

Enabling Sustainability and Compliance for Technological Transformation in Procurement and Supply Chain

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Abstract

This research focuses on the role emerging technologies have in driving changes in procurement and supply chain management processes toward better sustainability and redoubtable compliance. Traditional procurement and supply chain management strategies undergo dramatic change continually becoming complex with the deep sustainability and regulatory compliance at the core of the sourcing landscape. This research delves into how such innovations as Artificial Intelligence (AI), Blockchain, the Internet of Things (IoT), and Digital Product Passports (DPPs) essentially revolutionize practice within procurement and supply chain logistics from 1PL to 6PL, along with their implications for sustainability and compliance. The research generally used a mixed-method approach, integrating a review of literature, analysis of case studies, and analysis of technology. This will provide a conceptual model of how these technologies will be incorporated into the supply chain operations presented in such a manner that it will bring quick, efficient, and responsive visibility of the activities that take place in the ecosystem of the supply chain in a manner that is compatible with global sustainability and regulatory standards. The research points out some of the challenges that are inherent in the technologies' development such as integration difficulties, lack of scalability, and strategic framework to be used in the implementation. This research will elaborate on the role of technology in driving sustainable procurement and supply chain management to give practical guidance to organizations seeking to achieve unsurpassed operational excellence while ensuring environmental responsibility and regulatory compliance.

Keywords

Artificial Intelligence, Blockchain, Internet of Things, Supply Chain Management, Procurement, Sustainability, Compliance, Digital Product Passports.

1. Introduction

The quick pace of technological advancement has sharply cut through traditional procurement and supply chain management. These functions have evolved into strategic drivers for competitive advantage, encompassing cost optimization objectives as well as sustainability goals and regulatory compliance (Radmanesh et al., 2023; Fatahi Valilai et al., 2020). In such a complex landscape, there is thus the need for a deeper understanding of these intricate connections between technology and procurement and the transformation of supply chains.

In history, the approach towards logistics strategies was defined by the degree of activities that were outsourced, which meant there were providers of services ranging from 1PL (first-party logistics) to 5PL (fifth-party logistics) providers (Hesse et al., 2004). However, due to modern technologies and the pace of globalization as well as development within the realm of e-commerce, the scope has currently been pushed to 6PL. The above form relatively newer categories that point out the growing integration between logistics and sustainable procurement (Govindan et al., 2018). Therefore, this paper emphasizes that it is extremely critical to understand the very specific technological changes

taking place for each phase of logistics flow in subtle detail and how they are affecting procurement in the contemporary era.

Making compliance needs like conflict minerals reporting, modern slavery laws, and anti-corruption statutes among others, part of organizational strategies with which they integrate indeed layers on newer levels of complexity into business operations today. This multi-dimensional challenge calls for a high-stake technology-embedded approach in which the technology works as a pivot to harbor an easily operated and automated compliance mechanism. In the given scenario, organizations with the aid of technologically advanced solutions can take a holistic look at their compliance protocol in which the issue of the flow of information is being looked after comprehensively, transparently, and efficiently.

In addition, the adoption of technology features in the realization of strong audit systems throughout the supply chain and, as a result, contributes to how the suppliers are scrutinized for the observance of the standards that are legal and ethical. In this respect, integration is also proven to help diagnose the risk indicators with accuracy in no time, and hence, the probable compliance breaches are guarded against. In that way, business is better aligned to stay ahead of global regulation, to ensure the highest standards of corporate responsibility, and to imbue accountability and integrity throughout supply chains. The discussion in this technology management shifts the focus of what technology can do for organizations to improve compliance processes but further positions it as one of their crucial assets in managing and improving organizational resilience (Sroufe et al., 2002).

1.1 Research Objectives and Significance

This paper tries to conduct a systematic inquiry around how artificial intelligence, blockchain, Digital Product Passports, and other emerging technologies impact basic procurement activities. Inquiry questions will cover issues on supplier selection and evaluation, contract negotiation, material and inventory management, and risk in the supply chain. Breaking this web will illustrate how technology has changed procurement practices at every point in the logistical value chain.

The second objective of the research is to identify the impact of advanced technologies on the processes of procurement in ensuring regulatory compliance and sustainability. As such, it is going to be centered on how AI, Blockchain, and other such innovations sustain the new generation of activities linked to compliance tracking and auditing, demanded by the continuous changes in regulation affecting labor standards, the environment, and ethical sourcing. Additionally, the capability of technologies will be considered to support the assessment of the carbon footprint, analysis of supplier sustainability, as well as the traceability of a product from end to end. In an ever-complicating regulatory landscape, and at the same time when the world requires increasingly that goods are produced in an ethical and sustainable manner, this investigation will look at how technology can ensure that procurement is compliant and responsible.

2. Literature Review

This paper presents a wide literature review on the impact of technology on the alteration of procurement strategies and its effect on sustainability. The literature review covers a wide range of technological innovations, which are not limited to e-procurement systems, artificial intelligence, and blockchain technologies. Moreover, the research studies examined cover the impact of these technologies on the efficiency, cost reduction, and transparency of procurement processes. Finally, the literature review also addresses how technological innovations serve as a basis and foster sustainable procurement practices in terms of improved environmental responsibility, social accountability, and even economic benefits. The following hence develops a comprehensive review of the dynamics between technology and procurement in the wider perspective of literature from empirical research to case studies and theoretical contributions. The reflection is within the synergies aimed at lighting the sustainable development goals and challenges in the materialization of their actualization, such as barriers to technological adoption, the need for digital literacy, and implications of technological obsolescence.

2.1 Practical Relevance

E-Procurement Technology Adoption in Indian Industries: A study focusing on e-Procurement technology's impact on Indian industries found that 77.3% of businesses are quite satisfied with their e-Procurement solutions. This study by D. Swamy et al. underscores the role of the technologies that are being implemented for the procurement

process and suggests the strategic advantages for the logistics and supply chain management approaches, which include even those that may be related to the 6PL model (Nanjundeswaraswamy et al., 2014).

E-Procurement System Adoption in a Taiwanese Notebook Company: Shin-Horng Chen thoughtfully observes the problems that were faced during the adoption of e-procurement systems while on the course of supply chain migration at a leading Taiwanese notebook company. The exploration raises important issues about the role of architectural innovations in procurement practices, and risks related to technology obsolescence. The study serves as a good example warning against ongoing adaptation and flexibility in integrating e-procurement solutions for sustainable procurement (Chen, 2010).

Some identified barriers to sustainable procurement in the Swiss public sector linked to the purchase of ICT hardware include those by Elz and Stuermer: Elz and Stuermer suggest that it is difficult to define green or sustainable procurement within the public sector. The barriers identified were no clear definitions of sustainable products, no market intelligence in terms of sustainable offerings, and inflexible procurement procedures and attitudes. These findings highlight that the shift toward sustainable procurement practices is complex and requires clear guidance and pioneering approaches (Welz et al., 2020).

Adoption of Digital Procurement in Airports Company South Africa (ACSA): Motaung and Sifolo explore the adoption of digital procurement at ACSA, pointing at specific barriers in the organization, such as potential job losses, concerns with cybersecurity, interoperability issues, skill gaps, and system downtimes. It presents an overall view of digitalization of the procurement process barriers, emphasizing the need to deal with both the technological and human factors in executing a successful digital procurement solution (Motaung et al., 2023).

E-Procurement Adoption Projects in the Italian Market: Belisari, Binci, and Appolloni review e-procurement systems in Italy and the central role of advisory services in their deployment. This case study therefore finds out how these services help the organizations to overcome the barriers to adoption of e-procurement, thus ensuring that the expected benefits are realized. The highlighted pressing need for external support and expertise in effectively dealing with the challenges of e-procurement implementation points to advisory services in their facilitation of technology-harmonious integration in the procurement process (Belisari et al., 2020).

These in-depth case studies show the multiple complexities of integration of technology into the procurement processes for sustainability ranging from pointing out the benefits of technological advancement through improved efficiency, to cost-effectiveness, and sustainability in procurement practice. They do, however, point to serious issues such as technological, organizational, and cultural barriers. Case studies would shed valuable insights on the significance of collaboration, innovation, and seeking external assistance while venturing into technology integration within procurement and would thus act as an aid for organizations looking at improving their procurement strategies for sustainability.

2.2 Theoretical Relevance

Technological development is now included as one of the processes characterizing procurement for Industry 4.0, which defines it as a critical step to enabling efficient, transparent, and sustainable practices in procurement. Key technologies behind this transformation include e-procurement systems, blockchain, artificial intelligence (AI), and the Internet of Things (IoT). The role of such technologies in promoting green supply chain management, especially in the renewable energy sector, therefore cannot be overemphasized, through improved efficiency and transparency toward sustainability challenges (Labaran et al., 2023; Ganesan et al., 2023). Further, Santhi and Muthuswamy (2022) elaborate on how technologies in the Fourth Industrial Revolution paved the way out from traditional as well as contemporary problems faced by supply chains through agility, transparency, and resilience (Raja Santhi et al., 2022). This narrative also supports Althabatah et al. (2023) in their assertion that it leads to enhanced advantages through the streamlining of supplier assessment and cost optimization through e-procurement and blockchain (Althabatah et al., 2023). It is not so often that the import of technology comes together with data on the effects, impacts, and benefits it may produce. In any case, the import of technology brought about efficiency in public procurement with its resultant positive effects on the realization of principles of the circular economy (Mandala et al., 2024).

A more detailed explanation of the role of the blockchain in sustainability by Hong & Xiao (2024) is in the incentivization of recycling, ease of accounting for carbon, and increased supply chain transparency through such innovative solutions made possible by the blockchain. Blockchain has the potential to create verifiable and immutable records of sustainable practices, hence resulting in the integrity and trustworthiness of green supply chains (Hong et al., 2024).

Technologies used for procurement from Industry 4.0 can have a direct impact on sustainability by enabling green supply chain practices and supporting the circular economy. According to the review, AI, IoT, and blockchain, all have their places within our future sustainable renewable energy sectors for better efficiencies in operations and management of resources (Labaran et al., 2023). Rejeb and Appolloni (2022) advance on how such technologies further allow for progressing to circular procurement, with better use of resources and recycling (Rejeb et al., 2022). In a corresponding result, it is shown by Santhi and Muthuswamy (2022) that Industry 4.0 technologies can have a substantial downward effect on the environmental impact on supply chains by enhancing the resiliency and transparency of the supply chain.

However, the integration of technology in procurement is not without a fair share of challenges and limitations. It comes with high initial costs, resistance to change, and requires specialized skills (Rezapour Niari et al., 2023). In the post-COVID-19 world, Mathiyazhagan et al. (2023) have emphasized that resilience and adaptability in sustainable supply chains are of key importance and require strategic investments in technologies and training (Mathiyazhagan et al., 2023). Importantly, the level of complexity in the implementation and organizational buy-in further reiterates a holistic approach required for integrating technology within procurement processes. Table 1 of literature review offers a multifaceted view concerning technological transformation in procurement, supply chain management towards sustainability, and compliance. From various scholarly works, it is evident that the use of current technologies such as AI, e-procurement systems, and blockchain in the procurement process is very instrumental in bringing efficiency, cost-effectiveness, and transparency. These technologies not only help in making operations easy but also help in supporting the practice of sustainable procurement through improved environmental stewardship, promotion of social responsibility, and offering economic benefits. The literature reviewed, therefore, emphasizes the strategic role of these innovations as a source of competitive edge, and it signals potential adoption barriers, such as the need for digital literacy and risks of obsolescence, among others. The review, however, finds promising benefits but also points to some gaps in today's academic understanding—in particular, when it comes to their practical implementation and real impact on procurement and sustainability.

Table 1. Literature review analysis

	Case Study	Author	Key findings	Technology used	Impact on procurement, supply chain and sustainability
1	Collaboration for Green Component Procurement in High Technology Industries	(Yan et al., 2016)	Collaborative strategies enhance sustainability and efficiency in procurement practices.	Collaborative strategies	Cost-effective means and efficient delivery time.
2	E-Procurement Technology Adoption in Indian Industries	(Nanjundeswaraswamy et al., 2014)	77.3% of businesses are quite satisfied with their e-Procurement solutions.	E-Procurement	Strategic advantages for logistics and supply chain management.
3	E-Procurement System Adoption in a Taiwanese Notebook Company	(Chen, 2010)	Architectural innovations are crucial in e-Procurement adoption but face obsolescence risks.	E-Procurement systems	Warning against ongoing adaptation and flexibility in integrating e-Procurement solutions.
4	Barriers to Sustainable Procurement in the Swiss Public Sector	(Welz et al., 2020)	Barriers include lack of sustainable product definitions and inflexible procurement procedures.	ICT hardware procurement	Complex shift toward sustainable practices requiring clear guidance.
5	Adoption of Digital Procurement in Airports Company South Africa (ACSA)	(Motaung et al., 2023)	Specific barriers include job losses, cybersecurity concerns, interoperability issues, skill gaps, and system downtimes.	Digital procurement technologies	Overall view of the digitalization process emphasizing the need to deal with technological and human factors.
6	E-Procurement Adoption Projects in the Italian Market	(Belisari et al., 2020)	Advisory services play a central role in overcoming barriers to e-Procurement adoption.	E-Procurement systems	Facilitation of technology integration in the procurement process.
7	Pricing in a 4PL Environment	(Björholt et al., 2011)	4PL services integrate technology for comprehensive supply chain solutions.	4PL services	Principles could act as fundamental building blocks for understanding the dynamics of 6PL.

2.3 Enabling E-Procurement

The E-procurement concept began developing towards the close of the 20th century when the first depictions of the internet and what e-procurement entailed became clear, changing entirely how business was done (Habtemichael et al., 2024). This can be seen with the push toward digital systems of procurement due to the extent that traditional procurement mechanisms were unattractive, mostly as a result of inherent weaknesses such as slow turnaround times, high processing costs, and an increasing potential for errors and fraud. Evidence of its potential can be presented in the early adopters like the Automotive industry with the development of the Automotive Network Xchange (ANX) in

the late 1990s (Handfield et al., 2002). E-procurement brought several developments in reengineering the process of procurement through digital means; a major contribution that this brought about was mostly owed to technological innovations and the changing needs in supply chain management. It then ensured that concreted innovations are based on strong ground of inefficiency characteristic of the conventional procurement system; rather, the driving goals behind the emergence drew from the foundation to strengthen them in a most befitting way for driving operational efficiency, expenditure reduction, and improved transparency in transactions. The development is attributed to be pushed by technological, organizational, and environmental, collectively bringing a great change within the procurement industry (Nawi et al., 2016; Perez, 2022; Rejeb et al., 2022).

The tools essential to e-procurement include software applications, platforms, and technologies meant to help and automate the respective aspects of the process. These tools have been developed in a way that they help the organization in managing their respective procurement activity effectively, starting from procurement of respective goods and services, and moving to negotiation of contracts and supplier relation management. The e-procurement tools will enable companies to ease their procurement process at a reduced cost, improve transparency, and enhance general effectiveness in procurement operations. Here, therefore, are some of the major tools often employed in e-procurement are shown in Figure 1.

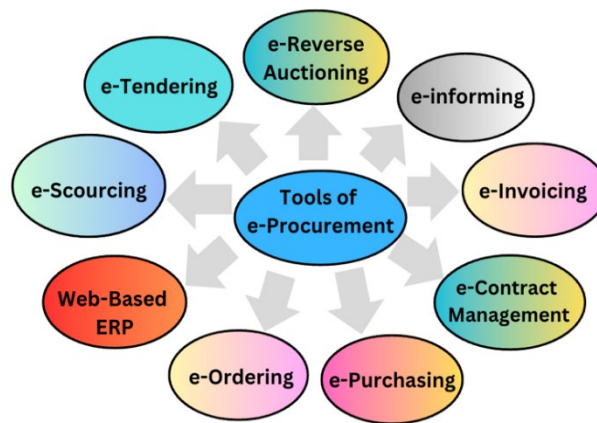


Figure 1. Causal Loop Diagram of the identified factors

The current situation of the e-procurement system represents, on the one hand, its mass implementation in the most of all industries and, on the other hand, the pursuit to achieve greater efficiency, transparency, and sustainable development in the process of procurement. The Internet-based applications and tools coming into play have fundamentally mechanized and standardized procurement activities from sourcing and ordering to invoicing and payment. Modern electronic procurement systems offer some functionalities at the most basic level, while other advanced technologies include artificial intelligence (AI) and machine learning to increase decision-making and predictive analytics. The applications have now become the epicenter for supplier relationship management, assisting in optimizing inventory for cost savings, and reduction in procurement cycles for operational efficiency. The e-procurement module integrates seamlessly with the e-business functions of a company and into the enterprise resource planning (ERP) systems, all focusing on a management approach regarding business processes with cohesive, free information flow and data analysis at any time.

Additionally, e-procurement is becoming more and more important in ensuring ethical and sustainable supply chains. E-sourcing, e-tendering, and e-invoicing are only a few of how e-procurement platforms encourage social responsibility and environmental standards compliance in the procurement procedures of business organizations. E-procurement strategies, as enabled by e-procurement practices, should be within the framework of encouraging efficient use of resources and fostering collaborative consumption and reuse practices required of a circular and shared model economy. Sustainability and compliance are therefore shared equal importance with operational efficiency when the technologies are adopted by businesses; thus, innovations are expected from the mix. This kind of evolution

reemphasizes strategic moves from traditional modes of procurement towards much more digital, interconnected, and sustainable ecosystems in shaping the future of supply chain management.

2.4 E-Procurement in Circular and Shared Economy and Role of 6-Party of Logistics (6PL)

Logistics is now one of the central ideas that subconsciously coordinate aggregate businesses across almost all industries today, for the success, seamless operation, and difficulty of the complex world of supply chain management. Logistics, at the basis, refers to the whole set of activities that are involved in effective and efficient planning, realization, and control, concerning forward and reverse flow, and storage of goods, services, and information from point of origin to place of consumption, so that the requirement of the customer are met. This is the complex process of high grade and wide scope of activities from how a company gets to procure materials till products are manufactured to the delivering stage of end products to the consuming customer, thus creating wide networks that cut across the whole world. The evolution of logistics has always provided adaptation for an altered business environment and the corresponding perennial technological innovation, apart from consumers' rising insistence on speed and service reliability. This evolution has born the bucket types of logistics providers with names ranging between first- through sixth-party logistics (1PL through 6PL). Each reflects different levels of service complexity and supply chain integration.

The 6PL subsequently provides a frontier review of the integration of supply chain management with artificial intelligence (AI) and automation towards efficiency, responsiveness, and sustainability. The 6PL is a theoretical breakthrough with an AI-driven model to be brought into supply chain management, intending to fully automate and optimize the operations of the supply chain through avant-garde technologies like AI, machine learning, and possibly blockchain. Such a high level of automation has the potential to bring great advancement in the areas of forecasting, inventory management, and overall visibility of the supply chain, which would otherwise bring costs down and improve service delivery due to accurate prediction of demand, coupled with streamlined processes of the supply chain.

However, it is quite visible from the reading of the literature review in conjunction with case studies that this innovative outlook for future supply chain management being offered through the concept of 6PL is largely theoretical and might face significant challenges during practical implementations. There are very many technical, organizational, and economic obstacles such a theoretical model would face, which will hinder practical transfer. Foremost among these is the development of very refined AI algorithms that can, among many others, manage complex supply chain tasks, assure high levels of data security, and privacy, as well as connecting disjointed systems across the supply chain. Further, the organizational change that would need to be affected to align with such a transformative approach would need humongous investment in technology and the development of skills, accompanied by a cultural change to accept automation and AI-based decision-making.

2.5 Technology Innovations towards Sustainability and compliance in Procurement and Supply Chain

The world economy is rapidly expanding, making integration with path-breaking new-age technologies into supply chains central to sustainability and operational excellence strategies. Unlocking technologies that will transform supply chains include blockchain, the Internet of Things (IoT), digital products and augmented AI, 3D printing, robotics, and cloud computing. All these technologies make unique contributions that add a lot to the enhancement of transparency, efficiency, and collaboration across the line. The developments, however, also bring challenges and gaps that exhibit sufficient need to be addressed suitably to leverage the respective potential. Besides, great chances regarding innovation and improvements exist to reinforce further the revolution of sustainable procurement and supply chain management. The Table 2 that follows provides further insights associated with contributions, challenges, and potential improvements for the technologies in the future.

Table 2. Technology Analysis Sustainability and compliance in Procurement and Supply Chain

Technology	Contribution to Sustainable Procurement and Supply Chain	Gaps and challenges	Potential for Innovation and Improvement
Blockchain	<ul style="list-style-type: none"> - Enhances transparency, traceability, and security - Facilitates trustless exchanges. Promotes ethical sourcing. 	<ul style="list-style-type: none"> - Complex integration data privacy concerns. - Requires blockchain literacy. 	<ul style="list-style-type: none"> - New consensus algorithms - Smart contracts for scalability - Collaboration for standards.
Internet of Things (IoT)	<ul style="list-style-type: none"> - Enables real-time tracking - Improves asset management and predictive maintenance. - Reduces wastage. 	<ul style="list-style-type: none"> - Internet dependency; security vulnerabilities - High costs - Requires sensor maintenance. 	<ul style="list-style-type: none"> - IoT security advancements - Low-power networks - Predictive analytics for demand forecasting.
Digital Passport Product and Augmented AI	<ul style="list-style-type: none"> -Advanced analytics for demand prediction -Enables personalized experiences and operational agility. 	<ul style="list-style-type: none"> - Integrating AI complexity - Data quality and bias - High data dependency. 	<ul style="list-style-type: none"> -AI and IoT integration for autonomous systems -Transparent AI decision-making processes.
Robotics	<ul style="list-style-type: none"> -Improves efficiency and safety in warehousing -Automates tasks allowing focus on complex issues. 	<ul style="list-style-type: none"> -High investment and maintenance costs -Technical expertise needed -Job displacement concerns. 	<ul style="list-style-type: none"> -Collaborative robots development -Advanced safety features -Ethical guidelines for automation.

2.5 Research Gap Two-way Perspective

Technology emerges with great anticipation in the current landscape of supply chain management and procurement. The use of technologies such as artificial intelligence (AI), blockchain, Internet of Things (IoT), digital payment platforms, 3D printing, and cloud computing, is bound to come into great use in the current era. That is quite a persuasive vision, looking to the future where the major advancements in redefining procurement and supply chain operations are driven by innovations in technology. But the realization of this potential depends on how mature these technologies are and if in practice, these technologies can be integrated into a maturity level of a supply chain or an existing framework.

The excitement for these technologies' stems from their vast capabilities. AI and machine learning, on the other hand, introduce predictive insight that can improve logistics and even inventory management. Blockchain promises improvement in both transparency and security through the establishment of trust between the transacting parties and over-provenance in the supply chain. IoT allows for asset monitoring and facility control in real time, providing a narrow outlook on the operation of the supply chain. Digital payment platforms allow financial transactions to run at a higher speed with less friction.

Practical factors include the absorptive capability in the supply chain, aligning technological capabilities with operational needs, and strategic frameworks for implementation. The "critical need," as the present analysis identifies is the need for further study that would look to the potential of such technologies, yes, to revolutionize supply chains, but also investigate the practicalities of embedding such technologies within ongoing operations. It proposes developing a strategic model and framework that will guide the differentiated integration of emerging technologies. This model type will have to consider the current state of development of technology, assess a supply chain system for adopting a certain technology, and suggest how the gulf between the potential of the new tech and practical application can be bridged. This view puts into highlights pragmatism in the integration of technologies in supply chains. It advocates for a balanced view that considers both the advantages and the challenges of adopting new technologies. Supply chain managers and researchers could be better posed to negotiate the complexities of technology integration toward efficiency, sustainability, and resilience of supply chains in light of fast-moving technological progress. This discourse on how best the industry can use technology in both the supply chain and procurement is presented within this paper without risks of the pitfalls and challenges attached to assimilation.

3. Methodology and Approach

3.1 A theoretical framework for integrating emerging technologies for sustainable supply chain

The creation of an all-encompassing theoretical framework is a significant step forward in utilizing the synergies of new technologies in the supply chain industry. This model outlines a systematic method for utilizing Artificial Intelligence (AI), Blockchain, Internet of Things (IoT), Digital Product Passports (DPPs), 3D printing, and Cloud Computing throughout various supply chain phases. This framework provides a plan for reaching operational excellence by considering how these technologies interact and their combined effects on supply chain efficiency, sustainability, and compliance, while following global sustainability standards. It emphasizes how technology can improve supply chain transparency, traceability, and resilience when facing disruptions.

The tactical implementation of this framework offers the potential to transform supply chain management by improving operations and guaranteeing adherence to environmental and regulatory requirements. Therefore, it notably impacts both the theoretical and practical aspects of supply chain management, leading the industry towards a more sustainable and efficient future.

of such technology by this model will not only represent the current challenges of sustainability but will enable the supply chain to be able to forecast and relate to the upcoming trends and regulatory changes.

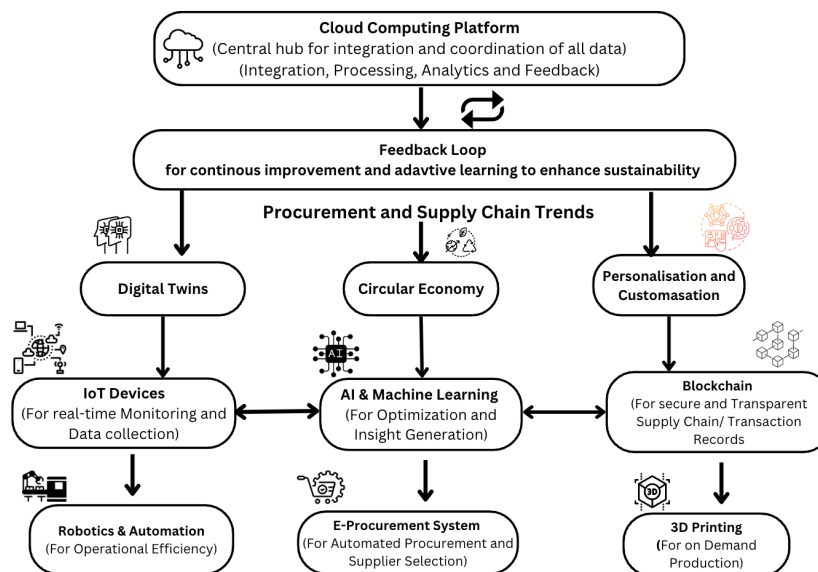


Figure 2. Integrated Technological Framework for Sustainable Supply Chain Management (ITS-SCM Model)

The proposed model as shown in Figure 2, is model contains fully developed technology that works hand in hand to adopt sustainable procurement and supply chain through the exploitation of modern technology developments in the form of the Internet of Things (IoT), Blockchain, Artificial Intelligence (AI), and Machine Learning (ML), Cloud Computing, E-Procurement Systems, 3D printing, Robotics, and Automation. This model will lead to the enabled performance of sustainability in supply chains, directing environmental responsibilities, transparency, efficiency, and adaptability in a manner that characterizes each procurement and supply chain operation. The systematic integration

Sustainability in procurement and supply chain implies another step towards more sophisticated, data-driven approaches that must be done to embrace the complexity of environmental sustainability, economic viability, and socially responsible activity. In the given model, the latest technologies are used to help in building a social system that is capable not only of performing sustainable procurement and supply chain but also of self-development. In basic terms, it means using data and connectivity to drive informed, ethically responsible, efficient decisions that may help push up or down every aspect of sustainability along the value chain.

3.2 Discussions over Integration of Technologies for Sustainable Supply Chain Process

The conceptual model with all the up-to-date technologies focuses on a new revolution in solving sustainability and compliance-related challenges in the procurement and supply chain management identified by the research gap. Such factors are evident in the preformed model structure that is developed to ensure flow information and processes increase decisions and amplification of efficiency in operation. Each of the components plays a very critical role in the model by showing the direction of data, insights, and feedback that power the system to work entirely as an integrated whole.

Some of the emerging technologies in the procurement and supply chain management industry have the potential to bring about developments, leading to operational efficiency, sustainability, and compliance. The relationship between technological innovation and impact on supply chain processes complexity draws a structured approach in capturing such developments that require a detailed road map for adaptation. Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the progress of the project. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest (NASA, 2023). The strategic roadmap that follows delineates the strategic path toward the integration of emerging technologies to become the artificial component of procurement and supply chain operations, running from Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT) to Digital Product Passports (DPPs), setting two prongs for the task in view, capturing the potential of efficiency and transparency to come with these technologies and the cooperation with environmental sustainability and regulatory mandates.

This journey of technologies as illustrated in Figure 3, implies a sense of going through the progression of different stages, right from the point of the initial assessment and planning to scale and continuous improvement. Thus, every critical step in road mapping goes in line with a series of strategic decisions and steps to be taken collectively and collaboratively to ensure that the implantation of technologies is successful. This would require an in-depth examination of the phases of the roadmap and articulation of the processes and strategic imperatives that would underpin the successful adaptation of technology in procurement and supply chain management.

Each phase in the roadmap describes a strategic framework for assisting organizations in stepping through their technological transformation of supply chains towards greater levels of sustainability, efficiency, and compliance.

The first phase signifies the root of the entire roadmap, whereby stringent criticism in minutiae is given on the prevailing procurement and supply chain setup. This stage includes looking critically at the operational efficiency of current sustainability practices and adherence to protocols. This is consistent with TRL 1-2 to the point where it is feasible to recognize the potential influence and application of the new technology in the organization's functioning. A gap analysis helps identify deficiencies and areas where technological intervention can be achieved. This stage, therefore, focuses on strategic interventions that are along the goals of organizations and sustainability objectives and the regulations that are formulated as a coherent base of strategy for the adoption of technology.

Further to the strategic needs identification and potential technological solution in existence, phase 2 refines the appropriate technologies selection process that is parallel to the identified gaps and organizational capabilities. This option covers the appraisal and scoring against technological maturity, scalability, and integration potential with existing systems. Phase 3 ensures that the technologies intended for implementation have a sound pilot testing and this puts the platform from which the technologies may be validated and systematically integrated into the entire setup. In this stage, adequate planning has been put in place that includes the intended thorough technical specifications, system configurations, and workforce training to ensure comprehensive technology integration. Sufficiently well-devised approaches taken for implementation need to minimize disruption and usually follow a phased approach towards management of complexities entailed in transition.

Phase 4 includes continuous monitoring post-implementation to provide some indicator of performance on the newly adopted technologies. In this stage, major key performance indicators (KPIs) are set in line with sustainability, efficiency, and compliance. Big data analytics come in for insights into performance trends and identification of areas that can be optimized to decide. Phase 5 aims to scale successful technologies across the whole supply chain, based on knowledge created in the phases of monitoring and optimization, and infusing a culture for continuous improvement. Focus on scale-up strategies to increase the benefits of technological innovations enabling increases toward sustainability and compliance. This phase displays and represents TRL 9, a very high operational deployment level of technology, with complete operation and continual improvement to meet the needs and difficulties encountered. Implementation of continuous improvement mechanisms that are bound to build an adaptive and resilient supply chain capable of evolving with war-foot changes in technological advancements and shifting regulatory landscapes are considered.

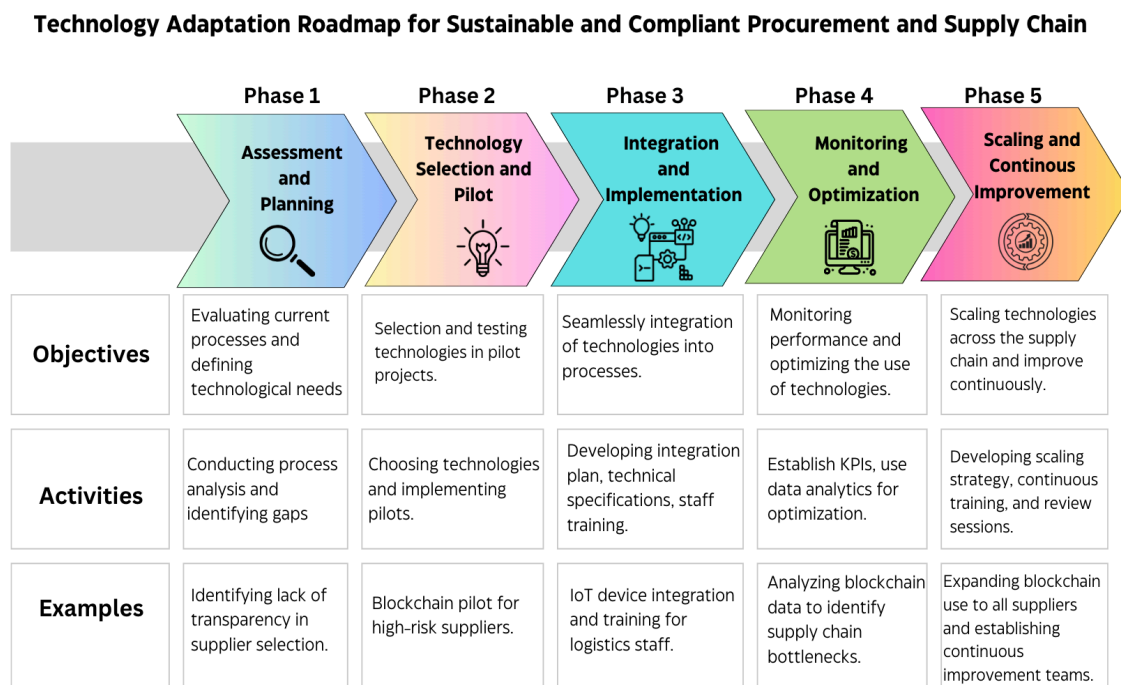


Figure 3. Technology Roadmap for Sustainable and Compliant Procurement and Supply Chain

4. Conclusions and Discussions

In general, this research emphasizes that technological change is pivotal to the transformation in procurement and supply chain management with better sustainability and regulatory adherence. It provides an overview of the synergy effect through the realization of technology integration, such as Blockchain, the Internet of Things (IoT), Digital Product Passports (DPPs), 3D Printing, Cloud Computing, Robotics, and every other technology in the supply chain that imparts the realization of potential services for interactive transparency, efficiency, and resilience of the supply system. It furthers the Integrated Technological Framework for the Sustainable Supply Chain Management (ITS-SCM) Model. This new model will provide a strategy for a blueprint for how to harness the collective development

of such technologies, not only in revolutionizing the supply chain but also ensuring that such critical challenges on sustainability can be taken up under very demanding regulatory standards. This is also of importance to organizations that are seeking a way through the complex dynamics thrown up by modern-day supply chains: those seeking to optimize their operations not only for performance but for being in conformance with environmental protection and legal directives.

The study in detail gives a very comprehensive review of the accepted individual and combined impacts of the specified technologies on supply chain processes. It will further bring out that digitalization has no bounds in the transformation of supply chains and accentuates the need for an all-rounded approach that will leverage the identified technological potential to achieve sustainability goals, and operational excellence, and remain compliant with the global set of standards. It also defines potential barriers that might prove true in the adoption of these technologies, like problems regarding integration, scalability, and the involvement of regulatory frameworks that support innovation. The paper thus offers solutions for some of these barriers and emphasizes the aspect of the creation of a culture of collaboration, continual innovation, and improvement. Therefore, it argues for the creation of such an ecosystem that will allow smooth adoption and use right across the supply chain of emergent technologies.

Future researchers can extend more research on the integration and interoperability of the supply chain ecosystem with emerging technologies like AI, IoT, and Blockchain. This part has identified research that brings to light issues in areas that either undermine data sharing, compatibility of systems, and the establishment of workflows over the technological basis. The research would aim to devise workable frameworks or guidelines that would enable the efficient combination of these technologies to improve supply chain efficiency, transparency, and sustainability. At the core of the full realization of how technological advancements avail their benefits in streamlining supply chain operations and enhancing collaboration between supply partners, lie herein.

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