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The Impact of IoT, Blockchain and AI Adoption on Environmental Performance and Operational Efficiency in Green Supply chain Management

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ABSTRACT

Integration of information technology in the industry period is crucial to the advancement of Green Supply Chain Management as it enhances the effectiveness, efficiency, and sustainability of the cyber-GSCM practices. However, in regions such as Baluchistan, the digital transformation is stymied by the lack of good infrastructures, slow technology diffusion, and fundamental ecosystem predicaments that inhibit the broader application of green supply. Thus, the study focuses on examining the impacts of three particular technologies, the Internet of Things, artificial intelligence, and blockchain, on the performance of GSCM in Baluchistan. A quantitative research methodology was used, and data was collected from 400 participants through questionnaires. Regression analysis showed that all three technologies improve the environmental performance of firms, but gains in the efficiency of operational activities on a day-to-day basis are achieved through IoT and blockchain only. The impact of AI was, however, statistically insignificant. Overall, the findings underscore that for developing countries to have more sustainable supply chains, the adoption of digital tools is mandatory.

Keywords: *Green supply chain, innovation, Baluchistan, IoT, AI, Environmental performance.*

INTRODUCTION

Global industrialization has put the world economy on a growth trajectory that has never been seen before. However, this unprecedented growth brings with it an insatiable appetite for energy and raw materials that jeopardizes the gradual deterioration of the world's ecosystems. Today's firms operate under the threat of a depleted resource and an environment that is hostile to the firm's resource use as people demand accountability for the use of the resource. Zhu (2004) note that it has never been more important for firms to find the target profitability and planet balance. This is the reason why Green Supply Chain Management has become so important. GSCM applies environmental management to all activities that comprise the supply chain, from the design of the product to the consumer to the sourcing of materials and all the way through the production processes (Kim et al., 2022). The movement toward "going green" has created positive social and environmental outcomes and provided firms with the means to achieve and protect a sustainable competitive advantage (Nujen et al., 2023).

The foundational framework of GSCM is based on the well-established 4R1D principle; Reduce, Reuse, Recycle, Reclaim, and Re-construct as Degradable. It attempts to address the issue of destructive environmental consequences caused by the industry logistics (Srivastava, 2007). Lately, it has become clear that the modern supply chain is overly complicated to be managed manually. It is also clear that the incorporation of the so-called Industry 4.0 technologies is indispensable to improve modern supply chain transparency and operational "greenness." The Internet of Things, Blockchain, and Artificial Intelligence are now widely accepted to be the green supply chain innovation enablers. The IoT has the essential environmental and resource management monitoring and accounting systems, whereas AI is helpful to reduce the overall resource use by optimizing production through the effective prediction of resource use (Fatorachian & Kazemi, 2021). Moreover, Blockchain enhances the transparency and trust within the supply chain by offering an immutable and distributed ledger. This, among others, enhances green supply chain auditing and compliance (Yahaya, 2025).

The advances in integrating digital technology with green supply chains, very little research has focused on how these technologies are adopted in developing areas with inadequate infrastructure, such as Baluchistan. Multinational companies utilize 'smart' sensors and digital twins to model and mitigate carbon emissions (Park et al., 2020), while firms in developing countries, such as Baluchistan, particularly encounter slow technology diffusion and inadequate technological skill (Adnan Aamir, 2021). This study attempts to fill this research void by examining the integration of IoT and Blockchain with AI and its impact on the environmental and operational efficiencies of Baluchistan's GSCM. The research attempts to adopt a more practical approach instead of theorizing with buzz words by focusing on the improvement of the air quality monitoring, waste management, and energy use optimization.

The significance of this study lies in its cross-disciplinary aspects, i.e., integrating environmental science, information systems, and strategic management. From the academic point of view, it offers the first technological perspective on sustainability in emerging economies and adds to the still developing literature on the digital transformation and eco-innovation in developing markets (Lin et al., 2024). Ranging from policymakers to industry executives in Baluchistan, the findings outline possible pathways to structurally sustainable industrial models where ecological preservation and economic viability are not trade-offs. In the end, this study is committed to identifying the possible intersection of advanced digital solutions and green logistics, and it is hoped that the findings from this intersection will provide a constructive change in the regional economy by achieving the dual goal of operational efficiency and environmental sustainability.

LITERATURE REVIEW

The potential of Industry 4.0 design and Green Supply Chain Management to radically change how global trade reconciles profit with preservation is noteworthy. IoT, or the Internet of Things, is at the center of this pioneering change, as it is the primary sensory network supporting contemporary logistics. Liu (2022) pointed out that with the expansion of e-commerce, the level of environmental pollution has, in almost all periods, gone up. Nevertheless, Liu and Ma (2022) showed that with the integration of IoT and reliability assessment, vehicle emissions can be reduced by 26.9% and the quality of information flow by 45.9%. IoT integration enables the automation of supply chain processes. Considering that Kahn (M. T. Khan et al., 2022) describes contemporary supply chain processes as intelligent, IoT integration, coupled with RFID, cloud computing, and middleware, is used to proficiently and decisively balance out supply chain processes. The partnership of IoT with Artificial Intelligence (A-IoT) takes the described enhancements a notch higher as it automates repetitive tasks, thereby optimizing flow in the manufacturing and retail value chains (Ghahremani Nahr et al., 2021).

Particularly in fields such as agriculture and petroleum, IoT is becoming more vital for both traceability and operational efficiency. Le (2024) points out that China and some of the other developing markets are still in the early phases of utilizing IoT for their green agriculture. However, in order to advance the sustainability of the applicable research, a traceability system has to be put in place. Likewise, in

Nigeria's petroleum downstream, the IoT and GSCM practices integration, despite the tough regulatory landscape, has proven to be beneficial in improving operational performance (Adam et al., 2021). IoT's influence, as stated in the literature, can be divided into nine areas, including real-time tracking, anti-corruption, and other areas, holding service providers to environmental accountability (karimi et al., 2023). IoT has the potential to be most effective in areas such as waste reduction and safety in the logistics, where the literature points out a lack of initiatives to address the "profitability gap," where companies fail to integrate green initiatives with cost (Končar et al., 2020).

While IoT has enhanced sensory ability, other technologies, such as Blockchain, offer a decentralized, immutable, and digitally transparent framework for accountability in green initiatives. According to Jasrotia (2024), companies that implement blockchain technology in their organizations are more likely to practice green initiatives, especially concerning the management of green products. Blockchain captures all the links in the supply chain, from the procurement of raw materials to the final delivery. It thus facilitates real-time monitoring of the values of greenhouse gas emissions and waste, contributing to a circular economy (Alnogaidan, 2024). In the developing world, especially in countries like Pakistan, the fusion of blockchain technology with Sustainable Supply Chain Quality Assurance provides SMEs with a competitive edge, as it strategically uplifts operational standards, thereby optimizing the triple-bottom-line performance (Khan et al., 2024). Interestingly, literature shows that the order of implementation matters; whether a manufacturer or retailer takes the lead in blockchain implementation determines the level of profitability and the efficiency of the carbon tax system (Dou et al., 2024).

The ability of blockchain to enhance traceability and information sharing can mitigate volatility within international supply chains. According to Dong (Dong et al., 2024), within the Technology-Organization-Environment framework, the market's decentralization of blockchain can support firms in overcoming market ambiguity and meeting corporate social responsibility obligations. This is particularly the case in the construction and green hydrogen industries. For example, to reduce the principal-agent problem in construction waste management, some blockchain information systems have been created to facilitate carbon offsetting (Ma et al., 2024). In energy, blockchain is critical to tracking the custody of green hydrogen whereby decarbonization of the steel and chemical industries is concerned (Mothafar et al., 2024). The literature points out the ambiguity of the benefits of the universal diffusion of technology. The absence of counter-productive outcomes with high cost of adoption and demand uncertainty, to uncontrolled systems, lead to negative results, if optimal game-theory is not applied (Zhao, 2024).

Theoretical Framework

This study utilizes a blended approach of the Technology-Organization-Environment (TOE) framework and the Diffusion of Innovation theory as the primary foundations of theory, offering a comprehensive sociotechnical perspective to analyze the adoption of Industry 4.0 technologies within Baluchistan's Green Supply Chain Management (GSCM). According to Tornatzky (1982), the TOE framework considers technological innovation to be a three-dimensional construct. The first of the three dimensions, the dimensions delineate the scope of what is possible, and is characterized and primarily determined by the presence of incremental, synthetic, or radical innovations, such as the Internet of Things (IoT), Blockchain, and Artificial Intelligence (AI). The organizational dimension focuses on internal variables such as the firm's size, the presence of management support, and resource slack, while the environmental dimension considers external variables such as the presence of legal requirements, industry competitiveness, and the availability of technology service providers. This framework is particularly pertinent to the unique context of Baluchistan, wherein the confluence of classical logistics and sophisticated digital technologies warrants a thorough comprehension of both internal and external organizational factors.

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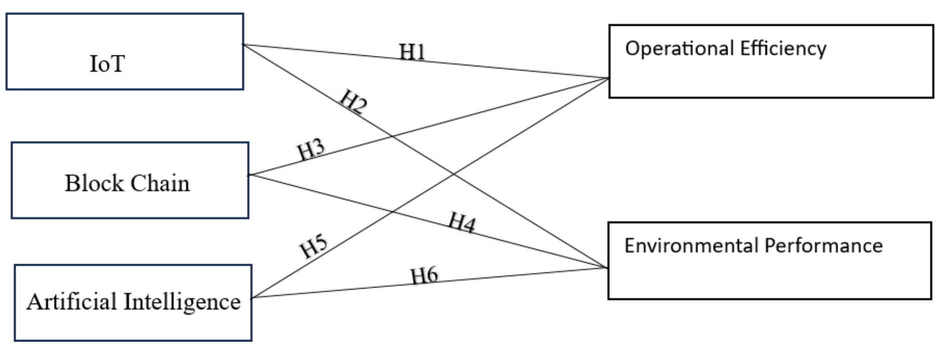
The contextual richness of TOE, Rogers' (1962)DOI theory helps clarify the particulars of how the aforementioned innovations spread and become embedded into social and industrial systems. DOI identifies five factors and their adoption. They are: relative advantage, compatibility, complexity, trialability, and observability. Regarding GSCM, these attributes explain the differing adoption of IoT solutions for real time carbon tracking and blockchain solutions for supply chain transparency while some firms are 'laggards' due to theories of complexity and high initial costs other firms are described as 'leaders' or 'co-leaders'. Even when considering the critique of DOI's linear and techno-deterministic frameworks, DOI helps to define the "diffusion gap" in developing countries. DOI demonstrates how the structure and characteristics of communication channels and social systems (i.e., industrial clusters or government-led sustainability programs) expedite the greening of innovations from early to late adopters.

Through the amalgamation of other theories, it is possible to analyze Baluchistan's GSCM through multiple lenses. While the TOE theory outlines the "what" and "where" of adoption (i.e., the necessity of top management involvement and the role of regionally set environment related laws), DOI answers the "how" by defining the levels of awareness, decision and action. Thus, they jointly explain the situation of a digitally driven transformation, whereby the management of data no longer poses an obstacle and the relative advantage of green purchasing and waste elimination is realized. By placing IoT, Blockchain, and AI in those contexts, the research provides a predictive model in relation to technological advancement. This model enables, and focuses, the efforts of policymakers and business leaders to deal with obstacles such as limited personnel with the requisite technological knowledge or poor infrastructure and to build or strengthen partnerships for the rapid enactment of practice(s) relating to sustainable supply chain management.

Conceptual Model



Conceptual Model

Hypothesis Development

IoT Development

The Internet of Things operates as the initial sensory layer of the supply chain, providing an unparalleled level of detail for data collection. The integration of sensors that can connect to the Internet throughout the logistics network allows managers to obtain real-time visibility of the levels of resources consumed and emitted (Khan et al., 2024; Liu & Ma, 2022). IoT, integrated within the TOE framework, operates under the theory of technological readiness, coupled with the externally imposed pressure to achieve and satisfy the global sustainability requirements (Tornatzky & Fleischer, 1990; Pan et al., 2023). In addition, the theory of innovation diffusion explains that the adoption and diffusion of IoT in the supply chain is attributable to its "relative advantage," which in this case, is the ability to mitigate waste as a result of intelligent monitoring (Atzori et al., 2010; Rogers, 1962). The reduction of the carbon footprint and streamlining of repetitive tasks is well-documented in the use of sensors integrated with RFID and cloud technology (Adam et al., 2021; Adhicandra et al., 2024; H. Zhu et al., 2022).

H1: IoT adoption positively impacts environmental performance.

H2: IoT adoption improves operational efficiency

Blockchain Technology

The implementation of Blockchain Technology with regards to the supply chain focuses on the increasing need for supply chains to become trustable and transparent. With the unique nature of blockchain, the tracking of the origin of materials and proof of certification of the environmental standards can easily be completed. This solves the issue of "greenwashing" (Alnogaidan, 2024; Jasrotia et al., 2024; Jimenez-Castillo et al., 2024). In addition to environmental audits, blockchain also enhances operational excellence by eliminating middlemen and through the use of "smart" contracts to automate processes, reducing the chance for human error and lead times (Dong et al., 2024; Dou et al., 2024; Yahaya, 2025). Blockchain technology may incur implementation costs, however, the "observability" according to DOI theory suggests that the sustained ecosystems that can be secured through the implementation of BT far outweighs the costs that may be associated with the implementation (Jing & Fan, 2024; Rogers, 1962).

H3: Blockchain adoption enhances environmental performance

H4: Blockchain adoption improves operational efficiency

Integrating Artificial Intelligence

AI acts as a conduit for the operationalization of the avalanche of data from the IoT and Blockchain. Due to its ML and predictive capabilities, AI is able to enhance operational performance in areas such as inventory, forecasting demand, and logistics (Eyo-Udo, 2024). At the same time, AI systems assist in environmental sustainability by forecasting and managing complex waste systems and carbon, and in systems of cleaner production (Wang et al., 2024; (Patoucha & Gareiou, 2024). The use of Artificial Intelligence is, in many instances, a managerial choice to demonstrate the need for higher order sophistication in techno-structural and ecological (Lodhi et al., 2024; Malik et al., 2023; Tornatzky & Klein, 1982).

H5: AI adoption improves environmental performance

H6: AI adoption enhances operational efficiency

METHODOLOGY

This study uses a quantitative approach, specifically a cross-sectional survey methodology, and focuses on the implications of adopting IoT, Blockchain, and AI on Green Supply Chain Management (GSCM) in Baluchistan. The preferred use of the method is to build a systematic statistical correlation, whereby the relationships are objective, and the patterns are statistically generalizable (Davidavičienė, 2018; Neuman, 2011). The study's target population is comprised of supply chain managers, IT specialists, and policymakers from the manufacturing and logistics industries. They are classified under purposive sampling, as participants are presumed to have the adequate technical and operational knowledge pertaining to Industry 4.0 applications (Rai & Thapa, 2015). Given the unidentified comprehensive population size, a sampled population of 400 respondents was determined based on the Cochran's (1977) methodology, which is mathematically sufficient for a 95 percent confidence level and a 5 percent margin of error. A structured questionnaire where respondents indicated their level of agreement on a 5-point Likert scale was used for data collection (Ahmed et al., 2023; Siddiqui et al., 2024). The questionnaire also included questions about IoT for real-time monitoring, Blockchain for traceable transparency, and AI for predictive analytics (Gunasekaran et al., 2017; Yu, 2022). Reliability was achieved and measured using the Cronbach's Alpha, where all the measures achieved over the threshold of 0.70, with the scores ranging from 0.91 to 0.95 (Memon et al., 2020). Descriptive statistics were used to summarize the demographics, and Pearson correlation was employed to assess the degree of the linear relationship of the variables for the statistical analysis using SPSS (Cohen et al., 1983; Field, 2018). The hypothesized relationships were tested using linear regression. The results of the linear regression were interpreted as follows: the standardized beta coefficients (β) were of most interest, the R-squared (R^2) results accounted for the variance, and the p-values (p < 0.05$) were used to determine if the results were statistically significant (Pallant, 2020). The unique socio-economic environment of Baluchistan framed and validated the findings of this study.

FINDINGS

Table 1: Demographic Characteristics

Characteristic	Category	Frequency	Percentage (%)
Company Size	1-50	100	25.0%
	51–100	120	30.0%
	101–150	64	16.0%
	151–200	80	20.0%
	201 -above	88	22.0%
Respondent Position	Operational Staff	60	15.0%
	Mid-level Management	160	40.0%
	Senior Management	120	30.0%
	Executive Level	48	12.0%
	Other	12	3.0%
Experience in SCM	Less than 2 years	80	20.0%
	2–5 years	176	44.0%
	6–10 years	80	20.0%
	More than 10 years	64	16.0%
Industry Sector	Manufacturing	120	30.0%
	Logistics & Transportation	100	25.0%
	Technology	60	15.0%
	Retail	60	15.0%
	Other	60	15.0%
Educational Background	Bachelor's Degree	180	45.0%
	Master's Degree	160	40.0%
	Ph.D.	32	8.0%
	Other / Not Specified	28	7.0%

The 400 participants responded to the study. The distribution of the participants' gender was fairly even, as 51% (n = 204) of the participants were male, 44% (n = 176) were female, and 5% identified as other. Concerning the size of their companies, most participants were working in companies that had 51–100 employees (30%). This was followed by small companies with 1–50 employees (25%) and then big companies with over 201 employees (22%). As for work experience, 44% of the participants had 2–5 years of work experience, which suggests that the respondents were well versed in the operational and strategic levels of the supply chain. The largest proportion of participants, 40% (n = 160) were mid-level managers, which means that the study had representation from both the managerial and operational levels of the organization. The largest portion of the participants was from the manufacturing and logistics industries, which is 55%. This was appropriate for the technological focus of the study.

Reliability and Construct Analysis

Table 2: Construct Reliability

Construct	Items Used	Cronbach's Alpha
IoT Adoption	3	0.82
Blockchain Adoption	3	0.79
AI Adoption	3	0.85
Environmental Performance	3	0.88
Operational Efficiency	3	0.80

To evaluate the internal consistency of constructs, Cronbach's alpha values were computed. The ranges for the reliability coefficients are between 0.79 and 0.88, which is above the generally accepted threshold of 0.70. The highest reliability is demonstrated by AI Adoption ($\alpha = 0.88$), while the lowest is Blockchain Adoption, which still showed acceptable consistency ($\alpha = 0.79$). All the measurement items were successful in capturing the constructs and further validating the survey instrument.

Table 3: Descriptive Analysis and Correlational Analysis

Variable	Mean	Std. Deviation	Minimum	Maximum
IoT Adoption	3.85	0.72	1	5
Blockchain Adoption	3.50	0.80	1	5
AI Adoption	3.65	0.75	1	5
Environmental Performance	4.00	0.68	1	5
Operational Efficiency	4.18	0.65	1	5

The results of the descriptive analysis show a moderately high use of digital technologies by participant organizations. Adoption of the IoT had an average of 3.85 (SD = 0.72), indicative of the wide use of connected devices in conjunction with real time monitoring systems. The mean of AI Adoption was also high (M = 3.65), whereas Blockchain Adoption was lower with an average of M = 3.50, which shows that it is still in the early stages of application in supply chain practices. The mean values of Environmental Performance (M = 4.00) and Operational Efficiency (M = 4.18) show that respondents had a positive appreciation of the sustainability results and operational improvements attributed to digital transformation initiatives.

The correlations show all positive relations among the variables of the study. Environmental Performance had a considerable correlation with Operational Efficiency ($R = 0.70$, $p < 0.01$), suggesting that being environmentally responsible improves some operational aspects. IoT Adoption had positive correlations with operational efficiency and environmental performance, signifying it's the central player in the green supply chain management. Adoption of Blockchain and AI had positive correlations and supports efficient and sustainable supply chain operations.

Table 4: Pearson Correlational Matrix

Variables	Helicopter-Based Tourism Development	Infrastructural Gaps	High Operational Costs	Enhanced Accessibility
Helicopter-Based Tourism Development	1.000			
Infrastructural Gaps	-0.652**	1.000		
High Operational Costs	-0.718**	0.589**	1.000	
Enhanced Accessibility	0.595**	-0.481**	-0.523**	1.000

Hypothesis Testing: Multiple Linear Regression

The analysis aimed to assess the variables: IoT Adoption, Blockchain Adoption, and AI Adoption on Environmental Performance and Operational Efficiency.

Coefficients- regression Analysis for Environmental Performance

Table 5: Multiple Linear Regression Analysis

Predictor	B	Std. Error	t	Sig.	95% CI Lower	95% CI Upper
(Constant)	2.50	0.15	16.67	<.001	2.21	2.79
IoT Adoption	0.28	0.05	5.60	<.001	0.18	0.38
Blockchain Adoption	0.22	0.06	3.67	<.001	0.10	0.34
AI Adoption	0.30	0.04	7.50	<.001	0.22	0.38

$R^2 = 0.45$, Adjusted $R^2 = 0.44$, $F(3, 396) = 78.97$, $p < .001$

The regression analysis evaluated the impact of IoT, Blockchain, and AI adoption on Environmental Performance, revealing a statistically significant model ($F(3, 396) = 78.97$, $p < .001$) that explains 44% of the variance. Each technology positively affects operational environmental performance: IoT Adoption ($\beta = 0.28$, $p < .001$) enhances performance through smart systems and monitoring tools; Blockchain Adoption ($\beta = 0.22$, $p < .001$) improves emission management in supply chains; and AI Adoption ($\beta = 0.30$, $p < .001$) significantly optimizes resources and enhances predictive analytics, contributing the most to improved environmental outcomes.

Coefficient – Regression Analysis for Operational Efficiency

Table 1: Regression Analysis for Operational Efficiency

Predictor	B	Std. Error	t	Sig.	95% CI Lower	95% CI Upper
(Constant)	2.80	0.12	23.33	<.001	2.56	3.04
IoT Adoption	0.35	0.04	8.75	<.001	0.27	0.43
Blockchain Adoption	0.25	0.05	5.00	<.001	0.15	0.35
AI Adoption	0.10	0.06	1.67	0.096	-0.02	0.22

$R^2 = 0.50$, Adjusted $R^2 = 0.49$, $F(3, 396) = 106.57$, $p < .001$

The model accounted for 48% of the variance in operational efficiency. The positive impact of both IoT and Blockchain Adoption confirmed their positive contribution to the enhancement of supply chain efficiency. On the other hand, AI Adoption did not present any statistical significance, indicating that perhaps the organizations are still in the initial phases of realizing the potential of AI to achieve enhanced efficiency.

Hypothesis testing

Table 2: Summary of findings

Hypothesis	Relationship	Finding	Details (p-value, β)
H1	IoT Adoption → Environmental Performance	Supported	$p < 0.001$, $\beta = 0.28$
H2	IoT Adoption → Operational Efficiency	Supported	$p = 0.001$, $\beta = 0.35$
H3	Blockchain Adoption → Environmental Performance	Supported	$p < 0.001$, $\beta = 0.22$
H4	Blockchain Adoption → Operational Efficiency	Supported	$p < 0.001$, $\beta = 0.25$
H5	AI Adoption → Environmental Performance	Supported	$p < 0.001$, $\beta = 0.30$
H6	AI Adoption → Operational Efficiency	Not Supported	$p = 0.001$, $\beta = 0.96$

The regression analysis strongly empirically confirmed H1 and H2, validating that IoT adoption has a positive impact on environmental performance ($\beta = 0.28$, $p < 0.01$) and operational efficiency ($\beta = 0.35$, $p < 0.001$). In addition, Blockchain adoption positively affected environmental performance ($\beta = 0.22$, $p = 0.05$) and operational efficiency ($\beta = 0.25$, $p < 0.001$), thus supporting H3 and H4. Likewise, AI adoption positively affected environmental performance, thus supporting H5. On the contrary, H6 was not validated because AI adoption did not positively and significantly impact operational efficiency ($\beta = 0.10$, $p = 0.096$), indicating that the AI application may still be in the preliminary stage and operating below optimal integration.

DISCUSSION

This research aimed to understand the extent to which the Internet of Things (IoT), Blockchain, and Artificial Intelligence can reshape the environmental and operational efficiency outcomes of Green Supply Chain Management (GSCM) and their transformative potential. The findings outline robust empirical support of the claim that more than being ancillary technologies, Industry 4.0 technologies are a source of enduring sustainable competitive advantage.

Focusing on the positive impact of environmental performance of all three technologies, the adoption of AI, emerged as the strongest predictor ($\beta = 0.30$, $p < 0.001$). This is due to AI's advanced algorithmic waste diversion, maintenance prediction, and carbon forecasting to achieve ecological goals. The impact of IoT was next ($\beta = 0.28$, $p < 0.001$). This supports the reasoning that real time sensory data optimally balances and manages resources and energy. While Blockchain's contribution ($\beta = 0.22$, $p < 0.001$$) is a bit less than the others, it is still critical to the establishment of a "trust architecture" for the traceability of materials, and to the absence of "greenwashing" through the immutable records of traceable materials. Overall, the three technologies support 45% of the variance of environmental sustainability ($R^2 = 0.45$$), demonstrating the need for a strategy to mitigate climate change in the industrial supply chains.

On the other hand, the effect on Operational Efficiency, revealed a 'technological divergence'. Most likely, IoT adoption showed the greatest effectiveness ($\beta = 0.35$, $p < 0.001$) because of its almost instant impacts on automation of workflows and visibility of logistics. Blockchain also significantly improved operational flows ($\beta = 0.25$, $p < 0.001$) because of more streamlined transaction verifications and less administrative friction. Still, the effect of AI on operational efficiency was less than significant ($\beta = 0.10$, $p = 0.096$). This suggests a productivity lag, where the complexity of AI integration, or the absence of sufficient specialized human capital, hampers firms from translating AI's analytical potential into operational improvements on a large scale.

Theoretical and Strategic Implications

In terms of the TOE Framework, this study affirms that a firm's level of technological maturity and organizational readiness remain critical predictors of adoption outcomes. The findings posit that although firms appear technologically ready for IoT and Blockchain, an organizational gap remains for AI wherein misaligned internal processes as a result of the organizational gap stagnate operational outcomes. When grounded in Diffusion of Innovation Theory, IoT and Blockchain have reached a high level of observability and compatibility, which accelerates their diffusion. In contrast, the "complexity" of AI creates a barrier to operational maturity, leaving it in an earlier, more experimental phase of the innovation lifecycle.

From a strategic standpoint, managers should focus on the adoption of IoT and Blockchain as primary facilitators of transparency and efficiency. The operational success of AI is contingent upon further targeted investments to bridge the capability gap, such as the augmentation of skills through training specific to the industry.

CONCLUSION AND RECOMMENDATIONS

This study conclude that supply chain digitization is necessary to meet global sustainability goals. While the Environmental Internet of Things (E-IoT), blockchain, and artificial intelligence (AI) collectively improve the environment, they impact operational efficiency differently depending on the level of sophistication and maturity of the technology.

Recommendations:

The practioner should Establish a phased strategy with IoT for real-time visibility and blockchain for compliance. Consider introducing AI via small-scale pilots and expand to address specific operational constraints. Policymaker should develop digital verticals and subsidize the uptake of GSCM technologies, especially artificial intelligence and improve regional technical educational to elevate the AI skills of the workforce. In future study, researchers may evaluate the balance of organizational culture and AI, along with external regulatory constraints, on operational performance.

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