The Role of Industry 5.0 in Achieving Circular Economy Goals: Integrating Smart Technologies for Sustainable Supply Chains

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Abstract **– This study investigates how Industry 5.0 technology stimulates circular economy practices to generate sustainable supply chain performance. Through the incorporation of new technologies like Artificial Intelligence (AI), the Internet of Things (IoT), and collaborative robotics, companies can reduce resource use and waste output consistent with circular economy. This study follows a quantitative research design, where data has been collected through cross-sectional survey from manufacturing firms which are currently practicing sustainable practices. The conceptual model proposed in this study emphasizes the connections between Industry 5.0 technologies, circular economy practices, smart technologies, resource efficiency and sustainable supply chain performance. The key findings revealed that adoption of Industry 5.0 technologies with good practice enhances resource utilization efficiency and has positive implications for sustainability performances as well. On the other hand, costs related to the adoption of technology and organizational barriers may act as impediments. This also contribute in enriching the knowledge base of sustainable industrial practices on Industry 5.0 which may benefit upon by the organizations and decision makers as well.**

The paper also provides recommendations on how to overcome barriers for widespread uptake by providing guidance to diverse players in the supply chain ecosystem. Thus, this research emphasises the convergence of digital and circular economy in order to achieve sustainability goals in industry.

Keywords **– Industry 5.0, circular economy, sustainable supply chain, resource efficiency, and smart technologies.**

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1. Introduction

Industry 5.0 is the transition from machine automation-oriented Industry 4.0 aroma to the one with a greater human-centric, evolutionary movement of synergy between man and machine. This new industrial revolution can be characterized by the paradigm of industry 4.0 which involves many emerging technologies including Artificial Intelligence (AI), Big Data, Internet of things (IoT) etc., and can serve towards sustainable and eco-friendly production through maximization of productivity in a sustainable manner [1]. If industry 4.0 was mainly powered by automation to enhance the efficiency with productivity, Industry 5.0 calls for co-operation among humans and machines through human knowledge and creativity aligned to technology along with enhancement of social needs, targeting new industrial ecosystem within society [2]. In addition to facing for Industry 4.0 era challenges, this latest paradigm possesses some new unique characteristics such as resilience and sustainability while keeping human at the core of production activity [3]. Nevertheless, the changeover is required for present day troubles such as resource deficiency and climatic disaster which positions Industry 5.0 as a game-changing facilitator of the circular financial system objectives [4].

The circular economy (CE) is an industrial model with environmental design that aims to reduce consumption of resources, pollution and energy loss through its mechanisms of material and energy loops closing.

This philosophy is often encapsulated via the "3Rs" (reduce, reuse, recycle) and is a challenge to the system that entails cycling of goods from their design through use to waste disposal [5]. The circular economy represents a shift from the linear old economy take, make and dispose which leads to a huge resource waste and so much environmental destruction [6]. By enabling businesses to rethink the way they produce, including recycling, reusing and repairing their products, this circular economy promotes sustainable practices [7]. The incorporation of Circular Economy (CE) principles within current industries can provide benefits such as improved sustainability performance, lower environmental harm and the generation of economic wealth through innovative business models [8]. Over recent years, sustainable development goals focusing on long-term sustainability benefits have gained momentum and the adoption of CE practices has been identified as an integral part [9] especially towards tackling global issues like climate change and resource depletion.

Another perspective on the role of Industry 5.0 within sustainability is by means to smart technologies during functional mechanisms in supply chains, which involves numerous obstacle-related matters for supply chain sustainability optimization pertaining [10]. While these technologies have the potential to deliver a range of benefits, the reality is that many organizations struggle to implement these technologies in an effective way that embodies circular economy principles [11]. Factors such as the complexity of supply chains and high rate of technological progress are hindering the integration of sustainable practices to reduce carbon emissions [12]. Moreover, few studies have explored how to use Industry 5.0 technologies to enable the shift toward a circular economy [13]. The idea of this research problem is to provide an integrative vision in terms of how technologies and innovations could be applied in supply chains for sustainability along with supporting circular economy initiatives [14]. Addressing these challenges really contributes to the long term sustainable competitive advantage of organisations and environmental sustainability [15].

The primary objective of this paper is to explore the role that Industry 5.0 technologies can play in enhancing the transition to a circular economy and sustainable supply chains. This research aims to investigate the ways that soft functionalities of digital transformation assimilate in the supply chains with circular economy approaches, focusing on uncovering means through which sustainability can enhance [1]. Circular economy integration with industry 5.0 and typology of resource efficiency, and waste minimization [3]. In addition, it seeks to highlight prospects for and barriers to using the same technologies though not limited to these in current supply chains [16].

Finally, the main outputs of ongoing research efforts will create a more sustainable industrial eco system in-line with Industry 5.0 and circular economy [17].

The objective of this task is to investigate the relations between Industry 5.0, circular economy and sustainable supply chain performance in the context of this research. These features involve the study of how AI, IoT and big data technologies are being applied to increase efficiency of resources, eliminate waste and promote sustainability within supply chains [6]. It will also deepen the analysis of stakeholder engagement and collaboration role in support the implementation of circular economy principles in Industry 5.0 context [7].

2. Literature Review

Leading global companies are looking to Industry 5.0 to transform manufacturing and supply chain management by more closely integrating people with machines. Such a transformation is an extension of Industry 4.0 that introduced ITs including Internet of Things (IoT), AI, and blockchain. These intelligent technologies are now being incorporated into supply chains to increase efficiency, enhance responsiveness and enable sustainability by waste reduction and resource optimization.

2.1. Overview

Industry 5.0 will transform manufacturing and supply chain management and further enrich human-machine collaboration past research focus on adoption of smart technologies, namely Internet of things (IoT), Artificial Intelligence (AI) and blockchain creating value in supply chains through efficiency gains and responsiveness capabilities development [18]. For example, [19] points out that this combination of technologies has triggered revolutionary transformations in supply chain practices by permitting instant interaction and automated information sharing between actors in a network thus improving operational efficiencies. In addition, [20] analyzes the ways in which these intelligent technologies enhance manufacturing operational performance and highlights the disruptive potential of smart technology to transform conventional supply chain processes. Industry 5.0 technologies not only improve productivity in literature, but also allow practices to be more sustainable through resource efficiency and waste reduction [21].

The circular economy (CE) framework is gaining traction as a necessary approach to supply chain sustainability.

The CE underlines the resource recapture, product reuse and wastes minimization which naturally clubbed with sustainable development goals [22]. Circular practices have been demonstrated to create considerable sustainability benefits by minimizing ecological burden and promoting resource efficiency across the supply chain [23]. The necessity of conglobating sustainable supply chain management with circling economic tenets toward the long-range targets of sustainability [24]. A sustainable supply chain offers a more complete take on sustainability as it goes beyond profit to also include environmental and social responsibilities. Incorporating circular economy strategies into supply chain models is a concept specifically mentioned in the literature as an area where traditional models must be re-thought, resulting in increased resilience and stability of sustainable supply chains [25].

Supply chain transparency, efficiency and sustainability are crucial to everything from smart logistics (which is of course all part of the supply chain) to Industry 4.0 solutions for intelligent supply chains that harness smart technologies in ways could previously only dream of. According to the authors [26], Internet of Things, blockchain and Artificial Intelligence are defined as key enablers for smart supply chains that allow data sharing and decision making on a real-time basis. For example, [26] investigate the impact of smart green supply chain management on digital transformation and green performance enabled by these technologies. In addition, the importance of enterprise architecture to support supply chain optimization with sustainable priority and demonstrating a digital tool that can help us perform sustainable practices [27]. Through the adoption of these emerging technologies, efficiency is experienced, and collaboration among supply chain partners improves with better sustainability effects [28]. Using smart tools is one of the key practices to realize Industry 5.0 and circular economy objectives that increase supply chain sustainability [29].

But to make your supply chain more sustainable, optimizing resource usage is key. Based on studies, doing this can reduce waste and environmental impact by a large percentage [30]. The sustainability benefits of green procurement practices in supply chain transformation, is resulting in cost savings and resource efficiency [31]. Moreover, sustainable supply chain management orchestrates the flow of materials and information in combinations with economic, social, and environmental dimensions [32]. The literature indicates that organizations focusing on resource optimization not only enhance their sustainability performance but also enhance competitive advantage in the market [33].

Although increasingly more among the papers addressing industry 5.0, circular economy and sustainable supply chains jailed each different, there appear to be many opening rooms which can be unattended in regular connection between these domains. More research is needed to examine how Industry 5.0 technologies can be integrated with circular economy characteristics in supply chains [34]. Despite the continuous increase in literature regarding pros and cons of these integrations, empirical studies addressing barriers and challenges dairy herd practitioners face when implementing such interventions are limited [35]. Given the complexity and dynamics of today's supply chain networks research in the future should focus on developing frameworks for circular supply chains based on industry 5.0 penetration capabilities [27]. Filling these gaps will advance the knowledge of how sustainable supply chains should be implemented in Industry 5.0 as well in circular economy environments.

2.2. Industry 5.0 Technologies

Industry 5.0 technologies encompass collaborative robotics, AI-enabled automation, and advanced human-machine collaboration systems. Their goal is to increase efficiency whilst promoting a softer way of producing and delivering products through these supply chain mechanisms. This dilemma is addressed by collaborative robots, which work side-by-side with human operators [36]. AI-based automation can take the guesswork out of decision-making, basing decisions on recorded data rather than speculation or theory and optimizing operations and reducing waste [37]. These technologies not only assist in simplifying processes but also advance sustainability goals by lowering resource consumption and maximizing efficiency [38].

2.3. Circular Economy Practices

Circular economy is all about reducing the waste and use of resource, product-lifecycle management. Through these practices, they work towards ensuring that resources are reused, recycled and repurposed to forge a closed-loop system with negligible environmental impact [39]. Integrating circular economy principles into supply chains can greatly enhance some sustainability results, e.g., less waste generation and greater resource productivity [40]. Product lifecycle management, possibly among the most critical albeit a common unit-based demand from circular supply chains helps ensure products are designed with extendable life and recycling-fit potential [41].

2.4. Smart Technologies in Supply Chains

The role of smart technologies, it could be said, it is a must-have these days. IoT-enabled smart devices such as forks lifts and convex cameras to one implement supply chain traceability using blockchain technology and sophisticated predictive analytics using AI. IoT allows for the monitoring of resources and processes in real-time, making decisions and managing resources [42]. According to [30], blockchain technology allows for the traceability and accountability needed along the supply chain, thereby supporting sustainability standards. Adaptive inventory and demand forecasting with AI-driven predictive analytics can also accelerate the efficient use of resources.

2.5. Resource Efficiency

The resource efficiency is an aggregate measure of how efficiently sustainable resources (materials, energy, and labor) used in the supply chain via application of Industry 5.0 technologies. Which signifies that improved resource efficiency is essential for sustainable supply chain performance because this brings about waste reduction along with energy consumption [43]. Research reveals that firms embrace advanced technology and circular economy practices to enhance resource efficiency while lowering costs and environmental impacts [44]. Solving the potential for sustainability issue by utilizing intelligent technology to optimally use resources for example, through using intelligent technology such as IoT technologies it is possible to greatly save energy and reduce waste which contributes towards sustainability increase [45].

2.6. Sustainable Supply Chain Performance

Sustainable supply chain performance is measured using metrics such as waste reduction, energy efficiency, material recycling and carbon footprint reduction. It will continue to make these sustainability signals better through Industry 5.0 technologies with circular economy practices [46]. Companies that choose sustainability as a core value in their supply chain operations avail benefits of better results by the prospect of achieving environmental goals, furthermore gaining competitive advantages over ones who do not [47]. Organization applying effective waste reduction strategies and making better use of resources are able to reduce carbon emissions tremendously and achieve greater sustainability [48].

2.7. Hypothesis Development

The inclusion of Industry 5.0 technologies, including collaborative robotics and AI-driven automation, should improve resource efficiency in the manufacturing and supply chain sectors. Utilization of resources, elimination or minimization of waste and improving productivity can be achieved through these technologies resulting into improved operations [49]. The example includes using collaborative robots to perform tasks more accurately and efficiently with reduced energy usage and waste of raw material [50]. Additionally, analytics powered by AI can help to optimize resource allocation and forecast maintenance requirements which will reduce downtime as well waste of resources [51]. The expectation is that an increasing number of organizations will obtain significant positive impacts on resource efficiency from the use of these advanced technologies to enhance sustainable supply chain practices [52].

H1: There is a relationship between Industry 5.0 Technologies and Resource Efficiency.

Circular economy practices substantially improve resource efficiency in manufacturing and supply chains. The approach of minimizing resource use, and maximizing the utility of material through waste minimization, appropriate resources utilization and product life cycle management can help organizations in reducing their reliance on resource [53]. Circular supply chain practices resulted in significant changes toward better performance among manufacturing firms, suggesting a positive connection between these practices and their resource efficiency [53]. Likewise, shows that adopting circular economy activities leads to sustainable supply chain performance for manufacturers indicating that manufacturing CE practices can provide efficient use of resources [54]. Some suggestions include an approach that mayor creek bough circular economy at their roots naturally reduce waste while sustainability both promote a more sustainable manner of resource management, which in turn leads to better operational efficiency and environmental benefits [55].

H2: There is a relationship between Circular Economy Practices and Resource Efficiency.

This paper examines the role of serenity and market sensibility in navigating a supply chain employing smart technologies, i.e., IoT, blockchain and AI which greatly improve resource efficiency. Such technologies support the capture and analysis of real-time data, allowing organizations to optimize allocation of resources while reducing waste [56].

Smart contracts, one of the most important features of blockchain technology, automate compliance processes and limit administrative burdens and increase operational efficiencies [57]. The other thing is that the IoT devices enable visibility of inventory levels and resource utilization for better decision making [58]. Thus, the assimilation of smart technologies results in more efficient resource use and greater levels of sustainability [59].

H3: There is a relationship between Smart Technologies in Supply Chains and Resource Efficiency.

The improvement of sustainable supply chain performance is, in turn, greatly reliant on resource efficiency. Minimizing waste means using resources, whether they be raw materials or energy or manpower, more efficiently; and keeping operational costs down is key to any sustainability initiative [60]. Moreover, [61] emphasize that good resource management leads to improved supply chain capabilities which in turn leads to better performance. Hence, resource efficiency and sustainable supply chain performance are closely related, which indicates that optimization of resources towards the supply chain is essential to success belonging to sustainability goals.

H4: There is a relationship between Resource Efficiency and Sustainable Supply Chain Performance.

The impact of industry 5.0 on sustainable supply chain performance is also largely through its contribution to operational efficiency and environmental sustainability by the use of technologies in Industry 5.0. Advanced technologies like Artificial Intelligence (AI), Internet of Things (IoT), and collaborative robotics can be integrated with smart manufacturing practices to enhance efficiency, minimize waste, and increase resource utilization [62]. The relation between supply chain network sustainable practices with the sustainable performance is positive, which implies that if one improves through Industry 4.0 technologies then other will also improve [62]. In addition, implementing Industry 5.0 approaches cultivates innovation and supply chain adaptability, resulting in enhanced sustainability performance [63]. Therefore, there is a positive association of Industry 5.0 technologies with sustainable supply chain performance.

H5: There is a relationship between Industry 5.0 Technologies and Sustainable Supply Chain Performance.

Circular economy practices are core to sustainable supply chain performance as they encourage the efficient utilization of resources and minimization of wastes [64]. Circular economy, proactive recycling and reuse leads to higher firm performance and sustainability directly. In addition, sustainable supply chain practices act as an enabler in achieving circular economy objectives hence enhancing the sustainability of whole supply chain [63]. Therefore, to implement sustainable practices and improve performance outcomes, supply chain management needs to incorporate the principles of circular economy [65].

H6: There is a relationship between Circular Economy Practices and Sustainable Supply Chain Performance.

Smart technologies amplify Sustainable supply chain performance vis-a-vis operational effectiveness and resource efficiency. For example, [66] shows that smart technologies including IoT and additive manufacturing provides agility and responsiveness to the sustainability-centric supply chains. This was followed by late in the year [67] they discuss visibility, ‘the transparency that IoT brings may improve decision-making capability and promote better sustainability.’ These developments will help assimilate sustainability and thus dome benefits for overall performance.

H7: There is a relationship between Smart Technologies in Supply Chains and Sustainable Supply Chain Performance.

2.8. Theoretical Framework

The theoretical background of the study introduces the basic assumptions that were the basis for connecting Industry 5.0 technologies with circular economy in supply chains. It works in the terms of the ideas and rationales behind sustainable and efficient supply chain systems. This chapter introduces the foundational theoretical viewpoints of entwined supply networks and the fusion of Industry 4.0 and circular economy thoughts and unpacking how they inform the evolution of sustainability in SCM.

2.8.1. Intertwined Supply Networks Theory

Introduces the notion of intertwined supply networks (ISNs) as a hope, where chains are interconnected and their interconnections make them more resilient or sustainable together than apart. As open systems, ISNs enable firms to adjust by altering the buyer-supplier roles and thereby ensuring that goods and services needed for social functioning are delivered [68].

And the necessary agility to adjust to changes have become important for sustaining, the performance of their supply chain after disruptions is like that observed through COVID-19 pandemic. The ISN also has a network of structural dynamics which enables cooperative actions that develop sustainability throughout the entire network thus providing mutually beneficial outcomes for all parties concerned.

2.8.2. Industry 4.0 and Circular Economy Integration

The adoption of circular economy principles will be vital for achieving sustainable supply chain performance, with the development of Industry 4.0 technologies in this area being also crucial. A view presented in a study [69] elaborates that Industry 4.0 capabilities such as IoT, big data analytics optimize sustainability performance through resource efficiency and better decision-making processes among others. This integration enables a proactive sustainability approach where circular economy principles like recycling and waste reduction can be better supported by innovative technologies and mechanics, creating significant impacts on economic, social, and environmental factors in supply chains. Although the benefits of these technologies are immense, they also come with challenges and obstacles to adoption which need to be overcome [70].

2.9. Conceptual Framework Development

This conceptual framework Figure 1 brings together fundamental components of industry 5.0 technologies, characteristics of circular economy and smart technology in connection with supply chain to improve sustainable supply chain performance.

This framework is informed by recent literature on the interconnections between these areas.

Industry 5.0 Technologies: Supply chains need cutting edge technologies AI, IoT and collaborative robotics to improve operational efficiency and sustainability at scale. According to, [20] states the need for models where institutions are supported in getting those technologies into their organization.

Circular Economy Practices: An assessment of circular economy practices in industrial behavior with environmental synergy driven by construction, share and cycling [71]. It compels to internally import circular practices into the realms of supply chain or operational management, which is about enhancing sustainability performance.

Smart Technologies in supply chains: Devise models to assess the sustainability implications of smart contracts and other supply chain technologies and demonstrate how these types of technological innovations can be enablers for sustainability [56]. The core of sustainable supply chain management is contextualized and thus facilitated by smart technologies which improve visibility and traceability.

Sustainable Supply Chain Performance: This framework claims that with the right integration of Industry 5.0 technologies, Circular economy practices and circular smart technologies will positively enhance sustainable supply chain performance. The single relationship is further backed up with empirical evidence suggesting organizations implementing these practices are more operationally efficient with a lower impact on the environment [72].

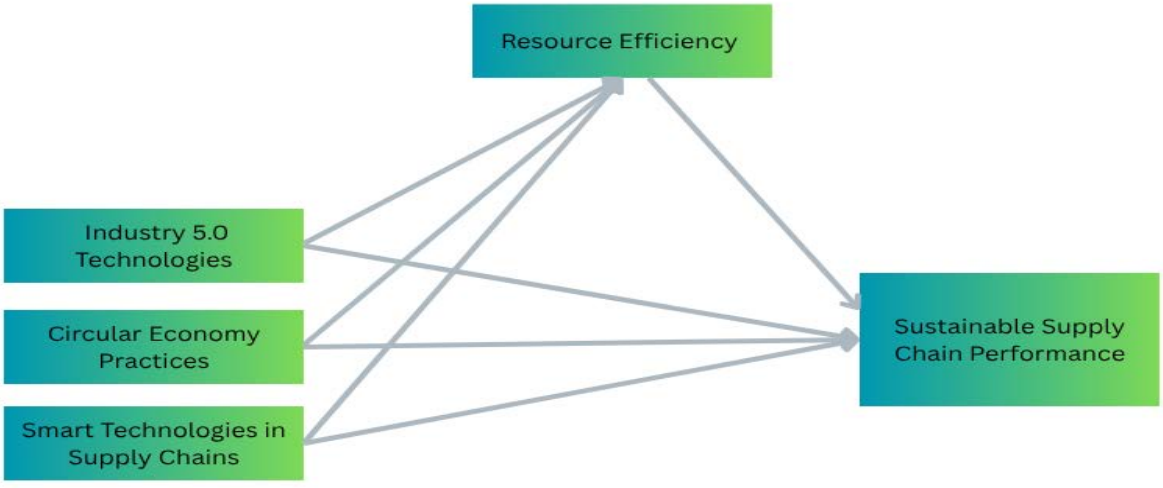

Figure 1. Conceptual framework

3. Methodology

This methodology starts with a literature review to take in account findings on Industry 5.0, circular economy and sustainable supply chains defined by existing studies. In this review identify common themes, frameworks, and models that have been identified in the literature specifically focused on emphasizing the role of emerging technologies such as Artificial Intelligence (AI), Internet of Things (IoT) and collaborative robotics in improving sustainability outcomes [73]. This literature review will additionally identify potential socio-technical barriers to and enablers of the implementation of these technologies with regards to circular economy practices [74].

After conducting the literature review, a conceptual framework followed by A framework will be established to visualize the link between the variables identified as the effect Industry 5.0 technologies have on resource efficiency, waste reduction, and sustainable supply chain performance. Furthermore, since the implementation of circular economy practices either requires working in collaboration between different actors or requires participation across socio-economic actors and stakeholders [72], stakeholder engagement will be considered as an important dimension in the framework. This research combined new and existing approaches used in previous studies to establish multi-dimensional frameworks of technological and operational practices [75].

Lastly, the paper will end with suggestions for empirical research that can validate the framework in real-world contexts. This will provide a scope for quantitative recommendations that can put the framework to operation and measure its performance in different industrial contexts, more so in developing economies covering Malaysia [76]. A conceptual methodology is proposed in a way that would not only help understand the relationship between Industry 5.0 technologies with the circular economy practices, but also bring some much-needed clarity and characteristics to this domain which can map out the research outcome to ensure improved sustainable supply chains.

4. Discussion

The discussion discusses the important implications of Industry 5.0 technology-based approaches within supply chains, when applied to the circular economy, in integrating the latter to the individual supply chains, and barriers and challenges for organizations to adopt the integrated solutions.

This section focuses on the impact of their integration on sustainability performance, provides implications for practitioners in terms of how these technologies can be applied, and gives guidance for further research on how they can extend knowledge and enhance the actual implementation of these practices in different industries.

4.1. Implications for Industry 5.0

The principles of a circular economy in the context of supply chain management relates to Industry 5.0 technologies that enable them. Digital technologies such as AI, IoT and collaborative robots can be integrated to drive resource efficiency and reduce waste [77]. Addressing the challenges and opportunities that exist with using Industry 4.0 technologies in construction supply chains potential parallels to similar applications in other sectors can be explored for advancing circularity [77]. Such integration not only assists in the reduction of wastage but also promotes recycling and reusing, adhering to circular economy.

4.2. Implications for Sustainability

Resource efficiency is considered a key factor in meeting sustainability targets, particularly in industrial supply chains, and the industry 5.0 and smart technologies play an important role to improve it. The implementation of smart technologies has the potential to foster more efficient operations, thereby minimizing corporate footprint and upholding better sustainability performance [78]. Event data analytics and real-time monitoring allow resource optimization, leading to sustainability goals. This confluence of technology and sustainability is crucial to ensure that supply chains are built for resilience but also keep the environment in consideration.

4.3. Barriers and Challenges

However, lot of barriers for implementing the industry 5.0 technologies and circular economy. High implementation costs, the unavailability of necessary infrastructure, and organizational resistance to change have hindered efforts to a certain extent [79]. Despite this, the adoption of these technologies remains a challenge for small and medium enterprises (SME) due to limited resources as well as interoperability challenges [80]. Furthermore, the aforementioned abstract perceptions about using of Industry 4.0 also justifies notion about uncertainty, in this case accentuating challenges in taking every necessary step of implementation [81]. These challenges must be addressed because they are crucial for enabling a transition to more sustainable supply chains.

4.4. Future Research Directions

Future empirical research should therefore be carried out to test and validate the proposed conceptual model that links Industry 5.0 technologies, circular economy practices, smart technologies, resource efficiency and sustainable supply chain performance. Future research can investigate the effects of specific Industry 5.0 technologies on sustainability performance in different sectors [82]. In addition, studies should also explore the impact of strategies to overcome barriers related to adoption behaviors, especially in SMEs [83]. Longitudinal studies could elucidate the contributions of these technologies and practices to long-term value in sustainable supply chains [84].

5. Conclusion

Hence, the research illustrates that the harmony of Industry 5.0 technologies is evident towards stimulating a circular economy and enhancing sustainable supply chain performance. High technologies like AI, IoT and collaborative robotics enable organizations to utilize resources optimally, reduce waste and practice circularity. It is concluded that implementation of such technologies not only creates sustainability but also from an operational standpoint makes supply chain effective thus which in turn matches with circular economy.

This conceptual framework deepens the understanding of sustainable industrial behavior in the context of Industry 5.0. The framework proposed serves as a pathway for organizations to traverse the present supply chains, comprehend the interconnectedness between Industry 5.0 technologies, circular economy approaches and sustainable supply chain performance. A framework that incorporates the technology trajectory with sustainability objective, contributors to both practitioners and the literature.

Therefore, to make the change happen, the policymakers and stakeholders should help by incentives relating to Industry 5.0 technologies development. All businesses, especially MSMEs should invest in training and capacity building to manage the transition towards sustainability with smart technology for resource efficiency. Therefore, it is also important to develop communications between industry and academia which can stimulate innovation and knowledge production that will lead the development of sustainable supply chain goals. Reducing the barriers to technology adoption while integrating circular economy principles can strengthen stakeholder roles that would lead to more resilient and sustainable industrial practices.

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