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The Mediating Role of Green Innovation in the Relationship Between Artificial Intelligence, Blockchain Technology, and Supply Chain Sustainability: Evidence from Egypt's Manufacturing Industry

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Abstract

In recent years, there has been a growing interest among scholars and industry professionals in the potential applications of artificial intelligence (AI) and blockchain technology (BT). Despite this attention, limited empirical research has explored the combined impact of these technologies on enhancing supply chain sustainability (SCS). This study aims to fill this gap by examining the influence of AI and BT on promoting sustainable practices within supply chains, particularly in the context of the Egyptian manufacturing sector. Employing a quantitative research approach, data were collected through structured surveys from a sample of 266 managers working in export-oriented industrial firms. The results demonstrate that both AI and BT significantly contribute to improving the sustainability of supply chains. Furthermore, the study highlights the important mediating role of green innovation in strengthening the relationship between these emerging technologies and sustainable supply chain outcomes. These findings provide valuable insights for decision-makers and practitioners striving to integrate advanced technologies and green practices to ensure long-term supply chain resilience and environmental responsibility in an evolving digital landscape.

Keywords: Artificial intelligence; blockchain technology;green innovation;supply chains sustainability.

1. Introduction

Supply chains today face various uncertainties and unexpected disruptions that can negatively affect their efficiency and resilience. In emerging markets, businesses have consistently sought to enhance their competitive edge by promoting supply chain sustainability through initiatives such as developing advanced information systems, creating flexible networks, and integrating cutting-edge technologies (Kouhizadeh *et al.,* 2021). Complex supply chains, which rely on interconnected networks of multiple companies for sourcing raw materials and distributing finished goods, have been especially vulnerable. Traditionally, organizations focused on investigating the root causes of disruptions to minimize associated risks (Dolgui and Ivanov, 2022; Snyder *et al.,* 2016). While strategies like just-in-time and lean management were previously employed to reduce vulnerabilities, they often left supply chains susceptible to adverse events (Buer et al., 2018). Nowadays, companies are adopting sophisticated information systems within their supply chains to boost transparency, enhance predictive capabilities, increase efficiency, and accelerate decision-making processes (Saberi *et al.,* 2019). These advanced systems include technologies such as artificial intelligence (AI), blockchain, machine learning, robotics (Sheu and Choi, 2022), and big data analytics (Choi *et al.,* 2020). AI, in particular, has opened up numerous possibilities in supply chain management by providing valuable benefits in overseeing procurement, logistics, manufacturing, and waste handling operations. When combined with AI, blockchain technology can be integrated with enterprise resource planning (ERP) systems to support better decision-making and facilitate the proactive development of sustainable policies. Key technologies like big data, AI, smart sensors, and blockchain applications act as vital internal assets that shape a company's capabilities and competencies (Saberi *et al.,* 2019). Specifically, blockchain technology offers a decentralized ledger system that records transactions as immutable blocks across a network of computers. Given this, it is important to examine how AI influences blockchain applications, especially concerning their roles in fostering green innovation and promoting sustainability within supply chains (Goyat *et al.,* 2020).

Green innovation involves adopting new methods in manufacturing, operations, or management aimed at reducing environmental risks, lowering pollution, and minimizing the negative impact on resources such as energy consumption. Additionally, green innovation acts as a strategic approach for implementing a product, a significantly improved or novel process, a new marketing strategy, or an innovative organizational method (Chen and Panichakarn, 2024). A sustainable supply chain integrates ethical and environmentally responsible practices into a competitive and efficient framework. Achieving full transparency across the supply chain is essential. Sustainability efforts need to cover areas such as raw material sourcing, last-mile delivery, and the management of product returns and recycling. Sustainable supply chains strive to balance operational effectiveness with long-term success and profitability. In essence, supply chain sustainability embeds ethical and ecological responsibility within a competitive and efficient system (Qiu *et al.,* 2020).

Artificial intelligence enables the swift gathering and analysis of data, while blockchain technology ensures transparency, security, and privacy among all participants (Min, 2019). Currently, supply chains leverage AI and blockchain-based platforms to improve their information processing capabilities (Li and Chan 2019; Cai *et al.,* 2021; Modgil *et al.,* 2022). This study emphasizes the enabling role that AI and blockchain technologies play in advancing green innovation and promoting sustainable supply chains. Nevertheless, existing research has yet to clearly define how AI and blockchain specifically contribute to the sustainability of supply chains.

2. Research Problem

The increasing complexity, globalization, and environmental demands on supply chains have elevated the importance of sustainability as a strategic objective for firms, especially in developing economies such as Egypt. Supply chains today face multifaceted disruptions including environmental risks, resource scarcity, and market volatility which challenge their ability to operate efficiently and responsibly (Dolgui & Ivanov, 2022). In response, companies are progressively turning to emerging digital technologies, notably Artificial Intelligence (AI) and Blockchain Technology (BT), to enhance operational visibility, transparency, traceability, and data-driven decision-making (Saberi *et al.,* 2019; Min, 2019).

While there is growing literature on the individual benefits of AI and BT in supply chain management, limited empirical evidence exists regarding their combined effect on supply chain sustainability (SCS). Most current studies examine these technologies in isolation, failing to capture their synergistic potential in driving sustainable development goals (Cai, *et al.,* 2021; Dutta *et al.,* 2020). Furthermore, the mechanism by which these technologies influence sustainability specifically through the lens of green innovation (GI) remains underexplored (Asadi *et al.,* 2020; Martínez-Falcó *et al.,* 2024). Green innovation represents an organization's commitment to reducing environmental harm through eco-friendly practices, sustainable product design, and efficient resource utilization.

In the Egyptian context, the government’s Vision 2030 emphasizes the integration of sustainability into industrial and economic development. However, a significant research gap persists regarding how Egyptian industrial firms can leverage AI and BT supported by green innovation to enhance the sustainability of their supply chains (Ali *et al.,* 2021). Without a clear understanding of these interactions, firms may miss critical opportunities to implement technology-driven solutions that align with environmental regulations and global competitive pressures.

Therefore, this research seeks to fill this gap by investigating the direct effects of AI and BT on supply chain sustainability, as well as the mediating and moderating role of green innovation in this relationship. This holistic approach is vital for providing practical insights that guide technology investments, policy-making, and organizational strategies in pursuit of sustainable industrial development in Egypt. this study seeks to answer the following questions:

1. To what extent does Artificial Intelligence (AI) influence the sustainability of supply chains in Egyptian industrial firms?
2. What is the impact of Blockchain Technology (BT) on supply chain sustainability within the same context?
3. How does Artificial Intelligence contribute to the development and application of Blockchain Technology in supply chain operations?
4. Does Green Innovation (GI) strengthen the relationship between Artificial Intelligence and supply chain sustainability?

5. Does Green Innovation also enhance the impact of Blockchain Technology on supply chain sustainability?

3. Theoretical framework

3.1 Artificial Intelligent

Artificial intelligence pertains to computer systems that possess the ability to reason and perform tasks more efficiently than humans, including picture identification, speech recognition, decision-making, and language translation (Riahi *et al.,* 2021). It denotes the capacity of AI to discern the most anticipated and prevalent attributes of a particular subject. AI can identify which attributes are desirable and which should be disregarded. Decide pertains to the capacity of AI to make a conclusion after assessing a multitude of attributes, subsequently identifying the most significant among them. Artificial intelligence is a computational system that utilizes data to execute tasks traditionally performed by humans, optimizing the likelihood of success. Artificial Intelligence significantly enhances the development of Supply Chain Management (SCM). One of the most powerful attributes of artificial intelligence is its ability to support decision-making at strategic, tactical, and operational levels (Cai *et al.,* 2021). AI contributes to enhancing the sustainability of supply chain management by improving the accuracy of forecasts and reducing production costs (Chang *et al.,* 2019). The primary objective of artificial intelligence technology is to address challenges and rectify inefficiencies created by human actions (Purnomo, 2024). AI is utilized to boost supply chain efficiency, with organizations increasingly adopting artificial intelligence and machine learning to gain sustainable insights across supply chain management, logistics, and warehouse operations (Riahi *et al.,* 2021).

3.2 Blockchain Technology

Blockchain technology comprises a range of applications and continually introduces innovative concepts (Swan, 2015). In recent years, interest in blockchain within the industrial sector has grown significantly (Kumar *et al.,* 2024). Many start-ups are actively investigating how blockchain can be applied to supply chain monitoring and auditing (Litke *et al.,* 2019). This approach creates an information chain where data are authenticated and stored within individual blocks. These blocks are then verified and linked to the preceding blocks in the transaction and knowledge chain as necessary (Rane and Potdar, 2021). Leading companies in the manufacturing industry should harness the inherent features of blockchain technology to address challenges that have traditionally hindered technological advancement. Additionally, blockchain offers the advantage of lowering transaction costs (Kouhizadeh *et al.,* 2021).

3.3 Green Innovation

Green innovation refers to the adoption of new methods in manufacturing, operations, or management aimed at minimizing environmental risks, reducing pollution, and lessening adverse impacts on resources such as energy consumption. It serves as a strategic approach focused on implementing new or significantly improved products, processes, marketing techniques, or organizational strategies (Purwanto, 2024).

This concept plays a vital role in guiding company decisions, strategies, management practices, manufacturing, and product development. Green innovation helps eliminate environmental barriers and encourages collaboration between customers and suppliers. By integrating environmentally conscious consumers, organizations can improve cost efficiency and environmental performance by fostering sustainable process innovations rather than concentrating solely on green products (Wong, 2020). It embodies a complex commitment from organizations to develop ecologically sustainable products and processes, incorporating social, environmental, and societal concerns into business models to meet stakeholder expectations. This strategic approach aligns economic objectives with ecological and social priorities, thereby supporting sustainable development (Martínez-Falcó *et al.,* 2024).

Green innovation is critical for reducing environmental pressures while maintaining economic growth. It involves the creation and application of green technologies that conserve natural resources and mitigate humanity's environmental impact (Soomro *et al.,* 2024; As Asadi *et al*., 2020) highlight, the goal is to advance green development and its protective effects through the efficient use of technological product innovations. It encompasses the development or enhancement of products, processes, promotional methods, formal frameworks, and institutional policies that lead to environmental improvements, whether intentionally or unintentionally, compared to alternative options (Olowoyin, 2021). Recognized as a key strategy to combat environmental degradation, green innovation is closely linked to pollution reduction, resource efficiency, waste minimization, and fostering broader innovation (Khan *et al.,* 2021).

The adoption of green technologies, including sustainable human resource management practices, is fundamental for conserving energy, protecting the environment, and enhancing operational efficiency, thereby supporting sustainable business models (Asadi *et al.,* 2020). Moreover, green innovation strategies, particularly those involving green product and process innovations, have been shown to significantly improve environmental performance, with process innovations typically having a stronger impact (Martínez-Falcó *et al.,* 2024).

3.4 Supply Chain Sustainability

According to Johny and Gurtu (2024), a sustainable supply chain is defined by its ability to promote human rights protection, fair labor practices, environmental advancement, and anti-corruption efforts. The progression of technology from the traditional industrial age to the current Industry 4.0 era has heightened the need for horizontal, vertical, and end-to-end digital integration. Research indicates that adopting Industry 4.0 technologies has a significant impact on the sustainability dimensions within supply chain networks. Supply chains serve as vital networks linking an organization's inputs and outputs. Historically, the focus has been on reducing costs, ensuring timely delivery, and minimizing transit times to allow sufficient handling of commercial operations. However, rising environmental, social, and economic costs associated with these networks, coupled with increasing consumer demand for sustainable products, have prompted many companies to adopt sustainable supply chains as the new benchmark for efficient logistics management. This shift reflects the understanding that sustainable supply chains are also profitable ones (Pathan and Kesavaraj, 2024).

Implementing sustainable supply chain innovation involves developing environmentally friendly products, sourcing materials ethically, and producing and distributing goods in a sustainable manner. Such supply chains fully integrate ethical and environmentally responsible practices within a competitive and effective framework. Achieving comprehensive transparency across the supply chain is essential. Sustainability initiatives must cover areas including raw material sourcing, last-mile logistics, as well as product returns and recycling processes (Chen and Panichakarn, 2024). Sustainable Supply Chain Management (SSCM) is a strategic framework that incorporates environmental, social, and economic considerations into supply chain operations to enhance sustainability and ethical standards across global networks. Its primary goals are to minimize environmental impacts, uphold ethical labor standards, and ensure economic viability throughout the supply chain (Dathe *et al.,* 2024). SSCM has evolved from focusing narrowly on environmental concerns to adopting a comprehensive approach that integrates the triple bottom line environmental, social, and economic factors (Bentalha, 2024).

4. Hypotheses Development and Conceptual Framework

Numerous studies have established a connection between supply chain sustainability and Industry 4.0 technologies, highlighting how these technologies facilitate the transformation of traditional supply chains into sustainable ones. Industry 4.0 enables improvements in productivity and efficiency across the supply chain, thereby generating new value. Among these technologies, artificial intelligence (AI) has garnered significant attention for its potential to enhance supply chain performance. AI contributes to supply chain sustainability by improving responsiveness to customer demands, enabling logistics networks to transport goods more swiftly, which in turn leads to higher returns and competitive advantages (AL-Khatib, 2023). Additionally, AI plays a vital role in addressing sustainability challenges by eliminating information asynchronization and managing complex environmental data (Wu and Tran, 2018). It supports decision-making processes that enhance supply chain sustainability and environmental performance (Dubey *et al*., 2017). Moreover, AI is instrumental in managing both intra- and inter-organizational environmental issues. Its application extends to sustainable practices in external supply chains, such as integrating supplier selection and eco-design to boost environmental outcomes (Raut *et al.,* 2019). Supply chain vulnerabilities pose risks to operations and can disrupt entire ecosystems, with both internal and external factors contributing to these disruptions (Dolgui and Ivanov, 2022). AI also fosters innovation and a proactive approach within supply chains by generating creative solutions and offering new methods that reduce the time and resources traditionally required for research and development (AL-Khatib, 2023). Consequently, it is essential to build capabilities within supply chains that enable members to remain competitive amid complexity and disruption. The concept of dynamic technological capabilities, an extension of dynamic capabilities, encompasses intangible factors that create competitive advantages (Li and Chan, 2019). Firms that effectively leverage AI to better understand market dynamics can implement improved decision-making systems to address supply chain disruptions and transition toward sustainability. Based on this, the present study aims to investigate the relationship between AI and sustainable supply chains.

Hypothesis 1 (H1): AI has a positive impact on supply chain sustainability.

With the globalization of production, supply chain structures have become increasingly dynamic to achieve a sustainable competitive advantage in the digital age (Clifford Defee and Fugate, 2010). Originally developed for financial applications, blockchain technology has demonstrated significant potential for use in supply chain management (Chang *et al.,* 2019). The application of blockchain technology shares many similarities with supply chain processes, making it highly adaptable across the entire supply chain—from raw material sourcing to the distribution of finished products to end customers (Rodrigues, 2018; Goyat *et al.,* 2020). Blockchain facilitates the creation of a distributed network among various supply chain participants, enabling real-time monitoring and tracking of activities in an immutable and transparent manner from any location. By integrating smart contracts, blockchain empowers secure and automated digital transactions between entities (Dinh and Thai, 2018). Beyond its capabilities in data storage and security, blockchain reduces transaction costs by removing the need for third-party intermediaries to authenticate transactions (Cai *et al.,* 2021). Furthermore, blockchain supports the monitoring of sustainability performance by allowing for supplier evaluation, ensuring direct product movement from producers to consumers, traceable packaging, and the tracking of environmental impacts throughout the supply chain (van Hoek, 2020). Closely linked to sustainable supply chain management, blockchain technology also contributes to advancing Sustainable Development Goals (SDGs). Achieving these goals requires effective management of supply and distribution processes across supply chain networks and embedding sustainability principles at every operational stage (Cammarano *et al*., 2022). Based on these insights, the following hypothesis is proposed:

Hypothesis 2 (H2): BT technology has a positive impact on supply chain sustainability.

Artificial intelligence (AI) algorithms are highly effective at handling vast amounts of data, which facilitates the management of complex blockchain transactions and datasets. When combined, AI and blockchain form a sophisticated framework for data security (Cai *et al.,* 2021). Public blockchain networks often face scalability challenges, but AI helps address these by predicting peak usage periods, distributing workloads evenly, and automating repetitive tasks. These improvements enhance the efficiency and scalability of blockchain systems (Ivanov *et al.,* 2021). Additionally, AI's capability for decision-making streamlines blockchain operations, such as automating identity verification and detecting fraudulent activities. Beyond this, AI rapidly analyzes blockchain data to extract valuable insights, benefiting sectors like supply chain management, finance, and healthcare. AI also plays a role in increasing the energy efficiency of blockchain networks (Dolgui and Ivanov, 2022). The validation of transactions within blockchain depends on consensus mechanisms, and AI can optimize these processes—especially in proof-of-stake or delegated proof-of-stake systems—by learning from historical data and adapting to emerging security threats in real time (Min, 2019). Overall, AI's analytical and predictive strengths enhance blockchain's adaptability, security, and efficiency, fostering innovation and broader adoption across various industries. Based on these observations, the following hypothesis is proposed:

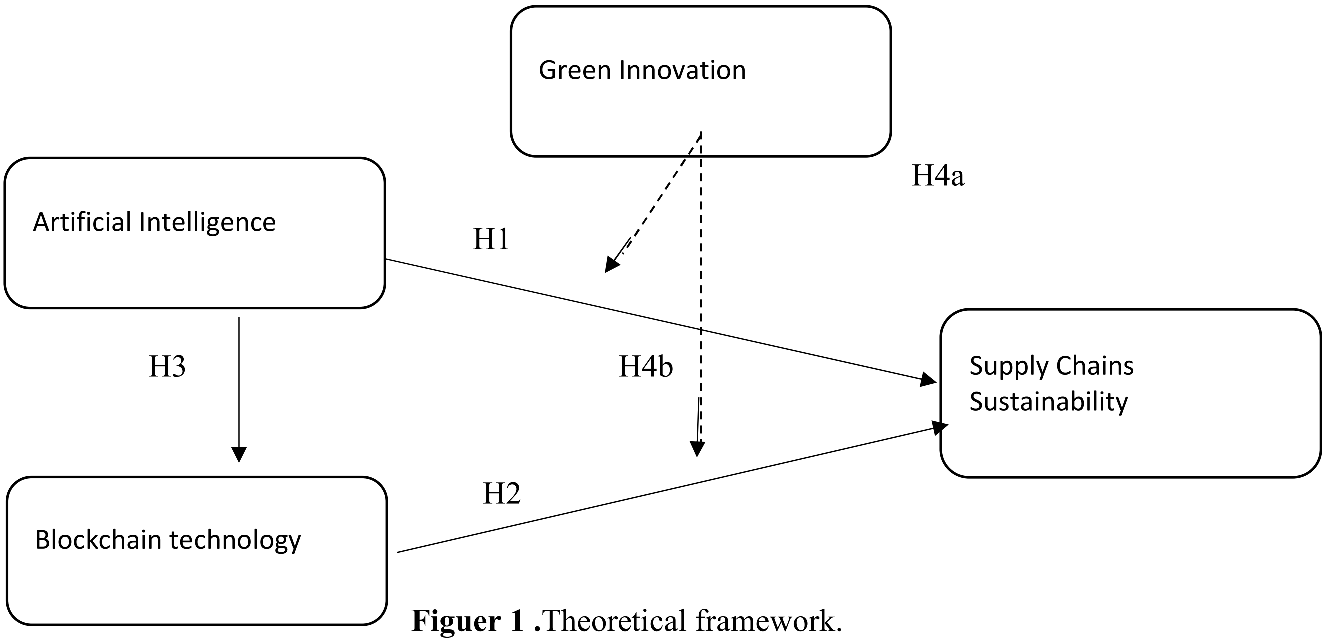
Hypothesis 3 (H3): Artificial intelligence has a positive impact on blockchain technology.

When combined with green innovation, artificial intelligence (AI) enables organizations to prioritize sustainability in their supply chain decisions. For instance, AI-driven insights informed by green innovation can assist companies in selecting environmentally responsible suppliers, optimizing resource utilization, and minimizing production waste, all while reducing costs and environmental impact (Hussain and Papastathopoulos, 2022). By analyzing both real-time and historical data, AI helps improve resource efficiency, decrease energy consumption, lower carbon emissions, and reduce waste, thereby promoting greener supply chains (Schilke, 2014). With green innovation as a guiding principle, AI facilitates the implementation of sustainable practices by identifying opportunities for reuse, recycling, and recovery throughout the supply chain (Cai *et al.,* 2021). Green innovation prioritizes transparency, and AI enhances this by monitoring and analyzing data across the entire supply network. This increased visibility enables stakeholders to assess their environmental impact accurately and report progress to customers and regulatory bodies (Ivanov *et al.,* 2021). Such transparency fosters trust, demonstrates a commitment to sustainability, and ensures accountability among all supply chain partners regarding eco-friendly practices. Furthermore, green innovation amplifies AI's influence on sustainable supply chains by directing AI applications toward environmentally conscious goals (Cai *et al.,* 2021). This synergy supports businesses in reducing their ecological footprint, conserving resources, and developing supply chains that are both profitable and sustainable. Based on these insights, the following hypothesis is advanced:

Hypothesis 4a (H4a): Green innovation positively moderates the relationship between AI and supply chain sustainability.

Blockchain technology offers an immutable and transparent ledger of every transaction, which supports green innovation initiatives by enabling the tracking of sustainable practices and ensuring adherence to environmental regulations. Through this transparency, green innovation promotes responsible sourcing, environmentally friendly manufacturing processes, and ethical labor standards, ensuring compliance at all stages of the supply chain (Dutta *et al.,* 2020). Blockchain facilitates the monitoring of eco-friendly materials, including recycled or sustainably sourced inputs, aligning with green innovation objectives. It also enables detailed tracking of resource consumption such as water and energy throughout the supply chain. By fostering circular economy principles, green innovation encourages the reuse, recycling, and repurposing of products and materials, with blockchain providing a clear, tamper-proof record of these flows to minimize waste and conserve resources (Vijay and Saravanan, 2024). When combined with green innovation, blockchain supports real-time monitoring of carbon emissions at each supply chain stage. The immutable nature of blockchain ensures that this environmental data is reliable, offering companies trustworthy insights into their ecological footprint. Additionally, blockchain securely stores and shares comprehensive environmental impact information, from raw material extraction to final product delivery (Kouhizadeh *et al.,* 2021). This transparency allows green innovation to communicate product sustainability effectively to consumers, regulators, and other stakeholders, fostering accountability and informed decision-making (Huang *et al.,* 2022). Green innovation also promotes integrating renewable energy within supply chains. Blockchain can verify and track the use of renewable energy sources, confirming that energy consumption across supply chain segments aligns with sustainability goals (Venkatesh *et al.,* 2020). Moreover, green innovation facilitates the incorporation of certification standards — such as carbon neutrality and fair trade — into blockchain records, streamlining compliance verification. Because blockchain immutably records each stakeholder’s sustainable practices, it simplifies certification validation and assures adherence to established benchmarks (Huang *et al.,* 2022). Ultimately, green innovation guides blockchain technology to enhance supply chain sustainability by embedding transparency, accountability, and environmentally responsible practices at every operational level. Therefore, the following hypothesis is proposed:

Hypothesis 4b (H4b): H4b: Green innovation positively moderates the relationship between BT technology and supply chain sustainability.



Figuer 1 . Theoretical framework.

5. Research Methodology

The Egyptian government has actively promoted the adoption of sustainable business practices within organizational operations. Consequently, many organizations across various sectors and levels have begun implementing sustainability initiatives aligned with Egypt's Vision 2030 for sustainable development (Ali *et al.,* 2021). To achieve the objectives of this study—examining the impact of artificial intelligence, blockchain technology, and green innovation on supply chain sustainability—a quantitative research approach was employed.

The study population comprised companies operating within Egypt's industrial sector. Due to the large size of this population and constraints related to time and resources, sampling techniques were utilized to collect primary data. Specifically, the focus was placed on medium and large industrial enterprises engaged in exporting activities. A preliminary technical analysis was conducted on registered exporters, based on data from the Export Development Authority and the official Ministry of Commerce and Industry website.

The final sample included participants from 90 small and medium-sized enterprises (SMEs) located in industrial zones across Egypt. A total of 400 questionnaires were distributed online, with 290 returned and 266 deemed valid for analysis. Prior to full-scale data collection, a pilot study involving 30 respondents was conducted to test the reliability of the survey instruments, resulting in confirmation that the scales required no modifications.

Data were gathered through self-administered online questionnaires sent individually to participants. A descriptive survey design was chosen to accurately capture the characteristics of the study variables. The survey employed a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), with 3 representing a neutral or undecided position. This scale was used to measure respondents' attitudes regarding the study constructs.

Demographic information collected included gender, age, education level, job position, and work experience. The measurement scales consisted of an 8-item scale for artificial intelligence (Davenport and Ronanki, 2018), a 6-item scale for blockchain technology (Treiblmaier, 2018), a 7-item scale for green innovation (Asadi *et al.,* 2020; Cheg *et al.,* 2024), and a 12-item scale for sustainable supply chain management. Table 1 summarizes the demographic and sample characteristics relevant to the main study.

Table 1. A summary of demographic and sample characteristics.

Demographic Variables	Criteria	Frequency	Percentage
Gender	Male	175	65.9 %
	Female	90	34.1%
Age	less than 30 years	65	24.6%
	From 30 to Less than 40	41	15.5%
	from 40 to less than 50	81	30.5%
	50years and more	78	29.4%
Functional Level	Head of Department	98	37,00%
	Director	79	29,60%
	General Director	49	18,40%
	Chairman	40	15%
Years of Experience	Less than 6 years	6	2,20%
	6-less than 10 years	28	10,40%
	11-less than 20years	197	74,10%
	20 and more	35	13,31%
Industrial Sector	Plastic &petrochemicals	104	39,00%
	Fertilizers & Cement	99	37,20%
	Steel & Iron	43	16,00%
	Others	21	7,80%

Source: This research.

The demographic characteristics of the respondents are summarized in Table 1. The sample comprised a majority of male participants, accounting for 65.9%, while females represented 34.1% of the total respondents. Age distribution indicated a relatively balanced representation across age groups, with the largest proportion (30.5%) falling within the 40 to less than 50 years' category, followed closely by those aged 50 years and above (29.4%). Participants under 30 years constituted 24.6%, and those aged between 30 and less than 40 years made up 15.5% of the sample. Regarding organizational hierarchy, 37.0% of respondents held the position of Head of Department, 29.6% were Directors, 18.4% served as General Directors, and 15.0% occupied Chairman roles. This distribution reflects a broad spectrum of managerial levels, providing diverse insights from different tiers of organizational leadership. The majority of participants demonstrated substantial professional experience, with 74.1% having between 11 and less than 20 years of experience. Those with 20 or more years of experience comprised 13.3%, while respondents with less than 6 years and between 6 to less than 10 years of experience represented 2.2% and 10.4%, respectively. In terms of industrial sectors, the sample was predominantly drawn from the plastics and petrochemicals sector (39.0%) and fertilizers and cement industry (37.2%), with the steel and iron sector accounting for 16.0% and other sectors comprising 7.8%. This distribution underscores the study's emphasis on key industrial segments relevant to the research context. Overall, the demographic composition of the sample provides a comprehensive and representative foundation for examining the study's research questions within the targeted industrial sectors.

Prior to testing the hypotheses in the main study, it is essential to verify the reliability and validity of the research variables. These analyses ensure that the questionnaire items are clearly and appropriately constructed. Validity is assessed using the Average Variance Extracted (AVE), where a value exceeding 0.5 indicates sufficient validity. Additionally, factor loadings (FL) and composite reliability (CR) are evaluated. Reliability refers to the consistency and stability with which the instrument measures a given variable, commonly assessed through Cronbach's Alpha. This coefficient ranges from 0 to 1, with higher values signifying greater reliability. An Alpha value of 0.7 or above is generally considered acceptable and indicative of adequate reliability.

Table 2. Validity and Reliability

Latent variable/construct.	Items.	Factor loading.	Composite reliability.	Alpha	AVE.
Artificial Intelligence (AI)	AI1	.803	0.81	0.79	0.62
	AI2	.780			
	AI3	.565			
	AI4	.556			
	AI5	.819			
	AI6	.794			
	AI7	.849			
	AI8	.759			
Blockchain (BT)	BT1	.747	0.82	0.754	0.67
	BT2	.687			
	BT3	.695			
	BT4	.617			
	BT5	.707			
	BT6	.619			

Green Innovation (GI)	GI1	.747	0.85	.794	0.656
	GI2	.687			
	GI3	.695			
	GI4	.617			
	GI5	.707			
	GI6	.619			
	GI7	.667			
Environmental SC Sustainability (ENS)	ENS1	.663	0.88	.674	0.659
	ENS2	.697			
	ENS3	.728			
	ENS4	.777			
Economic SC Sustainability (ECS)	ECS1	.722	0.90	.636	0.51
	ESC2	.751			
	ECS3	.595			
	ECS4	.733			
Social SC Sustainability (SOS)	SOS1	.621	0.86	.769	0.65
	SOS2	.771			
	SOS3	.872			
	SOS4	.828			

Source: This research.

Table (2) presents the results of the reliability and validity analyses conducted for the latent variables in the study. The factor loadings for each item ranged from 0.556 to 0.872, indicating satisfactory individual indicator reliability across all constructs. Composite reliability (CR) values varied between 0.81 and 0.90, exceeding the commonly accepted threshold of 0.70, which confirms the internal consistency of the measurement scales. Cronbach's Alpha coefficients ranged from 0.636 to 0.794, with most constructs demonstrating values above the recommended cutoff of 0.70, suggesting acceptable to good reliability. The slightly lower alpha value observed for Economic Sustainability (0.636) may warrant cautious interpretation but remains within a reasonable range for exploratory research. Average Variance Extracted (AVE) values were all above 0.50, ranging from 0.51 to 0.659, thereby confirming adequate convergent validity for all constructs. Collectively, these results indicate that the measurement instruments used in this study are both reliable and valid, supporting their suitability for subsequent structural model analysis.

Regression analysis is a widely applied statistical method across disciplines such as social sciences, physical sciences, biology, business, and engineering, used to explore and establish relationships between interconnected variables. For this study, the research hypotheses were evaluated using structural equation modeling (SEM), with the results detailed in Table 3 of the findings section.

Table 3. Testing Research Hypotheses

Hypothesis	Path coefficient (β)	t-statistics	*p*-values	Results
H1. AI has a positive impact on Supply chain sustainability.	0.556	12.774	0.05	Supported
H2. BT technology has a positive impact on Supply chain sustainability.	0.920	15.515	0.05	Supported
H3. AI has a positive impact on BT technology.	0.715	5.355	0.05	Supported
H4a. GI positively moderates the relationship between AI and Supply chain sustainability	0.41	11.51	0.02	Supported
H4b. GI positively moderates the relationship between BT technology and Supply chain sustainability.	0.135	9.62	0.019	Supported

Table 3 summarizes the empirical findings derived from testing the proposed hypotheses regarding the influences of artificial intelligence (AI), blockchain technology (BT), and green innovation (GI) on supply chain sustainability. The results indicate that AI has a statistically significant positive effect on supply chain sustainability ($\beta = 0.556$, $t = 12.774$, $p < 0.05$). This finding corroborates existing literature asserting that AI enhances supply chain processes through improved data analytics, forecasting accuracy, and resource optimization, which collectively contribute to more sustainable operational outcomes. The high t-value suggests a robust effect, emphasizing AI's critical role in promoting environmental, social, and economic sustainability within supply chains.

Even more pronounced is the impact of blockchain technology on supply chain sustainability ($\beta = 0.920$, $t = 15.515$, $p < 0.05$). This strong positive relationship reflects blockchain's capacity to enhance transparency, traceability, and security across supply chain activities. By providing immutable transaction records and facilitating trusted information sharing among stakeholders, blockchain technology reduces inefficiencies and supports compliance with sustainability standards, thereby significantly advancing sustainable supply chain practices.

The analysis further reveals that AI significantly influences blockchain technology ($\beta = 0.715$, $t = 5.355$, $p < 0.05$). This suggests that AI not only directly supports sustainability but also enhances blockchain functionality, for example, by optimizing data processing, improving consensus algorithms, and enabling intelligent automation within blockchain networks. This interdependency highlights a synergistic relationship where AI acts as an enabler, amplifying blockchain's effectiveness in sustainable supply chains.

Importantly, green innovation was found to positively moderate the relationship between AI and supply chain sustainability ($\beta = 0.41$, $t = 11.51$, $p = 0.02$). This indicates that the presence of green innovation strengthens the positive impact of AI on sustainability outcomes. Green innovation likely guides AI applications toward environmentally focused objectives, such as energy efficiency, waste reduction, and sustainable sourcing, thereby enhancing AI's sustainability benefits.

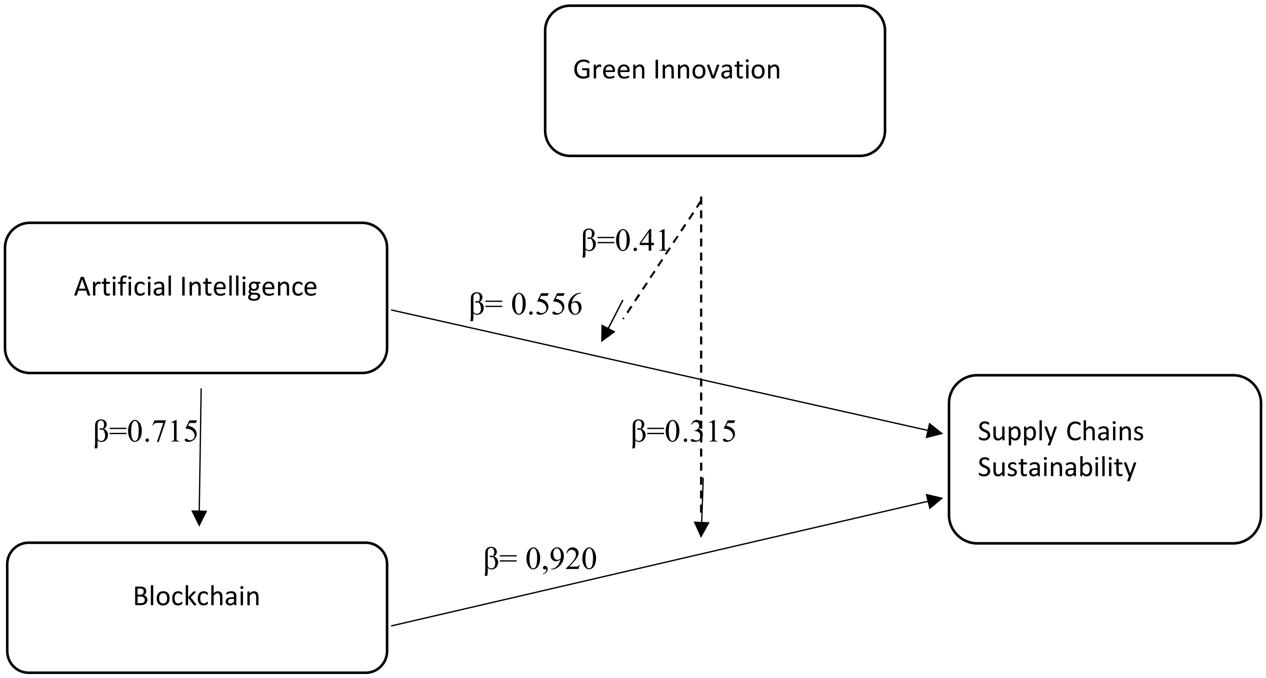
Similarly, green innovation also positively moderates the effect of blockchain technology on supply chain sustainability ($\beta = 0.135$, $t = 9.62$, $p = 0.019$). Although the moderating effect is smaller compared to AI, it remains statistically significant, suggesting that green innovation likewise amplifies blockchain's contributions to sustainability. This may occur through promoting eco-friendly practices that blockchain can transparently track and verify, such as responsible supplier selection and sustainable product lifecycle management. Collectively,

these findings underscore the critical interplay between emerging digital technologies and green innovation in fostering sustainable supply chains. The strong direct effects of AI and blockchain technology highlight their fundamental roles as drivers of sustainability, while the moderating role of green innovation emphasizes the need for strategic alignment of technological capabilities with environmental innovation to maximize sustainable outcomes. These insights provide valuable implications for both theory and practice, advocating for integrated approaches that leverage AI and blockchain technologies within a green innovation framework to build resilient, efficient, and sustainable supply chains capable of meeting the demands of a globalized and environmentally conscious market.

Table 4. The Model Fit

degrees of freedom (df)	$\chi2$/df	GFI	AGFI	CFI	NFI	RMSEA
2	1.571	0.940	0.92	0.930	.933	0.041

The model fit was assessed using several commonly accepted indices. The chi-square to degrees of freedom ratio (χ^2/df) was 1.571, indicating a good fit as values below 3 are generally considered acceptable. The Goodness-of-Fit Index (GFI) was 0.940 and the Adjusted Goodness-of-Fit Index (AGFI) was 0.92, both exceeding the recommended threshold of 0.90, suggesting a satisfactory model fit. The Comparative Fit Index (CFI) and Normed Fit Index (NFI) were 0.930 and 0.933, respectively, indicating excellent comparative fit relative to the null model. Additionally, the Root Mean Square Error of Approximation (RMSEA) was 0.041, well below the 0.05 cutoff, further supporting the adequacy of the model. Collectively, these indices confirm that the proposed model fits the data well.



Figer 2. Structural Estimates.

Note: *Means significance level at 5%

6. Discussions and Conclusions

This study primarily aims to explore the effects of artificial intelligence (AI) and blockchain technology on supply chain sustainability, focusing on the mediating influence of green innovation within manufacturing enterprises in Egypt. To fulfill this objective, the study conceptualizes AI and blockchain as essential components driving sustainable development in the industrial supply chain context.

The analysis demonstrates that AI exerts a significant and direct positive influence on supply chain sustainability, a finding that aligns with earlier research (AL-Khatib 2023; Raut *et al.,* 2019; Dolgui and Ivanov, 2022; Li and Chan 2019). Additionally, the interrelationship between AI and blockchain technology is confirmed, supporting observations from prior studies (Schilke, 2014; Hussain and Papastathopoulos, 2022; Choi *et al.,* 2020). Importantly, the study reveals that green innovation fully mediates the relationship between AI and supply chain sustainability, as well as between blockchain technology and sustainability outcomes. These results underscore the consistent and complementary roles of AI, blockchain, and green innovation in enhancing supply chain sustainability, reinforcing current literature while providing fresh insights into their interconnected effects (Hussain and Papastathopoulos, 2022; Raut *et al.,* 2019; Dolgui and Ivanov, 2022; Dutta *et al.*, 2020).

Furthermore, the findings suggest that deploying advanced technologies like AI and blockchain within Egyptian manufacturing firms contributes substantially to improving supply chain sustainability across various dimensions, including administrative, operational, production, and logistics functions. This technological adoption offers these organizations a distinct competitive advantage over more conventional competitors. The mediating role of green innovation highlights its strategic importance as an enabling framework, empowering firms to secure competitive benefits across different industrial sectors. Therefore, integrating AI and blockchain technologies to foster green innovation appears vital for sustaining and advancing supply chain resilience, especially in the face of dynamic and disruptive challenges.

Practically, the study offers guidance for companies considering investments in AI and blockchain to support green innovation and supply chain sustainability. This includes embracing innovative methods, processes, and services designed to maintain uninterrupted supply chain operations and ensure long-term viability, in alignment with Egypt's sustainability goals.

Managers should consider: (1) assessing their current technological capabilities, including AI and blockchain, to detect both internal and external innovation opportunities impacting the supply chain; (2) evaluating whether their existing infrastructure can effectively leverage these technologies to support sustainability objectives; (3) recognizing blockchain's growing superiority in managing extensive data flows compared to AI; (4) carefully analyzing investment decisions concerning AI and blockchain technologies; (5) adopting digital tools that facilitate real-time data sharing and communication to enhance supply chain transparency and efficiency; (6) integrating environmental and social responsibility into growth strategies to meet evolving consumer expectations; and (7) embedding sustainability into organizational strategy to maximize the benefits derived from advanced technological applications.

This research examines how artificial intelligence (AI) and blockchain technologies contribute to supply chain sustainability, emphasizing the intermediary role played by green innovation. The study fills a research gap in Egypt by extensively exploring the combined impact of AI and blockchain on sustainable supply chains. It highlights that AI and blockchain each uniquely support green innovation efforts, which in turn promote sustainability within supply chains.

Empirical results indicate that both AI and blockchain have a meaningful positive influence on the sustainability of supply chains. Furthermore, green innovation acts as a mediator in these relationships, suggesting that the adoption of environmentally friendly innovations is a critical pathway through which these technologies enhance sustainable supply chain outcomes. This underscores the importance of integrating technological advancements with green practices to build more resilient and sustainable supply networks.

The findings contribute to the growing body of knowledge on leveraging digital technologies in supply chain sustainability and offer important insights for practitioners seeking to implement effective sustainability strategies through the use of AI, blockchain, and green innovation.

7. Limitations and Future Research directions

This study has certain limitations that future research can address. Firstly, while this research focuses on sustainable practices within supply chain sustainability (SCS) and green innovation (GI), other emerging approaches such as lean manufacturing and viability practices were not considered. Secondly, the reliance on self-reported questionnaire data may introduce biases, including response bias and social desirability bias. Thirdly, the focus on new technologies presents challenges, indicating a need for further investigation into how different contexts influence sustainability efforts.

Future research could explore several directions. For instance, incorporating additional practices like lean or resilient strategies and examining their mediating effects on performance would be valuable. Studies could also investigate the implications of these technologies within the context of Industry 4.0 across various sectors, recognizing that each may face distinct challenges and opportunities. Furthermore, examining the impact of artificial intelligence and blockchain on supply chains across different regions, taking into account variations in technology adoption and regulatory frameworks, would enrich understanding. Research into effective methods for employee training and adaptation to new technologies could help organizations maximize benefits. Lastly, future work should aim to identify best practices and develop comprehensive frameworks for the successful implementation of AI and blockchain in supply chain management.

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Appendix A: Questionnaire

Variables	Indicator	Constructs and items
Artificial Intelligence (AI) (Davenport and Ronanki, 2018)	AI1	AI has optimized internal business operations
	AI2	AI creates a space for employees to be more creative by automating the tasks
	AI3	AI makes for better decisions in the firm
	AI4	AI indicates plans for new products
	AI5	AI identifies new markets for the firm
	AI6	AI helps the firm optimize external processes such as distribution and sales
	AI7	AI enables the firm to capture and apply scarce knowledge when needed
	AI8	AI reduces headcount through automation
Blockchain Technology (BT) (Treiblmaier, 2018)	BT1	Blockchain technology brings the transparency to the supply chain system
	BT2	Block chain technology achieves persistence of information in the firm
	BT3	Blockchain technology helps the firm update and take decisions on contractual agreements
	BT4	Block chain creates new areas of competitive advantage for firms and supply chains
	BT5	Blockchain technology enables the development of strong network
	BT6	Blockchain technology establishes trust among supply chain partners and enables speedy information sharing
Green Innovation (Asadi et al., 2020; Cheg et al., 2024),	GI1	According to its green operations, the company obtains price bonuses or price advantages to obtain certain market shares
	GI2	The company conducts a statistical survey of its operations to create new products
	GI3	The company works to innovate green processes to reduce the cost of a unit of production or transportation or to build quality
	GI4	The company makes its sustainable products that meet quality requirements
	GI5	The company is interested in activities that support process innovation, such as purchasing, maintenance, and accounting, which is one of its primary internal concerns.
	GI6	The company creates capabilities and schedules that improve process efficiency and enhance the utility of completing any job
	GI7	The company conducts coordinated idea meetings that involve changes in the production process that are planned to reduce costs, waste and lead times or improve the efficiency of operations and production.

Environmental SC Sustainability	ECS1	The company reduces operational costs as a result of constantly saving resources in all operations activities
	ESC2	The company is working to grow its market value, such as increasing sales revenues and market share
	ECS3	The company achieves appropriate growth in profits as a result of the efficiency of its operations practices
	ECS4	The company seeks to achieve appropriate growth in profits as a result of the sustainable marketing process
Economic SC Sustainability	ENS1	The company works to reduce any activities that do not add value and reduce waste that has an environmental impact
	ENS2	The company reduces the use of harmful substances and disposes of materials (gas, liquid, solid, and volatile organic compounds) in a way that does not harm the environment
	ENS3	The company seeks to rely on previously reused or recycled materials
	ENS4	The company reduces energy use (fuel, noise and radiation) that may cause direct or indirect harm to the environment.
Social SC Sustainability	SOS1	The company maintains the health and safety of employees at work
	SOS2	The company works on employee satisfaction and engagement at work
	SOS3	The company educates and trains employees, develops their skills, and invests in human capital
	SOS4	The company works to reduce the rate of consumer complaints and increase the level of consumer satisfaction

المستخلص

شهدت السنوات الأخيرة إهتمامًا متزايدًا من الباحثين والممارسين بالذكاء الاصطناعي (AI) وتكنولوجيا البلوك تشين (BT) ومع ذلك، لا تزال الدراسات التجريبية التي تناولت تأثيرهما المشترك على إستدامة سلاسل الإمداد محدودة. تهدف هذه الدراسة إلى سد هذه الفجوة من خلال دراسة تجريبية لتأثير الذكاء الاصطناعي وتكنولوجيا البلوك تشين في تحسين إستدامة سلاسل الإمداد. وقد تم إعتماد المنهج الكمي، حيث جُمعت البيانات الأولية من خلال إستبيانات وُزعت على عينة مكوّنة من 266 مديرًا من شركات صناعية مُصدّرة في مصر. أظهرت النتائج وجود تأثير إيجابي ملموس لكل من الذكاء الاصطناعي وتكنولوجيا البلوك تشين على إستدامة سلاسل الإمداد، كما كشفت عن أن الإبتكار الأخضر يؤدي دورًا وسيطًا مهمًا في العلاقة بين الذكاء الاصطناعي وتكنولوجيا البلوك تشين من جهة، وإستدامة سلاسل الإمداد من جهة أخرى. وتقدم هذه النتائج رؤى مهمة للمنظمات لتبني ممارسات مستدامة، وتعزيز الإبتكار الأخضر، ودعم مرونة وإستمرارية سلاسل الإمداد في ظل بيئة تكنولوجية سريعة التغير.

الكلمات المفتاحية : الذكاء الاصطناعي؛ تكنولوجيا البلوك تشين؛ الإبتكار الأخضر؛ سلاسل الإمداد المستدامة.