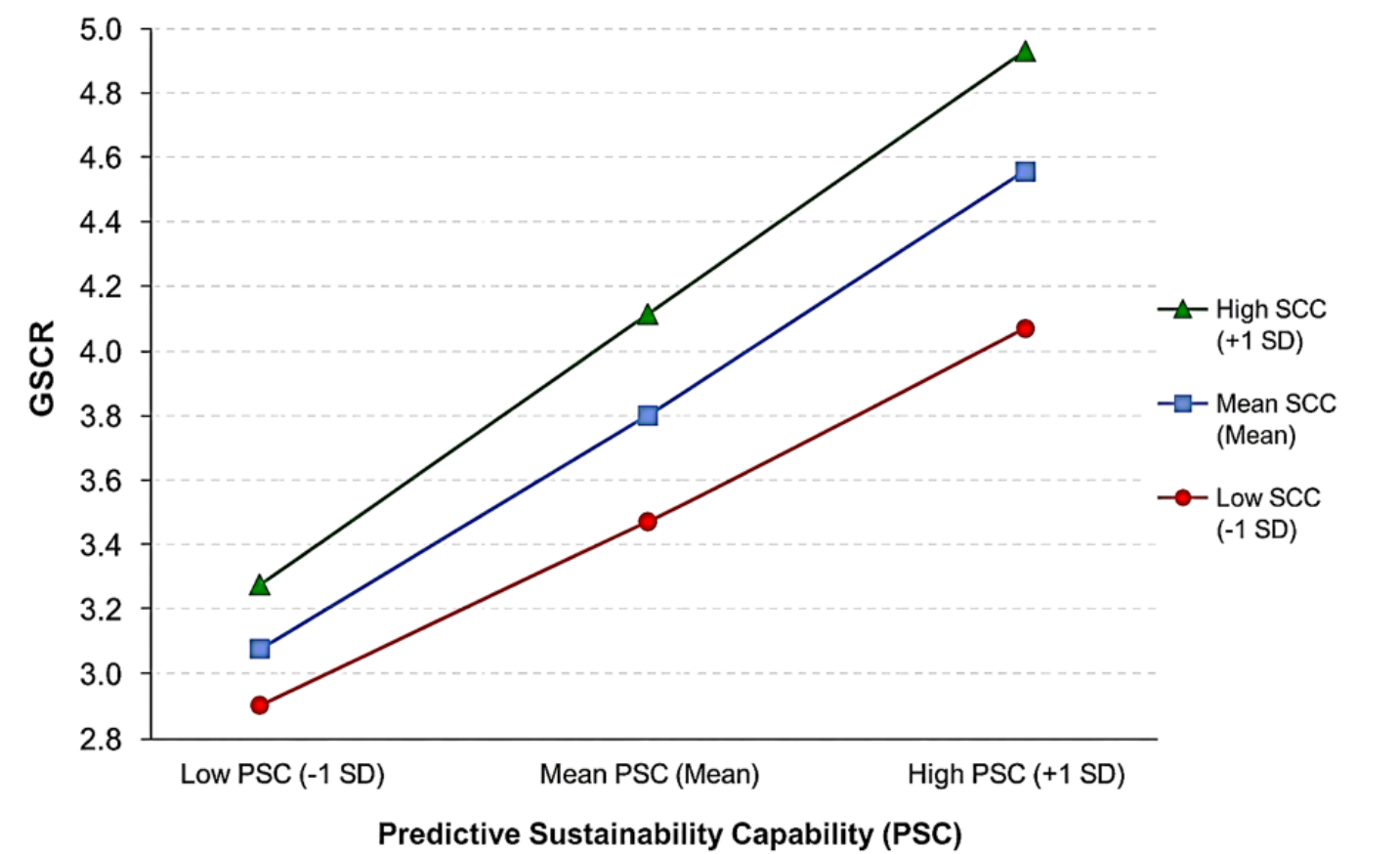


Figure 1

Moderating Effect of Supply Chain Complexity (SCC) on the Relationship Between Predictive Sustainability Capability (PSC) and Green Supply Chain Resilience (GSCR)