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Blockchain-Based Security Factors on Sustainable Supply Chain Management in UK Manufacturing Firms: A Hybrid SEM-ANN Approach

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Abstract: Recently, there has been a notable surge in the intricate complexities of global supply chain management (SCM), which is gaining researchers' attention. Supply chain sustainability is put at risk by security issues in blockchain technology that affect everything from infrastructure to management. For sustainable supply chain management (SSCM), these elements are deemed crucial. To address this, the purpose of this research is to examine the impact of blockchain security factors on SSCM among United Kingdom manufacturing firms. Based on the resource-based view (RBV) theory and the Technology–Organisation–Environment (TOE) framework, the research hypotheses and framework were developed. To achieve the research objectives, a hybrid approach that combines structural equation modelling and artificial neural networks (ANNs) was adopted to perform the analysis. The research findings indicate that privacy, network, confidentiality, and managerial factors are vital to promoting SSCM. Furthermore, the ANN analysis highlights that managerial (trust management) and supplier privacy factors are the most important constructs. Unlike prior research that theoretically assumed that all relationships are linear, this has been a novel study that has successfully validated that there exists a nonlinear relationship between the RBV theory and the TOE framework. Based on the outcomes, the study's contributions, its practical implications, and future research avenues are discussed.

Keywords: blockchain; security issues; sustainability; supply chain management; Industry 4.0

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1. Introduction

Global supply chain complexities have attracted a lot of attention recently, and they have been exacerbated by the pandemic, its economic fallout, and the recent Ukraine conflict [1]. These incidents have clearly demonstrated the vulnerability of modern supply chains, prompting a recent report from McKinsey & Company that highlighted their growing complexity and the integration of sustainability considerations [2]. The importance of successfully integrating sustainable practices into supply chains was emphasised by Jabbour et al. [3]. Sustainable supply chains (SSCs) represent the critical convergence of economic, social, and environmental goals that correspond to the interests of stakeholders [4]. Carter and Rogers [5] described SSCs as being characterized by the intentional and open incorporation of a firm's social, ecological, and economic objectives. This involves coordinating inter-organisational processes to achieve long-term economic success and enhance supply chain durability. Detwal et al. [6] argued that to remain competitive and thrive in today's market, incorporating sustainable practices into a firm's SC is necessary. Varriale et al. [7] emphasised the critical role of information transparency and availability in encouraging supply chain sustainability. Considering this imperative, organisations must promote measures to improve the efficiency, security, transparency, and dependability of information flow within supply chains. Furthermore, recognising the revolutionary potential of emerging technologies, such as blockchain and advanced analytics, as SSC enablers increases the significance of implementing such novel solutions [8–10].

The term Industry 4.0 (I4.0) made its debut in 2011 in Germany as a pivotal component of the country's advanced technology strategy, aiming to enhance industrial competency and exert an impact on comprehensive business operations [11–13]. I4.0 involves a digital evolution wherein the tangible realm of industrial production converges with the digital domain of information technology, enabling the digitisation and interlinking of the production process [14]. From a practical viewpoint, the adoption of I4.0 technologies is expected to lead to a 122 percent increase in firms' cash flow, and value creation between manufacturers and suppliers is expected to be USD 3.7 trillion [15]. In the same vein, Vitasek et al. [16] affirmed that Walmart adopted blockchain technology to overcome payment dispute issues. Among various I4.0 technologies, blockchain has received considerable attention. According to Javaid et al. [17], blockchain technology preserves information about a product's sub-assemblies, parts, and sales channels. Additionally, it lessens costs and disruptions associated with retrieval at any point in the supply chain [17]. In the same vein, Bottoni et al. [18] affirmed that blockchain is the backbone of supply chain management.

Although there are significant advantages to using blockchain technology in sustainable supply chains, there are also major obstacles, especially for manufacturing firms. Given the importance of handling sensitive supply chain data properly, privacy and confidentiality issues are of paramount importance [10,19]. Enabling the seamless use of blockchain while recognising the principles of sustainability, network scalability, and efficiency remains a significant obstacle that demands careful thought and creative solutions [20,21]. To fully realise the transformative potential of blockchain in promoting sustainable practices throughout supply chains, these concerns must be addressed. For instance, Kokaras and Foti [22] argued that due to privacy concerns, the blockchain usage cost increased by 2.5 times. IBM [23] indicated that firms must consider blockchain-based risks at the individual and firm levels.

In the prior literature, there is a noticeable gap in the scope and focus on blockchain applications in supply chain management. The majority of studies have focused on identifying and comprehending the drivers and factors that support the adoption of blockchain technology in SCM. However, there has been a serious gap in fully and holistically addressing blockchain security issues. More in-depth analysis and discussion in scholarly work are required due to the complex terrain of security risks surrounding blockchain technology, including privacy, network, confidentiality, and management factors. To ensure a thorough grasp of blockchain deployment and help businesses overcome security issues and fully realise the potential of this game-changing technology, this knowledge gap must be addressed. Based on this, the following research objectives have been derived:

I. To examine the role of blockchain security risks in sustainable supply chain management;
II. To analyse the most important blockchain security factors in promoting sustainable supply chain management.

The remainder of this article is structured as follows. The next section summarises the past literature and also outlines the theoretical framework that lays the foundation for hypothesis development. After that, the adopted methodology is presented. The next section presents and interprets the empirical results. Then, the study findings are discussed. Finally, the study limitations and future research directions are provided.

2. Theoretical Framework and Hypothesis Development

2.1. Resource-Based View (RBV) Theory

The resource-based view (RBV) theory of the organisation provides the basis of this study's exploration of the postulated relationship. According to the RBV theory, a firm's organisational resources and capabilities—which are characterised as being limited, distinctive, and difficult to replicate—are what ultimately enable it to create value. According to Kessler [24] and Barney [25], this distinguishing advantage can lead to persistent competitive superiority, improving the firm's overall performance. While capabilities refer to the organisation's capacity to effectively integrate and distribute these resources, resources cover all material and intangible assets that are under the organisation's control or management [26]. The resource-based view (RBV) has been gaining a lot of interest in the supply chain management and operations fields. By focusing on the use of organisational resources, the RBV is best able to explain how a competitive advantage might be obtained. An organisation has comparatively more influence over its internal strengths and weaknesses than it has over external opportunities and threats [27].

In the prior literature, the association between blockchain technology and supply chains is well grounded in RBV theory. For instance, Nagariya et al. [27] examined blockchain-based resilience strategies to promote supply chain performance among small and medium firms. In the same vein, Nandi et al. [28] conducted an empirical study to investigate the role of blockchain technology in enhancing supply chain performance. Similar to this, the RBV was used by Nandi et al. [29] to demonstrate how supply chains and blockchain technology are related. Finally, using the theoretical framework of the RBV, Paul et al. [30] investigated the effects of blockchain technology on the supply chain and its sustainable performance. This study argued that blockchain technology encourages actors to change their attitudes to achieve sustainable performance.

2.2. TOE Framework (Technology, Organisation, and Environment)

The resources and capacities of the organisation were evaluated in this study using the TOE framework [31]. In order to obtain a competitive edge, organisations often modernise their resources and knowledge. These improvements affect the technological (T), organisational (O), and environmental (E) dimensions, in accordance with the TOE framework [32,33]. The technological aspect has to do with the importance and suitability of technological developments brought about by these improvements. Identifying the organisational decision-making framework and strengths that enable these improvements falls within the organisational context. Regarding a wider connection with competitive environmental concerns, the environmental context includes the readiness of markets, industries, and regulatory agencies to adopt these advances. In addition to evaluating blockchain technology in operations and supply chain management [34], prior research adopted the TOE framework for sustainability technology, blockchain technology, and information service competence [35]. The TOE framework is commonly used by academics to investigate the relationship between the current states of these three aspects and the acceptance and implementation of a particular phenomenon [32,33].

The TOE framework is frequently used in RBV-based research to understand the drivers and enablers of particular technological developments. For instance, this framework is used to examine the drivers of IT enablement [36], the influences on mobile business usage and its value [37], and the factors influencing the utilisation and benefits of Enterprise Resource Planning (ERP) systems for small and medium-sized manufacturing and service firms. Table 1 shows a summary of prior research work.

Table 1. Summary of literature review.

Authors	Study Type	Study Focus	Theory	Country	Sector	Outcomes
Dehshiri and Amiri [38]	Empirical	To identify and evaluate the challenges and obstacles of blockchain technology to achieve a sustainable supply chain.	Z-number theory	Iran	Agriculture	The results depicted that the infrastructure of blockchain technology is considered the most important in promoting an SSC.

Table 1. *Cont.*

Authors	Study Type	Study Focus	Theory	Country	Sector	Outcomes
Vishwaarma et al. [39]	Review and Empirical	To identify the challenges of blockchain technology to enable healthcare SSCM.	None	India	Healthcare	The findings highlight that managerial, infrastructure, and security threats are the major challenges.
Wang et al. [40]	Empirical	To examine and identify the barriers to blockchain adoption in a sustainable SC.	Stakeholder theory	China	None	The results highlighted that factors related to management, data, and infrastructure are the most important barriers to blockchain in an SSC.
Njualem [41]	Review	To study and examine the role of blockchain technology in an SSC.	None	None	None	The findings indicate that technical-driven barriers need attention to promote an SSC.
Vazquez et al. [42]	Interview	To examine the role of blockchain in SSCM.	None	Developed countries	Manufacturing	The results indicate that a blockchain-based SC significantly surpasses a conventional SC.
Ayan et al. [43]	Review	To review the role of blockchain technology in promoting a sustainable supply chain.	None	None	None	The review findings indicate that future research should be conducted in manufacturing, agriculture, and healthcare sectors.
Bai et al. [35]	Conceptual	To examine the blockchain enablers for improving sustainable supply chain transparency in the Coca Industry.	TOE	Ghana	Cocoa	The outcomes indicated that technical factors are the main enablers factor.
Kshetri [44]	Conceptual	To identify the blockchain characteristics that promote SSCM in developing countries.	None	Developing countries	Multi-sector	The results indicate that an unfavourable institutional environment and high technology costs are the main factors.

Table 1. *Cont.*

Authors	Study Type	Study Focus	Theory	Country	Sector	Outcomes
Khan et al. [45]	Empirical	To examine the role of blockchain technology in promoting sustainable supply chain and organisational performance.	Practice-based view	China and Pakistan	None	The outcomes highlight that blockchain technology has a positive impact on an SSC.
Saberi et al. [46]	Conceptual	To identify and discuss the factors related to blockchain adoption in SC networks.	None	None	Manufacturing	The findings suggest that blockchain security factors are important to enhance sustainability in the SC.

2.3. Hypothesis Development

2.3.1. Privacy Factors and Sustainable SCM

Privacy considerations are fundamentally connected to the implementation of blockchain technology in sustainable supply chain management (SSCM) [27]. According to the resource-based view (RBV) theory, organisations can gain a competitive edge by using unique and essential assets, such as blockchain's improved privacy features [47]. Encryption and decentralised data storage, two of blockchain's improved privacy features, are in line with the RBV's emphasis on utilising unique resources to improve organisational skills in SSCM. The Technology, Organisation, and Environment (TOE) framework, which acknowledges blockchain as a technical advancement influencing organisational procedures and sustainable development in supply chain management, further strengthens this linkage [29].

In prior studies, the privacy factor gained significant attention. For instance, the review work of Sahoo et al. [48] suggests that privacy is among a common set of risks in blockchain in the supply chain management domain. In the same vein, the review work of Kshetri [44] posited that security and privacy issues play a key role in the adoption and implementation of blockchain technology in the food supply chain. Based on their empirical work, Li et al. [47] recommended that customer privacy concerns in blockchain technology be addressed to promote sustainable supply chain performance. Based on the above discussion, the following hypotheses have been proposed:

H1a. *Customer privacy (CP) has a positive impact on sustainable supply chain management (SSCM).*

H1b. *Supplier privacy (SP) has a positive impact on sustainable supply chain management (SSCM).*

2.3.2. Network Factors and Sustainable SCM

It is critical to understand how sustainable supply chain management (SSCM) and blockchain network elements, particularly network integrity and authentication, relate to one another. In accordance with the resource-based view (RBV) theory, organisations can view blockchain's network integrity and strong authentication mechanisms as distinctive and valuable resources. These qualities make it possible to interact in a safe, transparent, and reliable manner throughout the supply chain, which gives SSCM a competitive edge. The Technology, Organisation, and Environment (TOE) framework, which emphasises that improvements in blockchain technology play a crucial role in revolutionising organisational processes, also correlates with this perspective [49]. The blockchain network's integrity protects the reliability of data and transactions throughout the supply chain, promoting organisational effectiveness and advancing sustainability objectives. Transparency and accountability in supply chain operations are crucial elements of sustainable practices, and authentication procedures inside the blockchain network create a credible identification structure [29]. Based on the above theoretical support, the following hypotheses have been formulated:

H2a. *Network integrity (NI) has a positive impact on sustainable supply chain management (SSCM).*

H2b. *Authentication (AUT) has a positive impact on sustainable supply chain management (SSCM).*

2.3.3. Confidentiality Factors and Sustainable SCM

The relationship between sustainable supply chain management (SSCM) and blockchain confidentiality elements, particularly secrecy and reliable infrastructure, is obvious and substantial. Pursuant to the Resource-Based (RBV) theory, organisations can consider blockchain's capacity to uphold confidentiality through cryptographic processes and durable infrastructure as important and special resources. By assuring the secure and private management of critical supply chain data, these factors enable organisations to gain a competitive edge in SSCM [12,29,30].

The Technology, Organisation, and Environment (TOE) framework, which acknowledges blockchain technology as a catalyst for change driving organisational processes and environmental sustainability, further strengthens this relationship. The secrecy aspects of blockchains provide confidentiality, which improves data privacy and security in the supply chain and encourages ethical and sustainable behaviour. The supply chain integration of sustainable practices is further supported by strong blockchain infrastructure, aligning with the organisational and environmental components of the TOE framework [33,37]. Based on the above theoretical support, the following hypotheses have been formulated.

H3a. *Secrecy (SEC) has a positive impact on sustainable supply chain management (SSCM).*

H3b. *Infrastructure (INF) has a positive impact on sustainable supply chain management (SSCM).*

2.3.4. Managerial Factors and Sustainable SCM

Sustainable supply chain management (SSCM) is mainly related to the integration of blockchain managerial variables, notably trust management and policy enforcement. These elements of blockchain can be viewed as important and distinctive resources for organisations using the resource-based view (RBV) philosophy. Blockchain-based trust management ensures dependability and transparency, encouraging moral and ethical supply chain practices [29]. The Technology, Organisation, and Environment (TOE) framework's organisational and environmental elements are aligned with the policy enforcement mechanisms in blockchain, which help ensure compliance with sustainability policies [33]. Based on the above discussion, the following hypotheses have been formulated. Finally, the theoretical framework is shown in Figure 1.

H4a. *Trust Management (TM) has a positive impact on sustainable supply chain management (SSCM).*

H4b. *Policy enforcement (PE) has a positive impact on sustainable supply chain management (SSCM).*

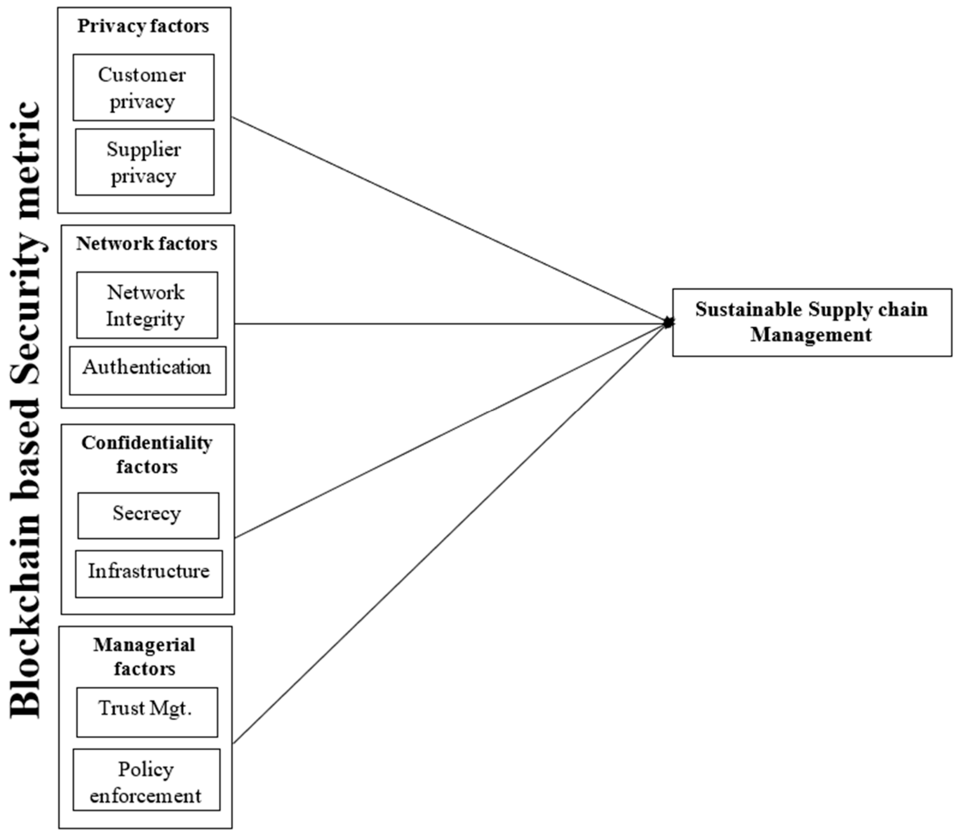

Figure 1. Theoretical framework.

3. Methodology

The current research study focuses on small and medium enterprises (SMEs) operating in the United Kingdom (UK). According to the UK government [50], an organisation that has fewer than 50 employees falls under the category of small, and a number of employees less than 250 constitutes a medium-sized manufacturing firm. Similar to prior studies, the sampling frame of the current research is based on the FAME database [51–53]. A simple random sampling technique was adopted to select manufacturing SMEs from the FAME database. The Qualtrics platform was used to construct a survey questionnaire, which was then made available online to people working in various manufacturing industries. The study respondents were the managers of the manufacturing firms. Additionally, as in a past study, the authors adopted other media to reach the respondents, like LinkedIn [52].

Before the actual data collection, pre-testing and pilot-testing steps were performed. Pre-testing ensured the suitability of the content of the questionnaire, and pilot testing indicated its clarity to the actual respondents. Additionally, ethical considerations were taken into account before and after data collection. Initially, more than 1000 SMEs were approached, and of these, 257 responses were collected. A final 237 responses were used for further analysis, with a response rate of 23.70%. Although the response rate was relatively low, it is still considered acceptable, as Hardigan et al. [54] argued that response rates to online surveys are always lower than to those conducted by other means. Table 2 shows the demographic statistics of the final dataset. The final dataset was initially screened using SPSS software. After that, SmartPLS software was used to perform partial least square structural equation modelling (PLS-SEM), as recommended by Hair et al. [55]. Finally, the artificial neural network (ANN) was developed using SPSS 21.0.

Table 2. Demographic statistics.

Items	Type	No. of Participants	Valid Percent
Gender	Female	107	45.15%
	Male	130	54.85%
Age	18–25	73	30.80%
	26–35	92	38.82%
	36–50	56	23.63%
	51 or above	16	6.75%
Education	Diploma	79	33.33%
	Bachelor's	133	56.12%
	Postgraduate	25	10.55%

The items related to the study variables were adapted from past studies. The privacy-related items were adapted from Castaneda et al. [56] and Swani et al. [57]. The items related to network, confidentiality, and managerial factors were adapted from Normalini et al. [58], Dong et al. [59], and PN [60]. A 7-point Likert scale was used, with responses ranging from strongly disagree (1) to strongly agree (7).

4. Analysis

4.1. Common Method Bias

Data for the current investigation were gathered from a single source. The self-reported characteristics of the data collection procedure raised the possibility of a potential risk associated with common method bias (CMB), according to Podsakoff et al. [61] study. To address this, both procedural and statistical methods were adopted to overcome CMB. In terms of a statistical remedy, Harmon's single-factor analysis was performed [62]. The analysis highlighted that a single factor accounted for a maximum variance of approx. 37%, which is less than the threshold limit of 50%. Furthermore, Kock and Lynn [63] and Kock [64] argued that a value of VIF less than 3.3 affirms that there is no CMB threat in the dataset.

4.2. Structural Equation Modelling

4.2.1. Measurement Model

Reliability and Validity

Based on prior literature recommendations, Cronbach's alpha (α), rho_A, and composite reliability (CR) techniques were adopted to perform a reliability analysis in PLS-SEM [55,65]. As suggested by Hair et al. [66], CR is a more appropriate approach in comparison with others. Thus, Table 3 shows the CR of all study variables. As suggested by Hair et al. [55], the threshold value of CR is ≥ 0.70; however, a value between 0.60 and 0.70 is also considered acceptable. The average variance extracted (AVE) and indicator loading were also used to measure convergent validity. In the PLS-SEM literature, an outer indicator loading ≥ 0.708 is considered excellent [55,66]. However, an outer indicator loading with a value between 0.4 and 0.7 can be retained if the value of AVE is ≥ 0.5 [66]. Additionally, the threshold value of AVE is $\geq$0.5 [55]. Table 2 indicates that all of the study constructs achieve the minimum threshold of AVE.

Table 3. Reliability and validity analysis.

Constructs	Items	Loading	VIF	Reliability	AVE
				CR	
CP	CP1	0.842	1.498	0.850	6.540
	CP2	0.815	1.465		
	CP3	0.766	1.419		
SP	SP1	0.793	1.384	0.821	0.605
	SP2	0.733	1.213		
	SP3	0.806	1.404		
NI	NI1	0.835	1.627	0.876	0.702
	NI2	0.861	1.793		
	NI3	0.817	1.586		
AUT	AUT1	0.803	1.326	0.862	0.676
	AUT2	0.819	1.847		
	AUT3	0.845	1.837		
SEC	SEC1	0.771	1.396	0.856	0.665
	SEC2	0.839	1.587		
	SEC3	0.834	1.549		
INF	INF1	0.775	1.260	0.820	0.603
	INF2	0.730	1.301		
	INF3	0.823	1.423		
TM	TM1	0.789	1.455	0.838	0.633
	TM2	0.847	1.540		
	TM3	0.748	1.276		
PE	PE1	0.880	2.081	0.915	0.718
	PE2	0.868	2.125		
	PE3	0.904	2.412		
SSCM	SSCM1	0.656	1.323	0.88	0.597
	SSCM2	0.778	1.712		
	SSCM3	0.771	1.707		
	SSCM4	0.838	2.072		
	SSCM5	0.807	1.859		

Discriminant Validity

To achieve discriminant validity, cross-loading and Fornell–Larker criteria were adopted. In the Fornell–Larker approach, the correlation between variables and the square root of the AVE for that construct is compared [67]. According to Fornell and Larcker [67] and Hair et al. [66], each latent variable's square root of the AVE must be greater than the correlation coefficient of the same construct to establish discriminant validity. Cross-loading is another method of evaluating discriminant validity. Table 4 presents the Fornell–Larker criterion values, and all of the indicators achieve the threshold limits.

Table 4. Discriminant validity.

Variables	CP	SP	NI	AUT	SEC	INF	TM	PE	SSCM
CP	0.808								
SP	0.414	0.778							
NI	−0.387	−0.625	0.838						
AUT	0.446	0.575	−0.591	0.822					
SEC	0.784	0.419	−0.400	0.447	0.815				
INF	0.361	0.754	−0.588	0.575	0.419	0.777			
TM	0.396	0.745	−0.762	0.615	0.406	0.693	0.796		
PE	0.394	0.642	−0.554	0.581	0.426	0.640	0.656	0.884	
SSCM	0.404	0.764	−0.812	0.683	0.411	0.714	0.681	0.645	0.772

Additionally, the goodness-of-fit measure has gained tremendous importance and undergone improvements in the SEM literature. As recommended by Henseler et al. [68], the researcher does not necessarily need to assess the PLS path model's goodness of fit. The application of goodness-of-fit measures is still rare [68] and not fully developed in PLS-SEM. Therefore, there is no reason to evaluate and report it.

4.2.2. Structural Modelling and Hypothesis Testing

To analyse the research hypotheses in PLS-SEM, a bootstrapping technique with 5000 resamples was adopted to examine the statistical significance of the relationship [55,66].

Table 5 presents the hypotheses and results of the study, especially focusing on the association between variables and their respective impact. The β-value and p-value (0.05, 0.10) were used to signify the acceptance or rejection of the hypothesis. Based on the results, H1b (SP → SSCM, β = 0.139, p = 0.003), H2b (AUT → SSCM, β = 0.141, p = 0.001), H3b (INF → SSCM, β = 0.072, p = 0.066), and H4a (TM → SSCM, β = 0.449, p = 0.001) were supported. Hence, H1b, H2b, H3b, and H4a were accepted. Conversely, the analysis highlights that H1a (CP → SSCM, β = −0.001, p = 0.491), H2a (NI → SSCM, β = −0.271, p = 0.001), H3a (SEC → SSCM, β = 0.029, p = 0.245), and H4b (PE → SSCM, β = −0.006, p = 0.446) were not supported. Thus, H1a, H2a, H3a, and H4b were rejected.

Table 5. Hypotheses testing.

Relationships	β-Value	t-Value	*p*-Value	f2	R2	Q2	Decision
H1a: CP → SSCM	−0.001	0.022	0.491	0.001			Not supported
H1b: SP → SSCM	0.139	2.799	0.003	0.043			Supported
H2a: NI → SSCM	−0.271	5.151	0.001	0.198			Not supported
H2b: AUT → SSCM	0.141	3.528	0.001	0.069	0.855	0.496	Supported
H3a: SEC → SSCM	−0.029	0.691	0.245	0.002			Not supported
H3b: INF → SSCM *	0.072	1.156	0.066	0.013			Supported
H4a: TM → SSCM	0.449	8.274	0.001	0.378			Supported
H4b: PE → SSCM	−0.006	0.137	0.446	0.001			Not supported

Note: * Significant at 90%.

5. Artificial Neural Network Analysis

This section provides reasons for the use of an ANN and highlights the results. Structural equation modelling (SEM) and multiple regression analysis (MRA) capture the linear relationships between independent and dependent variables. However, their suitability falls short of comprehensively elucidating the intricate dynamics of decision-making processes [69]. Siddik et al. [70] argued that an ANN does not require a normal distribution in order to capture both linear and nonlinear relationships. Sharma et al. [71] affirmed that an ANN is appropriate for determining the predictive power of any bias. Furthermore, the compensating assumption underpins both SEM and MRA, implying that a drop in any of the exogenous elements within the model can be offset by a rise in others [34]. All of the blockchain security factors are non-compensable and crucial for long-term success in the current study. For instance, the rejection of CP or NI cannot be compensated for by other variables because every construct is unique and distinct in nature. Thus, the hybrid technique of SEM-ANN is used to solve this difficulty and capture linear and nonlinear associations within a non-compensatory architecture [70,72]. Furthermore, the hybrid SEM-ANN methodology is a significant methodological advancement. Given the advantages and acceptability of the ANN technique, it is used in this study to assess the association between every predictor and the dependent variable. The ANN algorithm employed in this study adopts a three-layer structure, comprising input, hidden, and output layers [70]. The analysis utilises a multi-layer perceptron (MLP) with feed-forward–backward-propagation (FFBP). To mitigate overfitting, a tenfold cross-validation procedure was implemented [69]. Consistent with the prior literature, a 90:10 data split for training and testing was adopted [69,73]. The assessment of model fit was determined through the calculation of "root mean square errors" (RMSEs) [73].

Table 6 indicates the RMSE values of both the training and testing sets. In the training set, the RMSE values range from 0.342 to 0.416, with a mean of 0.377 and a standard deviation of 0.026. On the testing set, the RMSE varies from 0.293 to 0.452, with a mean of 0.337 and a standard deviation of 0.046. Furthermore, Table 7 highlights the sensitivity analysis for different input variables on the output variable (SSCM). The sensitivity analysis indicates that TM (100%) is the most critical construct to promote SSCM, followed by SP (77%), NI (74%), AUT (65%), and INF (58%). On the other hand, PE (50%), CP (28%), and SEC (22%) are the least critical constructs.

Table 6. RMSE values of neural network.

Training		Testing		Total Samples
N	**RMSE**	**N**	**RMSE**	
216	0.416	21	0.452	237
213	0.353	24	0.364	237
210	0.351	27	0.293	237
210	0.366	27	0.332	237
214	0.408	23	0.349	237
209	0.404	28	0.302	237
215	0.367	22	0.327	237
211	0.342	26	0.303	237
212	0.375	25	0.322	237
212	0.383	25	0.324	237
Mean	0.377		0.337	
S.D	0.026		0.046	

Table 7. Sensitivity analysis.

NN	CP	SP	NI	AUT	SEC	INF	TM	PE
1st	0.056	0.189	0.302	0.161	0.049	0.110	0.039	0.094
2nd	0.065	0.158	0.122	0.138	0.026	0.107	0.292	0.091
3rd	0.063	0.182	0.136	0.154	0.037	0.126	0.214	0.088
4th	0.056	0.207	0.133	0.111	0.025	0.136	0.239	0.093
5th	0.065	0.032	0.154	0.274	0.029	0.056	0.209	0.180
6th	0.035	0.131	0.270	0.058	0.064	0.185	0.162	0.095
7th	0.072	0.192	0.097	0.089	0.027	0.118	0.293	0.110
8th	0.086	0.155	0.093	0.112	0.093	0.101	0.256	0.102
9th	0.050	0.271	0.164	0.161	0.061	0.095	0.129	0.069
10th	0.049	0.116	0.079	0.116	0.051	0.179	0.275	0.134
MI	**0.060**	**0.163**	**0.155**	**0.137**	**0.046**	**0.121**	**0.211**	**0.106**
NI	**28%**	**77%**	**74%**	**65%**	**22%**	**58%**	**100%**	**50%**

Note: NN = neural network; MI = mean importance; NI = normalised importance.

6. Discussion and Conclusions

The main purpose of this research is to investigate the impact of blockchain-based security variables on sustainable supply chain management in UK manufacturing firms. Based on the RBV theory and TOE framework, the research hypotheses were developed. To achieve the research objectives, two empirical analyses were performed: PLS-SEM and ANN. The findings of PLS-SEM indicate that SP, AUT, INF, and TM have a significant association with SSCM. On the other hand, the ANN results indicate that TM, SP, NI, AUT, and INF are vital factors in promoting SSCM in UK manufacturing firms.

The research findings indicate that customer privacy has no direct relationship with SSCM. The outcomes are supported by past studies [74,75]. Although CP is a vital variable from a regulatory and ethical standpoint, it may not have direct linkages with SSCM. A possible explanation for this outcome is that manufacturing sustainability efforts within SCM promote resource efficiency, waste reduction, and the minimisation of the carbon footprint, which are unrelated to CP and data handling. Thus, H1a has been rejected. On the other hand, the study outcomes highlight that supplier privacy has a positive and significant association with SSCM. The study outcomes are supported by past studies [76,77]. Thus, H1b has been accepted.

Additionally, the empirical findings highlight that network integrity has no direct association with SSCM. The possible explanation for this outcome is that SMEs lack financial resources, which limits their investment in advanced cybersecurity measures necessary for ensuring robust network integrity. Additionally, SMEs may lack the necessary professionals, and consequently, SMEs are vulnerable to security threats. Due to financial and expertise-related constraints, network integrity has no direct association with SSCM. Therefore, H2a has been rejected. In contrast, the findings indicate that authentication (AU) has a direct and significant relationship with SSCM. Thus, H2b has been accepted.

Furthermore, the empirical findings highlight that secrecy (SEC) has no direct impact on SSCM. The possible explanation for this outcome is that SSCM initiatives emphasise transparency, ethical sourcing, and stakeholder engagement. It is argued that maintaining secrecy can hinder the transparency and collaborative efforts necessary for achieving sustainability goals. Thus, H3a has no significant association with SSCM. On the other hand, infrastructure (INF) has a positive and significant impact on SSCM. Therefore, H3b has been accepted.

Finally, the results indicate that policy enforcement (PE) has no direct association with SSCM. A possible explanation for this outcome is that SSCM requires a holistic approach involving culture, commitment, and operational changes beyond policy mandates. Mere enforcement does not foster the necessary organisational mindset and systematic changes needed for SSCM practices to thrive within SMEs. Thus, H4b has been rejected. In contrast, trust management (TM) has a positive and significant relationship with SSCM. Thus, H4a is supported and has been accepted.

7. Contributions and Implications

Based on the findings, this study makes a twofold contribution. Firstly, this research integrates the resource-based view theory (RBV) and the Technology, Organisation, and Environment (TOE) framework to study the role of blockchain-based security variables in SSCM in UK manufacturing firms. The study offers a comprehensive understanding of how these security variables influence SSCM. Lastly, the analysis using the ANN highlights that all of the blockchain-based security variables are essential to promote SSCM. Furthermore, the ANN findings indicate that blockchain-based security variables are a combination of social (people), technical, and technological factors. This highlights that the factors need attention.

Apart from its contribution, this research has threefold practical implications. Firstly, the outcomes highlight the importance of UK manufacturing firms focusing their investments on security measures, including privacy and network aspects, to strengthen their SSCM initiatives. The strategic allocation of resources in these domains can improve data protection, foster trust, and promote a more sustainable supply chain ecosystem. Secondly, managers should invest in blockchain technology for its potential to enhance sustainable supply chain management and technological functions. Recognising it as a disruptive force, they can leverage blockchain's capabilities, including transparency, privacy, and confidentiality, to improve supply chain efficiency and sustainability. Finally, for the successful implementation of SSCM, firms should adopt a holistic approach that encompasses not only policy enforcement but also trust management and robust infrastructure. Merely enforcing policing is insufficient; cultivating a culture of trust and investing in necessary technology and firm infrastructure are equally critical aspects of a comprehensive SSCM strategy. Moreover, the recognition of blockchain-based security factors can aid policymakers in formulating strategic decisions concerning supply chain management in manufacturing industries. For instance, it provides insights into which factors should be prioritised in both the short and long term to enhance sustainable supply chain management.

8. Limitations and Future Research Directions

To contextualise the results of this research, it would be advantageous to discuss the research limitations that pave the way for future research directions. First, the RBV theory has gained considerable scholarly attention in the study context. However, it is important to note that the RBV theory has been criticised for its lack of resource classification. Therefore, there is a compelling opportunity to expand the existing framework by incorporating other theories, like the sociotechnical systems theory. Second, the survey-based approach utilised in this study has inherent limitations, including the potential for common method bias (CMB), as identified by Ali and Johl [13]. However, conscientious measures were undertaken to mitigate the impact of CMB. In future research, the inclusion of multi-respondent or longitudinal studies can serve as valuable strategies to effectively address this concern and enhance the robustness of the findings. Thirdly, the dataset was gathered from manufacturing firms in the United Kingdom, raising the possibility of sampling biases. Therefore, future research should consider extending its scope to encompass various industries or countries. Fourth, the study utilised a questionnaire survey approach, which has inherent limitations. Therefore, in future research, it is advisable to adopt a mixed-method approach. Finally, the empirical findings indicate that a few variables have no significant association with SSCM. This indicates that some other variables need to be considered. Thus, future research should enhance the framework by adding mediating and moderating variables.

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