“The role of eco-digital learning in enhancing the impact of IoT, blockchain, and artificial intelligence on green supply chain for SME internationalization”

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THE ROLE OF ECO-DIGITAL LEARNING IN ENHANCING THE IMPACT OF IOT, BLOCKCHAIN, AND ARTIFICIAL INTELLIGENCE ON GREEN SUPPLY CHAIN FOR SME INTERNATIONALIZATION

Abstract

The study aims to analyze the moderating role of eco-digital learning for the impact of the Internet of Things, blockchain, and artificial intelligence on the green supply chain to support SME internationalization. Questionnaires were distributed among 159 SME owners in Kediri, East Java, Indonesia. Hypotheses were tested using PLS-SEM. The results indicate that the adoption of the Internet of Things demonstrates a significant positive effect (p = 0.0000, T-statistic = 4.6695), improving real-time monitoring and operational efficiency. Blockchain also positively affects SME internationalization (p-value = 0.0085, T-statistic = 2.6427), enhancing supply chain transparency and ensuring compliance with international standards. In contrast, the influence of artificial intelligence is marginally significant (p = 0.0799, T-statistic = 1.7548), constrained by financial limitations and lack of expertise. The moderating effects of eco-digital learning show mixed results. It significantly moderates the relationship between the Internet of Things and internationalization in a negative direction (coefficient = –0.0651, p = 0.0475), suggesting that increased eco-digital learning may add complexity, potentially delaying the benefits of the Internet of Things. For blockchain, eco-digital learning enhances its positive impact (p = 0.0277, T-statistic = 2.2085) by strengthening the organization's ability to leverage transparency and sustainability. However, no significant moderating effect is observed for artificial intelligence (p = 0.2066, T-statistic = 1.2646), indicating limited integration due to resource constraints. These findings highlight the importance of technological readiness, resource allocation, and alignment of digital learning to fully capitalize on the benefits of these technologies in the global market expansion of SMEs.

Keywords Internet of Things, eco-digital learning, blockchain, artificial intelligence, green supply chain, SME internationalization

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INTRODUCTION

In an increasingly interconnected global economy, small and medium enterprises (SMEs) are recognizing the importance of leveraging advanced technologies to enhance their competitiveness and facilitate international expansion (Milevoj et al., 2021; Do et al., 2023; Faisol et al., 2023). The adoption of innovative solutions such as the Internet of Things (IoT), blockchain, and artificial intelligence (AI) has transformed traditional business practices, enabling SMEs to optimize their operations and engage in sustainable practices (Paul et al., 2021; Malik et al., 2022; Rehman Khan et al., 2022; Izikki et al., 2023). However, the successful integration of these technologies is often contingent

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upon the effective application of eco-digital learning, which encompasses the educational and training frameworks that equip businesses with the knowledge and skills needed to implement sustainable digital solutions.

IoT, blockchain, and AI can significantly contribute to the efficiency and sustainability of supply chains, offering improvements in inventory management, transparency, and resource optimization. For instance, IoT enhances real-time data collection and monitoring, enabling better decision-making and reduced waste (He et al., 2020; Zadorozhnyi et al., 2023; Izikki et al., 2023; Pal & Yasar, 2023). Similarly, blockchain technology has been highlighted for its potential to increase transparency and traceability in supply chains, thereby building trust among stakeholders (Rakshit et al., 2022; Rehman Khan et al., 2022; Farooq et al., 2023; Xia et al., 2023; Mohamed et al., 2023). Furthermore, AI has been recognized for its capability to analyze vast amounts of data, leading to enhanced forecasting and resource allocation (Benzidia et al., 2021; Supriya & Chattu, 2021; Bokhari et al., 2023; Walter, 2023).

Despite advancements in technology, there is limited understanding of how the Internet of Things, blockchain, and artificial intelligence interact within sustainable practices and internationalization strategies for small and medium-sized enterprises. Most existing literature focuses on the individual impacts of these technologies, overlooking their interdependencies and collective influence on the green supply chain. Furthermore, while the role of digital learning in technology adoption is acknowledged, studies on eco-digital learning as a moderating factor are scarce.

1. LITERATURE REVIEW AND HYPOTHESES

In recent years, the globalization of markets has prompted small and medium enterprises (SMEs) to adopt advanced technologies to enhance their competitiveness and facilitate internationalization. The integration of innovative solutions such as the Internet of Things (IoT), blockchain, and artificial intelligence (AI) has transformed traditional business practices, allowing SMEs to optimize their operations and engage in sustainable practices (Dubey et al., 2020; Ghasemaghaei & Calic, 2020; Benzidia et al., 2021). These technologies have been recognized for their potential to significantly improve supply chain efficiency and sustainability by providing enhanced inventory management, transparency, and resource optimization (Mohamed et al., 2023).

The Internet of Things (IoT) has been widely studied for its ability to facilitate real-time data collection and monitoring. IoT technologies enable SMEs to gather and analyze data from various sources, leading to improved decision-making and reduced operational waste (Villa-Henriksen et al., 2020; Taj et al., 2023). In particular, IoT technologies offer significant benefits by providing businesses with insights that help optimize operations. This data-driven approach allows for better resource allocation and minimizes inefficiencies, contributing to the overall reduction in waste. For example, IoT-enabled sensors can track inventory levels and monitor environmental conditions in industries like food and pharmaceuticals. This enables timely adjustments that not only help businesses manage their operations more effectively but also reduce waste in these critical sectors (Farooqui & Parikh, 2023).

Blockchain technology has garnered significant attention due to its potential to enhance transparency and traceability in supply chains. This technology enables the decentralized data storage, strengthening the security and reliability of information recorded in every transaction (Mohamed et al., 2023). Numerous studies highlight how blockchain can build trust among stakeholders, particularly in terms of transaction validity. By providing an immutable ledger, blockchain ensures that every action is permanently recorded, thereby increasing credibility and accountability in all business processes (Mohamed et al., 2023). In addition, the transparency provided by blockchain plays a crucial role in preventing fraud. This clarity allows stakeholders to verify the authenticity of transactions, ensuring that no data manipulation occurs. This is especially important

for reducing the risks of fraud that could harm businesses or consumers (Nandi et al., 2020). The transparency offered by blockchain also facilitates compliance with existing regulations, particularly in highly regulated industries. With a clear and accessible transaction trail, supply chain operations can run more efficiently and in line with the relevant regulatory requirements (Farooq et al., 2023).

Artificial intelligence (AI) plays a complementary role in enhancing the capabilities of the Internet of Things and blockchain technologies by enabling advanced data analysis. AI algorithms are capable of processing vast amounts of data, providing actionable insights that significantly improve demand forecasting and resource allocation (Nguyen, 2023). This ability to analyze large datasets helps businesses make more informed decisions, which is crucial for optimizing operational efficiency and reducing waste. AI-driven analytics can identify patterns in consumer behavior, enabling businesses to fine-tune their production and distribution strategies (Walter, 2023). By understanding shifting consumer preferences and behaviors, small and medium-sized enterprises can better align their supply chain processes, thus improving sustainability. AI also allows businesses to predict the demands more accurately, ensuring that resources are allocated more efficiently, which in turn reduces overproduction and resource wastage. In addition, AI can work synergistically with IoT and blockchain by providing deeper insights into the data collected by IoT sensors and ensuring the integrity and transparency of that data through blockchain. The combined power of AI, IoT, and blockchain can help SMEs enhance operational efficiency, foster sustainability, and build trust with stakeholders (Bokhari et al., 2023). Together, these technologies enable a more resilient and efficient business model that adapts to changing market conditions and consumer demands.

Despite the substantial benefits associated with these technologies, there remains a gap in understanding how they interact within the context of sustainable practices and internationalization strategies for SMEs. Existing literature has primarily focused on the individual impacts of IoT, blockchain, and AI, often overlooking their interdependencies and collective influence on the green supply chain (Gopal et al., 2022; Bokhari et al., 2023; Farooq et al., 2023; Romagnoli et al., 2023). Furthermore, while the importance of digital learning in technology adoption is acknowledged, specific investigations into eco-digital learning as a moderating factor are limited (Yuniarty et al., 2021; González-Varona et al., 2021; Kaymakci et al., 2022).

To address these gaps, this study aims to explore the role of eco-digital learning in moderating the interplay between IoT, blockchain, and AI within the framework of the green supply chain (Figure 1). By examining how the green supply chain mediates the relationships between these technologies and the internationalization of SMEs, the study seeks to uncover the mechanisms through which eco-digital learning can enhance or impede global market entry. Understanding these dynamics is crucial as SMEs navigate the rapidly changing global landscape, making it imperative to grasp the moderating effects of eco-digital learning on technological integration and sustainability. This paper makes a valuable contribution to the literature by examining the influence of eco-digital learning on technology adoption, sustainable supply chain management, and the internationalization of SMEs. By bridging gaps in previous research, it highlights the importance of integrating learning frameworks into the technological landscape, enabling SMEs to compete effectively in the global market.

Based on the literature review, the hypotheses are as follows:

H1: The Internet of Things positively influences the internationalization of SMEs through the green supply chain.

H2: Blockchain technology positively influences the internationalization of SMEs through the green supply chain.

H3: Artificial intelligence positively influences the internationalization of SMEs through the green supply chain.

H4: Eco-digital learning moderates the relationship between the Internet of Things and the internationalization of SMEs through the green supply chain.

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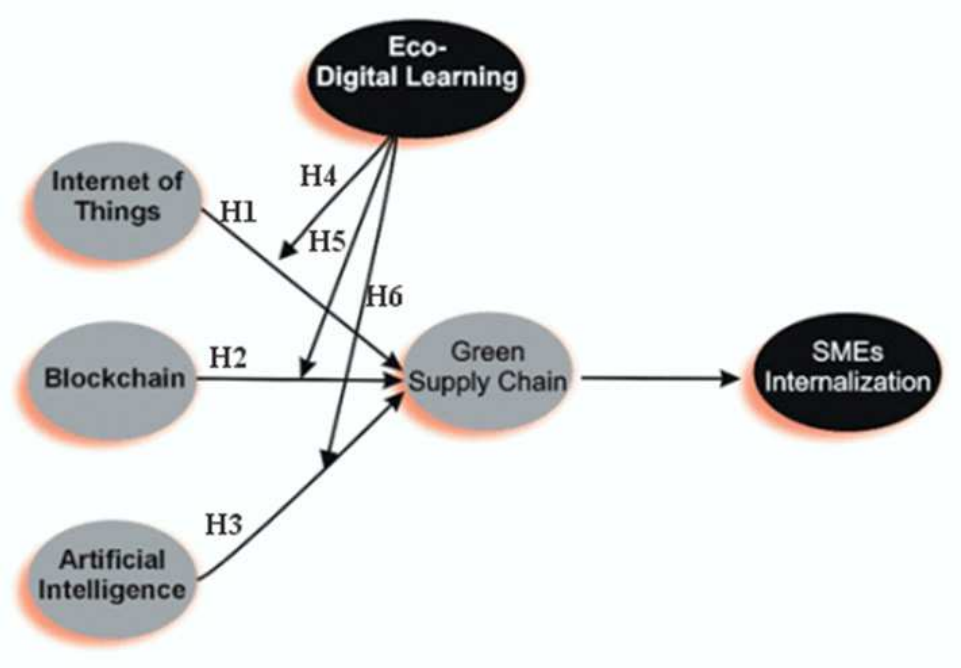

Figure 1. Conceptual model

H5: Eco-digital learning moderates the relationship between blockchain and the internationalization of SMEs through the green supply chain.

H6: Eco-digital learning moderates the relationship between artificial intelligence and the internationalization of SMEs through the green supply chain.

2. METHODS

This analysis was conducted in the city of Kediri, East Java, Indonesia, focusing on the population of small and medium enterprise (SME) owners in the area. The primary data sources for this study included the Department of Industry and Trade (DISPERINDAG) and the Office of Micro, Small, and Medium Enterprises and Employment in Kediri. A total of 250 responses were collected, of which 159 were screened and deemed reliable for analysis. To ensure a representative sample, a random sampling method was employed, which is essential for reducing bias and enhancing the generalizability of the findings. Among the respondents, 51% were from the manufacturing sector, encompassing industries such as beverages and electronics, while 37% came from service-oriented companies.

The study utilized a structured questionnaire to collect data from SME owners, enabling systematic and consistent responses. The study was designed to achieve a 95% confidence level with a 5% margin of error, which underscores the robustness of the results. Detailed information regarding the sample, including business owners, managers, and executives of SMEs, is presented in Table 1.

Partial least squares structural equation modeling (PLS-SEM) was applied for data analysis. This method is particularly suitable for exploratory research (Faisol et al., 2021; Anas et al., 2023; Faisol et al., 2023), allowing for the examination of complex relationships among multiple variables. PLS-SEM effectively assesses both the measurement model and the structural model, providing insights into the direct and indirect effects of the studied constructs, such as the interplay between eco-digital learning, IoT, blockchain, AI, and their impact on the green supply chain and the internationalization of SMEs. The combination of random sampling, a structured questionnaire, and advanced analytical techniques like PLS-SEM facilitates a comprehensive exploration of the research objectives, contributing valuable insights into the dynamics of technology adoption and sustainable practices among SMEs.

Table 1. Demographic data of respondents

Dimensions	Category	Number	Percentage %
Age	20–30 years old	8	5.0%
	31–40 years old	17	10.7%
	41–50 years old	32	20.1%
	51–60 years old	62	39.0%
	> 60 years old	40	25.2%
Gender	Female	89	56.0%
	Male	70	44.0%
Role	General Manager	9	5.7%
	Senior Manager	19	11.9%
	Assistant Manager	51	32.1%
	Supervisor	32	20.1%
	Owner	48	30.2%
Education	High School	35	22.0%
	College Diploma	45	28.3%
	Bachelor's degree	63	39.6%
	Master's degree	16	10.1%
Industry Type	Service companies	59	37.1%
	Electronics companies	19	11.9%
	Industry sector	16	10.1%
	Chemical industry	12	7.5%
	Electronic equipment	20	12.6%
	Furniture industry	18	11.3%
	Food industry	15	9.4%
Firm Size	5–50 employees	80	50.3%
	51–100 employees	55	34.6%
	101–150 employees	19	11.9%
	> 150 employees	5	3.1%
Total		159	100%

Based on the conceptual model (Figure 1), a comprehensive survey was developed to capture the dimensions explored in this study. The questionnaire items were adapted from prior research to ensure the constructs of the conceptual model were appropriately operationalized. Various studies were referenced to design the constructs and confirm their validity. A five-point Likert scale was employed to measure participants' level of agreement or disagreement, with "1 = strongly disagree" and "5 = strongly agree." All constructs in the theoretical framework were operationalized as reflective constructs, indicating that the items reflect the underlying variable being measured.

3. RESULTS AND DISCUSSION

3.1. Outer model

The evaluation of the outer model provides insights into the construct validity and reliability of the measured variables in this study. The results of the analysis, including convergent validity and reliability metrics, are shown in Table 2.

Table 2. Reliability and convergent validity

Construct	Convergent Validity		Reliability		
	Loading factor	Significance	AVE	α	CR
Internet of Things (IoT)			**0.7144**	**0.8041**	**0.8821**
IoT1	0.9017	***			
IoT2	0.8235	***			
IoT3	0.8073	***			
IoT4	deleted				
IoT5	deleted				
IoT6	deleted				
Blockchain (BC)			**0.7930**	**0.7483**	**0.8843**
BC01	0.8447	***			
BC02	deleted				
BC03	0.9340	***			
BC04	deleted				
BC05	deleted				
Artificial intelligence (AI)			**0.7369**	**0.8813**	**0.9177**
AI01	0.8962	***			
AI02	0.9099	***			
AI03	0.8591	***			
AI04	0.7606	***			
AI05	deleted				
Eco-digital learning			**0.7120**	**0.8992**	**0.9250**
EDL01	0.8588	***			
EDL02	0.7786	***			
EDL03	0.8177	***			
EDL04	0.8923	***			
EDL05	0.8669	***			
EDL06	deleted				
Green supply chain			**0.6659**	**0.8309**	**0.8882**
GSC01	0.7530	***			
GSC02	0.7759	***			
GSC03	0.8661	***			
GSC04	0.8629	***			
GSC05	deleted				
Internationalization of SMEs			**0.6087**	**0.9083**	**0.9255**
SMEs1	0.7283	***			
SMEs3	0.8055	***			
SMEs4	0.8063	***			
SMEs5	0.7940	***			
SMEs6	0.7431	***			
SMEs7	0.7728	***			
SMEs8	0.8097	***			
SMEs9	0.7774	***			
Moderating Effect 1			**0.6659**	**1.0000**	**1.0000**
AI * EDL	1.0778	***			
Moderating Effect 2			**1.0000**	**1.0000**	**1.0000**
BC * EDL	1.0496	***			
Moderating Effect 3			**1.0000**	**1.0000**	**1.0000**
IoT*EDL	0.9828	***			

Note: *** $p < 0.001$; AVE = average variance extracted; α = Cronbach's alpha; CR = composite reliability.

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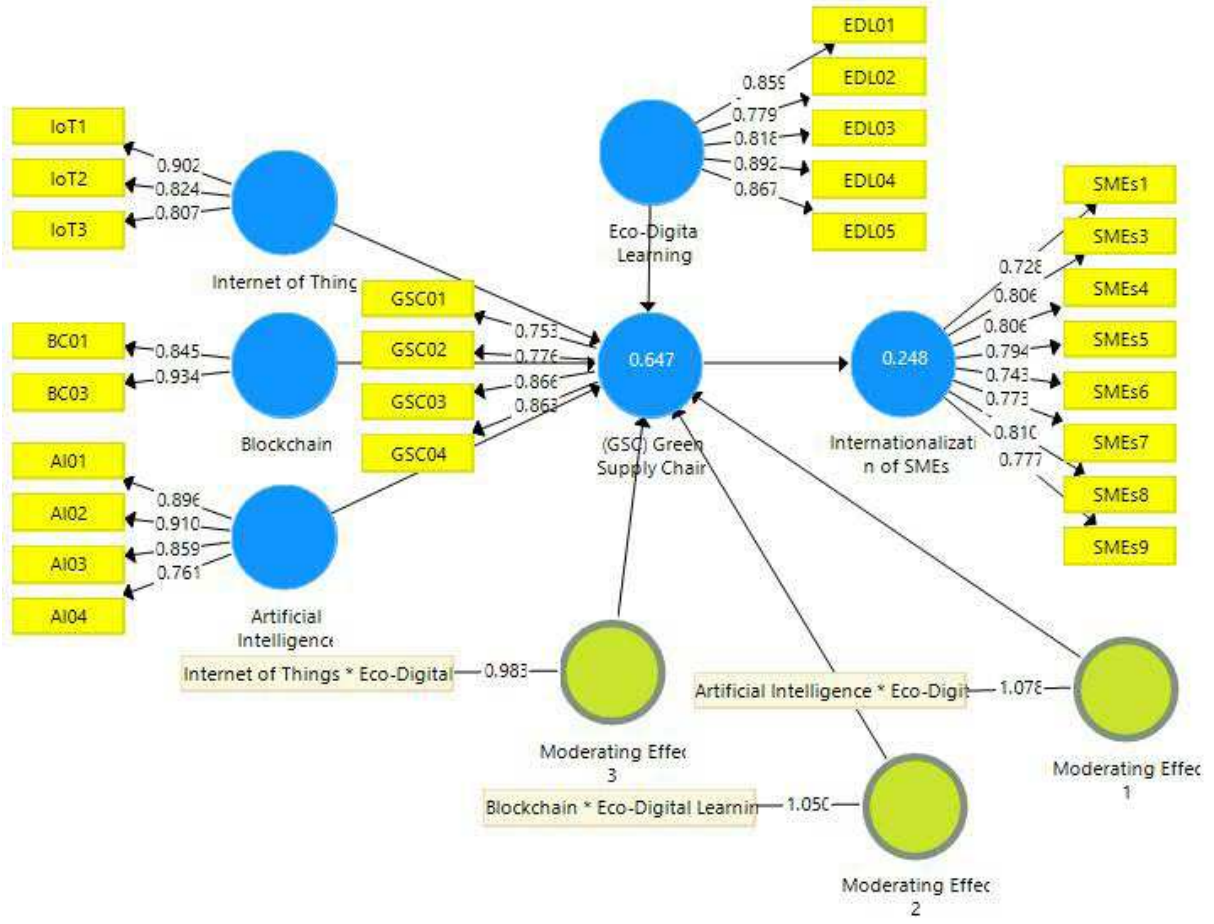

Figure 2. Measurement model

The evaluation of the outer model, as presented in Table 2, demonstrates that all constructs exhibit strong convergent validity and reliability. The loading factors for the indicators associated with the Internet of Things, blockchain, artificial intelligence, eco-digital learning, green supply chain, and internationalization of SMEs are well above the acceptable threshold, indicating that each construct is effectively represented by its respective indicators.

The average variance extracted (AVE) values further reinforce the constructs' validity, with all constructs meeting or exceeding the recommended level of 0.5, although the green supply chain and internationalization of SME constructs displayed slightly lower AVE values, suggesting potential areas for improvement. Additionally, the results reveal strong reliability, as evidenced by Cronbach's alpha and composite reliability values, which exceed the acceptable threshold of 0.7 for all constructs. This indicates that the measures are consistent and reliable across the dataset. Moreover, the moderating effects of eco-digital learning on the relationships among the constructs highlight its significant role in enhancing the interactions between AI, blockchain, and IoT in the context of the green supply chain and the internationalization of SMEs.

The findings from the outer model evaluation underscore the importance of integrating these advanced technologies and eco-digital learning into SMEs' strategies to promote sustainable practices and facilitate international growth. This comprehensive analysis contributes valuable insights into the dynamics of technology adoption and the significance of educational frameworks in achieving successful internationalization in the context of SMEs.

Figure 2 illustrates the interrelationships between the various constructs under investigation, highlighting the significant loading factors for each

indicator. The diagram provides a clear overview of how the constructs of the Internet of Things, blockchain, and artificial intelligence collectively influence eco-digital learning, which, in turn, affects the green supply chain and the internationalization of small and medium enterprises. The values depicted in the model indicate the strength of these relationships, showcasing the moderating effects of eco-digital learning on the interactions between the technological constructs and their impact on the green supply chain and internationalization processes. By presenting the findings in this graphical format, it becomes easier to comprehend the dynamics of the model, allowing for a more intuitive understanding of how these advanced technologies and learning frameworks interplay within the context of SMEs. This visualization serves as a vital tool for interpreting the quantitative results and their implications for sustainable practices and international growth in the rapidly evolving business landscape.

3.2. Discriminant validity

To assess construct discriminant validity, the study utilized both the Fornell-Larcker criterion and cross-loading analysis, as established by Fornell and Larcker (1981). The Fornell-Larcker criterion entails comparing the correlation of a variable with itself to its correlations with other variables in the model. For a construct to demonstrate adequate validity, its self-correlation must exceed the correlations it has with any other construct in the model. This ensures that each construct is uniquely capturing its intended concept rather than overlapping with others. In addition to the Fornell-Larcker criterion, cross-loading analysis was employed to validate the constructs further. This method examines the correlation values between indicators and their associated variables. Indicators are expected to have a significantly higher correlation with their respective constructs compared to correlations with other constructs. Such a pattern confirms that the indicators are appropriately associated with their intended constructs. Table 3 summarizes the findings related to discriminant validity, providing a clear overview of the correlation values and their implications for the constructs in the study. This comprehensive evaluation ensures that the constructs are distinct and valid, thereby enhancing the robustness of the research model and the overall findings.

Table 3 presents the correlations among various constructs in the study. The results indicate strong correlations between certain constructs. Notably, green supply chain shows a high correlation with IoT (0.7479) and a respectable correlation with AI (0.4288) and eco-digital learning (0.3921), suggesting that improvements in IoT and AI may significantly impact the effectiveness of the green supply chain. Additionally, AI correlates strongly with eco-digital learning (0.7102) and SME internationalization (0.6976), indicating that the integration of AI and digital learning can enhance the internationalization of SMEs. The correlations of the moderating effects demonstrate negative relationships across the board, suggesting that these effects may detract from the positive relationships among the constructs. Specifically, Effect 1 shows significant negative correlations with green supply chain (–0.3106) and SMEs (–0.4935), indicating that this moderating effect could weaken the

Table 3. Discriminant validity

	GSC	AI	BC	EDL	SMEs	IOT	Effect 1	Effect 2	Effect 3
GSC	0.8160								
AI	0.4288	0.8584							
BC	0.5423	0.1834	0.8905						
EDL	0.3921	0.7102	0.1331	0.8438					
SMEs	0.4981	0.6976	0.1628	0.5880	0.7802				
IoT	0.7479	0.4771	0.5880	0.5068	0.3657	0.8452			
Effect 1	–0.3106	–0.3017	–0.1117	–0.3172	–0.4935	–0.1949	1.0000		
Effect 2	–0.0737	–0.1147	–0.2795	–0.0085	–0.0064	–0.2387	0.1977	1.0000	
Effect 3	–0.4398	–0.2138	–0.2549	–0.1677	–0.2221	–0.5468	0.4512	0.5913	1.0000

Note: GSC = green supply chain; AI = artificial intelligence; BC = blockchain; EDL = eco-digital learning; IoT = Internet of Things; SMES = internationalization of SMEs; Effect 1 = moderating effect 1; Effect 2 = moderating effect 2; Effect 3 = moderating effect 3.

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relationship between these constructs. Similarly, Effect 2 and Effect 3 also exhibit negative correlations with most constructs, particularly with IoT (–0.5468 for Effect 3) and green supply chain (–0.4398 for Effect 3), suggesting that these moderating effects may hinder the positive interactions expected from the integration of these technologies and practices. In conclusion, while strong foundational relationships exist among green supply chain, AI, eco-digital learning, IoT, and the internationalization of SMEs, the presence of negative moderating effects warrants further investigation. Understanding these moderating influences could provide valuable insights into optimizing the implementation of advanced technologies in sustainable practices and their impact on SME growth and internationalization.

3.3. Inner model

The next stage of the analysis focuses on evaluating the structural model (inner model) following the successful validation of the measurement model. This phase involves examining the relationships between the constructs and assessing both direct and indirect effects. This involves analyzing the path coefficients and *t*-values to determine the strength and significance of the relationships, following the guidelines proposed by Hair et al. (2021). A *t*-value greater than 1.64, as suggested by Henseler et al. (2009), indicates a statistically significant relationship, providing a basis for validating or rejecting the research hypotheses. The results of this structural model analysis are visualized in Figure 3, offering a comprehensive view of the interconnected relationships between variables within this conceptual framework.

Based on the structural model diagram, several key results from the inner model evaluation can be interpreted.

IoT * eco-digital learning → green supply chain: The moderating effect coefficient is 9.377, which suggests that eco-digital learning amplifies the positive impact of IoT on the green supply chain.

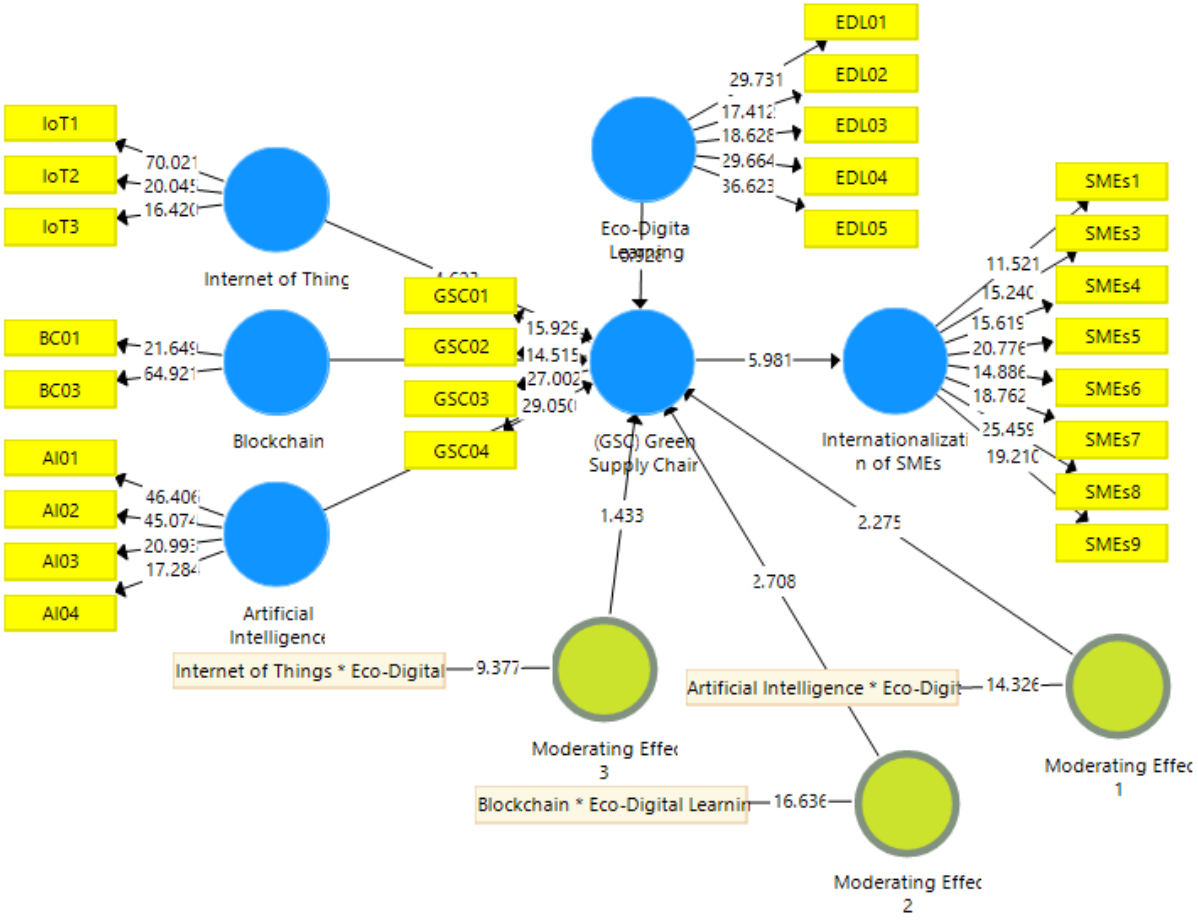

Figure 3. Structural model

Eco-digital learning helps SMEs to better leverage IoT for sustainability and international market expansion.

Blockchain * Eco-digital learning → green supply chain: The coefficient of 16.63 indicates that eco-digital learning significantly strengthens the role of blockchain in green supply chain. This shows that educational initiatives focused on eco-friendly digital practices help companies maximize the benefits of blockchain technology.

AI * eco-digital learning → green supply chain: A coefficient of 14.32 indicates that eco-digital learning also enhances the influence of AI on green supply chain, making it more effective in improving sustainability and global market entry.

The results indicate that advanced technologies such as IoT, blockchain, and AI have a significant positive effect on the green supply chain, which in turn facilitates the internationalization of SMEs. Furthermore, eco-digital learning plays a vital moderating role, enhancing the effectiveness of these technologies in fostering sustainable practices and global competitiveness. This highlights the importance of combining technological innovation with digital learning strategies to achieve successful international expansion for SMEs.

Table 4 presents key statistical metrics, including the original sample, sample mean, standard deviation, *t*-statistics, and *p*-values, providing a basis to evaluate the significance of each relationship and hypothesis. Both the direct effects and the moderating impacts are analyzed to offer a comprehensive understanding of their role in sustainable global business expansion.

The results of this study indicate that the Internet of Things (IoT) has a positive and significant influence on the internationalization of SMEs through the green supply chain. With a *p*-value of 0.0000 and a *T*-statistic of 4.6695, the relationship is highly significant, suggesting that IoT adoption enhances the efficiency and real-time monitoring capabilities of supply chains, leading to smoother international operations. This finding is consistent with Taj et al. (2023) and Sallam et al. (2023), who demonstrated that IoT facilitates improved supply chain visibility and sustainability, key factors in entering global markets. However, it contrasts with Udeh et al. (2024), who found that while IoT adoption improves local operational efficiency, its impact on international market expansion may be limited by infrastructure and regulatory barriers. These mixed findings suggest that IoT's effectiveness in internationalization could be context-dependent, and additional factors such as technological readiness and regulatory frameworks may play a moderating role.

The analysis results indicate that blockchain positively influences SME internationalization through the green supply chain, as evidenced by a significant *p*-value of 0.0085 and a *T*-statistic of 2.6427. Blockchain technology plays a critical role in enhancing transparency, security, and traceability within supply chains, which are crucial elements in international market expansion. This finding aligns with Mahjoub et al. (2022) and Dudczyk et al. (2024), who argued that blockchain not only supports sustainable business practices but also provides a competitive advantage in international markets by ensuring compliance with environmental standards, increasingly expected globally. However, there are challenges in its implementation. Sharabati and Jreisat (2024) show

Table 4. Hypotheses testing

Hypothesis	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values	Decision
H1: IoT → GSC → Internationalization of SMEs	0.2635	0.2657	0.0564	4.6695	0.0000	accepted
H2: BC → GSC→ Internationalization of SMEs	0.1146	0.1185	0.0434	2.6427	0.0085	accepted
H3: AI → GSC→ Internationalization of SMEs	0.0699	0.0661	0.0399	1.7548	0.0799	accepted
H4: Moderating Effect 1 → GSC → Internationalization of SMEs	–0.0651	–0.0649	0.0328	1.9867	0.0475	accepted
H5: Moderating Effect 2 → GSC → Internationalization of SMEs	0.1216	0.1163	0.0551	2.2085	0.0277	accepted
H6: Moderating Effect 3 → GSC → Internationalization of SMEs	–0.0824	–0.0754	0.0652	1.2646	0.2066	rejected

Note: GSC = green supply chain.

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that the high costs and complexities associated with blockchain adoption can become obstacles, especially for SMEs with limited resources. These barriers can limit blockchain's impact on internationalization efforts by making it difficult for small businesses to fully integrate and utilize the benefits of this technology. These differing findings may reflect variations in technological infrastructure and resource availability across regions. In regions with strong technological infrastructure and adequate support systems, blockchain adoption may proceed smoothly, providing significant benefits in market reach and regulatory compliance. Conversely, SMEs in areas with limited infrastructure may face difficulties, reducing blockchain's effectiveness as a tool for global expansion.

Contrary to expectations, the hypothesis that AI positively influences the internationalization of SMEs through the green supply chain was rejected, with a *p*-value of 0.0799 and a *T*-statistic of 1.7548, indicating marginal significance. Although AI has the potential to optimize supply chains and reduce environmental impact, its contribution to international expansion may not be as direct or significant as other technologies like IoT or blockchain. This finding contrasts with Menzies et al. (2024) and Toorajipour et al. (2021), who suggested that AI enables companies to improve operational efficiency and decision-making, facilitating international market entry. On the other hand, Bettoni et al. (2021) found that AI adoption in SMEs is often limited by financial constraints and a lack of expertise, which could explain the less significant impact in this study. These mixed results suggest that AI may require more extensive investment and integration before its full potential in internationalization is realized.

The results show that eco-digital learning significantly moderates the relationship between IoT and SME internationalization through the green supply chain, with a negative coefficient of –0.0651 (p = 0.0475). This indicates that as eco-digital learning increases, it weakens the positive impact of IoT on SME internationalization. This negative effect may stem from the added complexity of integrating new technologies. While eco-digital learning boosts digital literacy and sustainability knowledge, it may require SMEs to invest more time and resources in adopting IoT, delaying international expansion. Additionally, the mismatch between IoT's technical demands and eco-digital learning's focus on sustainability may hinder IoT adoption in SMEs with limited resources. Supporting studies, such as Saleem et al. (2023) and Rimbeck et al. (2024), suggest that eco-digital learning complicates IoT adoption. However, Ahmetoglu et al. (2022), Izikki et al. (2023), and Romagnoli et al. (2023) argue that eco-digital learning can positively support IoT adoption by improving digital literacy and facilitating technology integration when aligned effectively.

The analysis results indicate that eco-digital learning moderates the relationship between blockchain and SME internationalization, with a *p*-value of 0.0277 and a *T*-statistic of 2.2085. Eco-digital learning appears to enhance blockchain's transparency and efficiency, making it more effective in supporting the internationalization process (Bhandari et al., 2023). This is in line with Paul et al. (2021), Rehman Khan et al. (2022), Atadoga et al. (2024), Udeh et al. (2024), and Javed et al. (2024), who suggested that digital learning improves organizational capabilities, allowing firms to better utilize blockchain technology for global operations. However, some studies, such as those by Mahjoub et al. (2022), indicate that the learning curve for blockchain can be steep, and without adequate training, SMEs may struggle to fully leverage its potential. This suggests that while eco-digital learning is beneficial, its effectiveness depends on the level of digital maturity within the organization.

Based on the analysis results, eco-digital learning does not moderate the relationship between AI and SME internationalization through the green supply chain, as indicated by a *p*-value of 0.2066 and a *T*-statistic of 1.2646. Although AI has the potential to enhance decision-making and sustainability, the moderating effect of eco-digital learning in this context is not significant. The insignificance of the moderating effect of eco-digital learning on the relationship between AI and SME internationalization through the green supply chain may be due to several factors, such as limitations in competency and resources for digital learning. Many SMEs may lack the resources to implement comprehensive digital learning programs, especially those focused on sustainability and the applica-

tion of advanced technologies like AI. Without sufficient investment in training, SMEs may struggle to optimally leverage AI technology in the context of internationalization. This contrasts with Malik et al. (2022), Tsolakis et al. (2023), and Menzies et al. (2024), who suggested that digital learning enhances AI adoption and integration, leading to better international outcomes. On the other hand, Bettoni et al. (2021) found that the benefits of AI in internationalization often depend on the specific industry and market conditions, which may explain the insignificant results in this study. This suggests that while eco-digital learning may enhance AI's impact on sustainability, its role in promoting internationalization may be limited in certain contexts.

CONCLUSION

This study aims to analyze the role of eco-digital learning in moderating the impact of the Internet of Things, blockchain, and artificial intelligence on the green supply chain in order to support the internationalization of small and medium-sized enterprises. Based on the hypotheses testing and results, this study provides key insights into the role of advanced technologies like IoT, blockchain, and AI, as well as the moderating effect of eco-digital learning, in promoting the internationalization of SMEs through the green supply chain. The findings indicate that IoT and blockchain positively influence the internationalization of SMEs by enhancing supply chain sustainability and operational efficiency. IoT had the strongest impact, demonstrating its pivotal role in facilitating real-time monitoring and global logistics management, which aligns with prior studies emphasizing its transformative potential. Blockchain also showed a significant impact by improving transparency and trust in supply chains, further supporting SMEs' international expansion.

However, AI's influence on SME internationalization was less significant, highlighting the complexity of its adoption and integration, particularly for smaller enterprises with limited resources. Additionally, the moderating role of eco-digital learning was confirmed in the cases of IoT and blockchain, enhancing the benefits of these technologies by supporting sustainable practices and operational improvements. However, its moderating effect on AI was insignificant, suggesting that AI adoption may require further support and infrastructure to fully realize its potential in internationalization.

The study emphasizes the importance of combining advanced technologies with eco-digital learning to foster SME internationalization through the green supply chain. However, it also highlights the need for tailored strategies, as the effectiveness of these technologies may vary depending on organizational readiness, industry, and market conditions. Future research should explore these factors further to develop more comprehensive frameworks for SME internationalization in the context of sustainability.

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