International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 04 | April – 2025 DOI: 10.55041/ISJEM02985
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

"Leveraging Green IT Innovations and Eco-efficient Manufacturing for Sustainable Supply Chain Optimization"

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Abstract: -

This paper focuses on the integration of Green IT innovations and eco-efficient manufacturing practices in optimizing sustainable supply chains. The emphasis is on the synergistic effect of Lean-Green strategies, which streamlines operations and minimizes environmental impacts. Combining Lean principles, such as waste reduction and efficiency improvements, with Environmental designed Industry 4.0 technologies promotes circular economy strategies and interminable product evolution. This research further explores the additive manufacturing throughout the chain of supply towards cost minimization, waste in production, and emissions. The developed bi-objective optimization model reveals the balance which the environmental sustainability needs to take relative to the economic performance. This study also identifies the emergence of eco-efficiency programs and further establishes the integration of maintenance processes in the operation of a lean supply chain. This study underlines the fact that a holistic approach should consider a combination of technological innovation and strategic decision-making to enhance resource efficiency and sustainability in supply chains. It is also valuable to organizations that will be implementing sustainable, eco-efficient practices in their operations.

Keywords: Green Innovation, Industry 4.0, lean supply chain, sustainable supply chains management (SSCM), Circular economy, Economic Design for Growth and Efficiency (EDGC)

1. Introduction

Global pressure is mounting for the manufacturing industry to adopt sustainability throughout the entire value chain with respect to acute environmental concerns in carbon emissions, resource depletion, and waste generation (Dahmani et al., 2021). The sustainability of manufacturing has been fundamentally acknowledged as the key factor driving long-term benefits both environmentally and economically. The electronics, textiles, and automotive sectors are characterized by large carbon footprints and ineffective utilization of resources during manufacturing. LCSCM, in this case, is adopted to mitigate such malpractices by industries. EI is implemented as part of LCSCM with nanomaterials, green energy technologies, and circular economy patterns (Solomon et al., 2024).

For example, applications of smart manufacturing technologies like IoT technological equipment and data analysis strengthen the environmental sustainability, energy efficiency of the manufacturing systems (Nimbalkar et al., 2017). The innovations are trackable and optimizable so that one can reduce waste and improve product and process sustainability (Li et al., 2021). Environmental Design ed circular economy principles further make the transition to sustainability more powerful by reducing environmental impacts along product lifecycles (Dahmani et al., 2021). One example of such transformation in the SMEs transformation highlights how eco-efficient manufacturing strategies support sustainability and help increase competitiveness for SMEs, as mentioned in Lim et al. (2022). Blockchain and big data also enhance the sustainability of industries like textiles and electronics because they increase the transparency, traceability, and efficiency of supply chains (Dharmayanti et al., 2023). By integrating green IT innovations, such as blockchain and big data, into sustainable manufacturing, supply chains may be optimized, environmental impacts minimized, and firm performance enhanced (Geng et al., 2021). It encompasses research into the relationship that exists between LLCSCM, Eco-Inno. This paper analyzes the interplay mechanisms among Climate-conscious supply chain model (CCSCM), Eco-conscious Innovation (ECI), and Production firm outcomes (PFO) in terms of how the adoption of sustainable practices and technologies impacts both environmental and economic outcomes. The paper is a test of the following hypotheses: Hypothesis 1: Sustainable design innovation (SDI), low carbon process improvements (LCPI), and sustainable logistics & Transportation (SLT) improve Eco conscious Innovation (ECI), performance firm production (PFP). This assumption reflects involvement of sustainable, decarbonization advancement in the entire SCM stages, especially product design, processes, and logistics, contributes to Eco-conscious Innovation as well as firm performance overall.

H2: The moderate role of Eco-conscious Innovation (ECI) in the relationship between LCSCM and performance of manufacturing facilities indicator (PMFI) significant. Explanation: In this, for example, forms that can be taken include green product designs or sustainable processes may play as a mediating role. It explains how low carbon practices lead to improved firm performance. H3: It clearly shows how the green innovation capability (GIC) impacts SMPs (Sustainable Manufacturing Practices), thereby affecting Sustainable Products.

1.1. Importance of Green IT Innovations and Eco-Efficient Manufacturing in Enhancing Sustainable Supply Chain Optimization

Eco-conscious Innovation is essential to bridge the gap between low carbon practices and improved business performance. Indeed, new sustainable technologies can be developed and implemented in businesses to reduce carbon emissions while improving competitiveness and profitability (Kumar and Rao, 2018). Sustainable nanomaterials, for instance, minimize waste, energy consumption, and emissions in the manufacturing process as part of transitioning to a circular economy (Solomon et al., 2024). The shift continues due to smart manufacturing technologies that allow manufacturers to optimize energy usage, minimize waste, and have a higher productivity rate (Nimbalkar et al., 2017). Ecoelligent manufacturing based on the idea of both intelligent systems and green manufacturing is also important in boosting energy efficiency and GDP of the entire world economy (Li et al., 2021). Environmental Design principles minimize the effects of products on the environment by declining resource utilization waste manufactured items. SMPs regarded as fundamental for improving the environmental performance, as companies find themselves at an advantage in more environmentally conscious markets (Leong et al., 2019). Blockchain, big data optimize supply chains further by enhancing transparency and efficiency. It is the integration of these technologies that makes possible traceability of products in the supply chain against sustainability aims and risk mitigation by firms (Dharmayanti et al., 2023). Lean as well as green manufacturing is improving operational efficiency with reduced environmental footprint as the practice integrates traditional lean manufacturing principles with green technologies (Ye & Lau, 2022).

1.2. Challenges in Implementing Sustainable Practices in Manufacturing and Supply Chains

Despite the evident advantages, there are a number of challenges that limit the implementation of sustainable practices in manufacturing. The primary reason for high carbon emissions in manufacturing is cost-cutting, which neglects the long-term environmental and economic costs of unsustainable practices (Kumar & Rao, 2018). In addition, low carbon solutions are not very well understood and lack awareness, especially among SMEs, who face financial constraints and lack skilled labor (Dangelico et al., 2017). Some factors have limited

ISSN: 2583-6129
DOI: 10.55041/ISJEM02985

the uptake of sustainable nanomaterials, including high production costs, lack of well-established regulatory frameworks, and ignorance on the benefits these materials provide (Solomon et al., 2024). Also, incomplete data and resistance from operators complicate the management of energy, leading to inefficient systems (Nimbalkar et al., 2017). In SMEs, limited finance and unwillingness to invest in new technologies enhance the stress experienced by SMEs in changing into green manufacturing solutions (Shamsul Bahrin et al. 2024). Different barriers exist in the case of blockchain and big data-optimized supply chains, including security threats, high cost of implementation, and a very radical change in organizational structure (Dharmayanti et al., 2023). Lastly, increasing threats of extreme weather and water dependence are further challenging the energy system in shifting to sustainable energy resources (Salam & Salam, 2020).

1.3. Problem Statement

The manufacturing sector globally needs to take up sustainable practices to minimize adverse effects of climate change and further reduce environmental degradation. Some challenges identified in manufacturing and other sectors include high carbon emissions, inefficient energy systems, and slow transitions to circular business models (Dangelico et al., 2017). Conversely, despite growing awareness of the need for sustainability, the main obstacles to low carbon supply chain method remain related to issues such as high production costs, restrictions on access to green technologies, and lack of regulatory clarity (Kumar &. Rao, 2018). This further gap exists in the green innovation capacity of SMEs, which stops them from embracing sustainable production practices and thus their overall performance is not improved (Geng et al., 2021).

This research trying to investigates the significance of Eco-Inno, smart manufacturing technologies, blockchain relation with the sustainability and competitiveness of manufacturing companies. The aim of the paper is to observe the relationship between low carbon supply chain method, Eco-Inno, and great positive outcome results for the idea relating to gainful insights into the strategies that can be used in order to overcome the barriers to sustainability in manufacturing. It provides a nutshell containing low carbon supply chain method, Eco-Inno, smart manufacturing through which very critically an extreme effort has been involved in making it accomplish the challenges toward sustainability. This paper seeks to discover how, from the driver innovation of green IT and eco-efficient manufacturing, sustainability in the process of manufacturing and supply chain activities can best achieve performance improvement as well as provide long-term sustainability of the environment**.**

2) Objectives: Exploring the outcome of Low Carbon Practices, Eco-Inno, and Emerging Technologies on Sustainable Supply Chain Performance:

1) **Look at the outcome of Climate-conscious supply chain model (CCSCM) on performance of manufacturing firm (PMF)** This aim seeks to establish if LCSCM- a practice, through less carbon in design of products, strengthening of methods, and logistics-influence the overall performance of manufacturing firms. The study looks forward to estimating how these practices help in moving towards environmental sustainability as well as promoting economic competitiveness. It will therefore support the spreading of Eco-conscious Innovation while making companies sustain performance.

2. **Mediation Effect of Eco-conscious Innovation to Boost Sustainability and Competitiveness: -**The study would also want to look into this moderating effect of Eco-conscious Innovation based on association that exists connecting these sustainable production practices and performance from the firms. In this respect, this research aims to show how EI can be a factor in minimizing carbon emissions as well as waste, thereby facilitating competitive gain in growth for companies.

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3)**Developing technologies, such as blockchain and complex data, as potential contributors to sustainability in production and supply chains**: This objective is an analysis of the contribution that emerging technologies can make to creating sustainability in production and supply chains. This will involve assessing how emerging technologies contribute to Eco-Inno, improve supply chain transparency, and support better decision-making for greener operations and resource use.

3. Literature Review

1. Introduction

This study was based on a structured quantitative approach guided by the existing theories of sustainability, supply chain management, and Eco-Inno. The online questionnaire was distributed to 50 manufacturing firms, out of which 45 responses were valid and analyzed by Smart PLS 3.0. This approach enables the testing of proposed hypotheses and looks at the interaction between low carbon practices, Eco-Inno, the outcomes of manufacturing firm (Geng et al., 2021). In addition, the review of literature published currently utilizes case studies, thematic coding with NVivo, and analytical tools such as life cycle assessments (Leong et al., 2019), value stream mapping, and energy management systems to assess energy efficiency and reduction in emissions in manufacturing operations. The study combines energy management technologies, Lean Manufacturing principles, and the IoTs in order to monitor to exceed approaches to generate power and hence reduce the ecological impact footprint of industrial activities (Nimbalkar et al. 2017). Industry 4.0 and its contribution to advancing green manufacturing practices is also researched upon (Dahmani et al., 2021).

2. Scope of the Review

It encompasses several sustainable practices and technologies critical to enhancing the performance of manufacturing firms and their supply chains. The core subjects include Climate-conscious supply chain model (CCSCM), Eco-conscious Innovation (ECI), sustainable nanomaterials, energy efficiency through smart manufacturing technologies, and circular economy practices. The review also evaluates the adoption of Lean environmental design principles with Industry 4.0 and discusses the application of blockchain and big data to optimize supply chains (Dharmayanti et al., 2023). Ecoelligent manufacturing, which integrates smart technologies with green manufacturing, is also discussed as an important trend in enhancing sustainability (Li et al., 2021). The review promotes an integration of greening strategies, environmental management, and the efficiency of resources into manufacturing activities to decrease their ecological footprint (Ye & Lau, 2022).

3. Theoretical Framework

Based on several established theoretical frameworks, this study draws to guide the exploration of sustainable practices in manufacturing and supply chains. The most fundamental frameworks are RBV and DCV, as they support integrating green innovation and eco-friendly practices into manufacturing strategies (Geng et al., 2021). The RBV theory focuses its concept on organizational internal valuables and abilities of developing the concept of Eco-Inno. On the contrary, DCV focuses its study on aspects associated with how businesses adapt and how they use business to develop firms' change toward sustainable technological involvement.

The theory is applied in the study of Climate-conscious supply chain model (CCSCM), Eco-Inno, sustainable materials, smart manufacturing technologies. Challenges that unit's s are facing include the high cost of production, need for clear regulatory frameworks, and barriers to the adoption of new technologies (Kumar & Rao, 2018). Here, the papers discuss how energy efficiency, waste reduction, and circular economy models can enhance environmental and economic performance. Themes, the research explores several key themes related to sustainability in manufacturing and supply chains: The research explores key sustainability themes in manufacturing and supply chains, focusing on the integration of low carbon supply chain method Practices

(LCSCM) with Eco-conscious Innovation (ECI) to reduce emissions, improve resource efficiency. In addition, it discusses the harmonization of Lean and Green Manufacturing, which integrates operational efficiency with environmental sustainability (Geng et al., 2021).

This is through discussions on blockchain and big data in an effort to better improve supply chains' transparency, optimize available resources, and performance (Dharmayanti et al., 2023). Then follows the outlook of Ecoelligent Manufacturing, following the probable capacity to make proper usage of energy consumption, minimize waste, and to further advance green innovation set by Industry 4.0 through the combination of intelligent and environment-friendly technologies.

4. Knowledge Transfer and Innovation Performance Outcomes

Dynamic collaboration and knowledge sharing between stakeholders may highly drive innovation within sustainable supply chains. The existing literature review suggests that dynamic Engagement along with data exchange are vital of development to innovative, context-specific solutions for sustainability. A strong relationship with external suppliers, customers, and regulatory bodies can enhance the capabilities of green innovation and build sustainable practices (Ye & Lau, 2022). Cross-functional integration within firms improves resource efficiency and drives innovation by developing a culture of continuous improvement and sustainability (Nimbalkar et al., 2017). Knowledge sharing and effective communication are particularly important in enabling firms to adopt new technologies and practices that enhance both sustainability and operational efficiency.

5. Critical Analysis

Such research provides critical insights that sustainable practice is transformative towards manufacturing performance enhancement and environmental impacts. The overall results are promising as sustainable nanomaterials were found to contribute positively towards reduction in emission and waste and integrating Lean Environmental Design with Industry 4.0 as an idea technologies enhanced sustainability (Dahmani et al., 2021). One identified enabler for Eco-conscious Innovation in supply chains is the interaction between blockchain and big data: it enhances both transparency and operational efficiency (Dharmayanti et al., 2023). The studies continue to indicate some challenges presented by the developments, including high production costs, ambiguous regulatory policies, and requirements of technological set-up infrastructure to support the adoption in env ecofriendly approach. The papers aim to show that strategic frameworks, government support, and dynamic capabilities overcome these barriers to the successful implementation of eco-efficient practices (Geng et al. 2021).

6. Differences underline in Literature

The literature reveals several key differences in the approaches to sustainability and innovation in manufacturing and supply chains, underscoring the complexity of implementing sustainable practices across different regions and industries. The literature identifies several key differences in the approaches to sustainability and innovation in manufacturing and supply chains. Research gaps exist in underdeveloped regions, particularly regarding low carbon practices in SMEs, which are influenced by local factors such as infrastructure and regulations (Geng et al., 2021; Dangelico et al., 2017). There are also variations in the sourcing, synthesis, and lifecycle management of sustainable nanomaterials, which impact the efficiency and environmental footprint of supply chains (Dharmayanti et al., 2023). Smart Manufacturing: The adoption of IoT and AI technologies has been shown to provide the most substantial savings in energy use as well as positive environmental impact when comparing smart manufacturing technologies against traditional cost-reduction-focused manufacturing techniques (Nimbalkar et al., 2017; Leong et al., 2019). Lean and Green are industryspecific; some process areas cannot be provided because they require high capital spending and are rather complex (Dahmani et al., 2021). Lastly, Big Data proves optimality in decisions for sustainability and Blockchain maximizes transparency and traceability that results in the maximization of green innovation and optimizes the efficiency of the sustainability Distribution network (Dharmayanti et al., 2023; Li et al., 2021).

7. The Literature Review Summary

The review of literature points out sustainable practices undertaken in manufacturing and supply chains. It shows that the nanomaterials sustain market development through making the processes more sustainable, which are highly important for reducing the environmental impacts and for further encouraging eco-friendly innovations within the supply chains (Dangelico et al., 2017). Improvement in energy efficiencies and reduction in environmental footprints is stressed upon using such smart manufacturing technologies like IoT, AI, or machine learning (Nimbalkar et al., 2017; Dahmani et al., 2021). Furthermore, the union of Environmental Design principles with Lean Manufacturing approaches is considered a significant factor for the reduction of wastes and resources efficiency (Leong et al., 2019). The innovation of blockchain and big data outlines various factors regarding how they enhance the aspect of Eco-conscious Innovation and transparency in supply chains (Dharmayanti et al., 2023). The review, at last, speaks of the need for integrated, all-rounded green manufacturing strategies that combine different technologies to catalyze efficiency and sustainability in both supply chain operations and management (Li et al., 2021; Ye & Lau, 2022).

4) Research Methodology

Most of the studies adopted a combination of quantitative and qualitative approaches with an applied research methodology in the selection of studies through the collection, analysis, and implementation of sustainable production technologies and supply chains.

1. **Surveys and questionnaires**: which were mainly standardized Likert scales, were employed to measure attitudes toward sustainable practices such as low carbon supply chains and green manufacturing. In one study, an online survey was conducted among 70 manufacturing firms, which received 45 responses for analysis. The collected data was analyzed using Smart PLS 3.0 to examine between sustainable application and manufacturing firm Output delivery performance.

2. **Analytical Instruments of Data:** Different studies made use of data analysis technique based on the software Smart PLS 3.0, NVivo, and hierarchical regression. Such analytical tools help understand relationships between sustainable practices and firm performance besides analyzing the qualitative data that has been developed through case studies and interviews.

3. **Case Studies & Systematic Literature Reviews:** This type of systematic reviews of literature and case studies were used to study the best practices and trends on green supply chain management (Leong et al., 2019). It also assisted in the energy impact analysis as follows: smart manufacturing applied to improve energy efficiency.

4. **Data collection technologies of the future**: The contributions of smart manufacturing to ensure sustainability outcomes involved real-time harvesting of operational performances and energy consumption from some of the studies through advanced technologies like IoT sensors.

5. Dependent and Independent Variables

The study identifies the main dependent and independent variables that influence the sustainability performance of manufacturing firms. Dependent variables: performance of manufacturing firm (PMF) is affected by Climate-conscious supply chain model (CCSCM), with Eco-conscious Innovation (ECI) as a mediator (Geng et al., 2021). Sustainability performance (SP) is influenced by sustainable manufacturing practices (SMP), with green innovation capability (GIC) acting as a mediator (Dharmayanti et al., 2023). Environmental Eco-Innovative Firm Performance (EIFP) is impacted by Blockchain (BC), Closed-Loop (CL) practices, and Sustainable Supply Chain Management (SSCM), moderated by Big Data-Optimized Supply Chain (BDOSC) (Ye & Lau, 2022).

Independent variables: Climate-conscious supply chain model(CCSCM), such as low carbon product design optimization (LCPD)), low carbon process enhancement (LCPE), low carbon Sourcing (LCS), and low carbon Transportation (LCT), directly influence firms' manufacturing performance (MFP) through Eco conscious Innovation (EI) (Geng et al., 2021). Green innovation proficiency (GIP) drives performance in sustainability Indicator (PSI), with sustainable manufacturing application (SMI) as a mediator (Dangelico et al., 2017). Blockchain (BC) affects firms' Eco conscious Innovation performance (EIFP), moderated by Big Data Optimized Supply Chain (BDOSC) (Dharmayanti et al. (2023).

6. Data Collection and Sampling

In studies, data gathering methods are employed in the form of surveys, interviews, and other advanced technologies. Sampling techniques depend on the scope of the study:

1. Surveys and Questionnaires: In one study, random sampling was used to pick 70 manufacturing firms with 45 valid responses. Another study employed a census approach to survey ISO 14000-certified SMEs, achieving a high response rate.

2. Interviews and Site Visits: Interviews and on-site observations collected qualitative data regarding the Making use of sustainable methods within manufacturing firms rigorously.

6. Research Gaps

The literature identifies several significant research gaps that need to be addressed to further the understanding of sustainable manufacturing and supply chain practices. These gaps provide directions for future studies:

Low carbon supply chain method of Underdeveloped Regions: Not enough studies in research on implementation of low carbon supply chain methods of underdeveloped regions. Future studies should focus on developing frameworks that consider the unique infrastructure, regulatory frameworks, and resource availability in these regions (Geng et al., 2021).

Integration of the analysis of data and creative production in Small Facilities: Research is needed on how the analysis of data and creative production can be optimized for used energy and cost reduction in SMEs facilities (Nimbalkar et al., 2017). Synergies Between EDGC, Lean Manufacturing, Industry 4.0: Future studies should explore the synergies between Lean Manufacturing, EDGC, and Industry 4.0 strategies to enhance sustainability, examining their economic and operational implications (Leong et al., 2019). Closed-Loop Systems and Renewable Energy Challenges: Further research is needed on the integration of closed-loop systems, lean and green manufacturing practices, and renewable energy challenges to advance sustainability in manufacturing and supply chains (Ye & Lau, 2022).

7) Discussion

Climate-conscious supply chain model (CCSCM) and Eco-Inno: LCPs have ability to decrease carbon footprints, whereas Eco-conscious Innovation produces new products, processes, and services that require fewer resources and waste less and thus lead towards a circular economy (Geng et al., 2021). Sustainable nanomaterials contribute to the reduction of emissions and the circular economy, specifically in the areas of water purification, packaging, and renewable energy by supporting most sustainable manufacturing methods (Dharmayanti et al., 2023).

Analysis of data and creative production: The integration of smart Production technologies and data analytics improves efficient energy and productivity. While the LCP reduces carbon footprints efficiently, more so, Eco-conscious Innovation offers new products, processes, or services that make it possible for the use of resources and subsequent waste to decline, hence propagating the circle economy (Geng et al., 2021). Most impressively, it is the sustainable nanomaterial contribution to emission reductions and the circular economy. It is very much in line with all the applications, be it water purification, packaging, or renewable energy, to more sustainable production methods (Dharmayanti et al. 2023). Manufacturing and the integration of analytic data and intelligent production methods improves efficiency of energy use and productivity. Real-time information used in optimization processes, reduces the consumption of resources, as well as enhancing sustainability goals (Nimbalkar et al. 2017). Lean Environmental Design and Industry 4.0: Combination of principles used in Lean Environmental Design with the application of the technologies Industry 4.0 as well minimize waste, enhance resource utilization, and increase environmental as well as economic performance of manufacturing (Leong et al. 2019). Blockchain and complex Data drive transparency, efficiency, supply chains traceability. They support Eco-conscious Innovation by improving decision-making and reducing inefficiencies (Dharmayanti et al., 2023). IoT in Energy Systems: IoT technologies optimize energy consumption through real-time data, support sustainable energy sources and contribute to energy-efficient production by integrating energy management into smart systems (Li et al., 2021).

9) Limitations

High production costs of sustainable nanomaterials: The high production costs of sustainable nanomaterials prevent widespread use by SMEs without cost reduction strategies (Dharmayanti et al.,2023). Resistance to smart production technologies: There are resistance to smart manufacturing technologies, especially in traditional settings, which require extensive training and awareness-raising to overcome skepticism (Nimbalkar et al., 2017). Generalizability of findings: The study mainly targeted ISO 14000 certified SMEs and cannot generalize the results of the study to other sectors or countries because different regulatory or normative environments prevail in different countries (Geng et al., 2021). The study has a correlational nature that cannot provide a causal conclusion, and future studies must address this by employing either an experimental or a longitudinal design (Li et al., 2021). Lean Integration, environmentally friendly design and industry 4.0: Further integration with Lean, Environmental Design and industry 4. 0 has been highlighted, some research on the economic implications in terms of return on investment (ROI) and long-term sustainable development is limited (Leong et al., 2019).

10) Interpretation of Findings

Here, it is found that the findings demonstrate the Moderating role is of the Eco-conscious Innovation in between low carbon supply chain methods and firm’s performance. Sustainable nanomaterials, adoption of intelligent production technologies, integrated Industry 4.0 enhance the efficiency of energy in all industries. Green innovation capabilities and environmentally responsible production practices enhance the performance of a firm by decreasing its impact of environment (Nimbalkar et al., 2017). Blockchain will facilitate Eco-conscious Innovation through big data with supply chains that are more transparent. IoT and energy-efficient manufacturing will also decrease emissions and waste by smart systems.

Implications

The study hereby gives the industries seeking to ameliorate the sustainability performance an insight. Eco-conscious Innovation and Low carbon Supply Chain method: Manufacturing firms need to develop Eco-conscious Innovation and low carbon supply chain methods that both enhance environmental and operational performance (Geng et al., 2021). Adopting Smart Technologies: It is possible that such waste minimization, energy consumption, and environmental footprint through the adoption of smart manufacturing technologies by manufacturers are achieved using sustainable nanomaterials and low impact manufacturing processes (Dharmayanti et al. 2023). Circular Design and Lean-Eco Strategies: Manufacturers must incorporate circular design and lean-Environmental Design strategies to enhance resource use with the reduction of wastes and increasing sustainability (Leong et al., 2019). Blockchain and complex data: Blockchain and complex data technologies are going to make better transparency and sustainability of the Procurement network that will allow a better decision-making process (Dharmayanti et al., 2023). Policy Support and Inter functional Coordination: Policymakers have to create regulatory systems and incentives to spur innovation. The manufacturer must invest in workers' training and strategic planning on how to revolutionize the system of manufacturing to be environmentally responsive (Geng et al., 2021).

11) Future Research & Application

Future studies should try to develop inclusive frameworks that seek to understand low carbon supply chain method effects on manufacturing output, especially for underdeveloped countries (Geng et al., 2021). It is also paramount that smart manufacturing technologies and data analytics be pushed further in the smaller facilities. Future studies shall also be exploring the economic ramifications of the integrated Lean, Industry 4.0 and EDGC, and approaches while considering closed-loop system, renewable energy challenges, and the cost effectiveness of sustainable nanomaterials (Nimbalkar et al., 2017). These results are beneficial for many sectors, such as low carbon supply chain method from a view of an economic innovation (Geng et al., 2021) and nanomaterials with environmentally friendly origin (Dharmayanti et al., 2023; Nimbalkar et al., 2017) applied in renewable energy and smart manufacturing technologies for enhancing a series of energies. Integrating Lean and & Industry 4.0 Environmental Design strategy and the use of blockchain and big data technologies have transformative potential and may improve supply chain transparency and reduce carbon footprints in textiles (Leong et al., 2019).

12) Recommendations

The key strategies in low carbon supply chain innovation strategies are the strategic application and adoption of Eco-Inno, optimization of logistics, appropriate use of sustainable nanomaterials, and smarter technologies for energy use (Dharmayanti et al., 2023; Nimbalkar et al., 2017). Lean strategy and Environmental design along with blockchain and big data should be adopted by manufacturers to increase transparency in supply chains (Geng et al., 2021).

13) Conclusion

Leveraging Green IT Innovations and Eco-efficient Manufacturing for Sustainable Supply Chain Optimization" deals with how EI mediates a link between low carbon supply chain application and improved output of manufacturing. Sustainable nanomaterial reduces waste and emission while smart manufacturing technology enhances efficiency in energy use and increases savings. Some additional strategies employed to further augment the sustainability of products include the industry 4.0, EDGC, and lean design strategy. Research emphasizes how sustainable manufacturing practices amplify green innovation's impact on performance, and technologies like blockchain and big data improve transparency and decision-making within supply chains. Despite such challenges, it is with lean and green that the IoT key component role in optimizing energy systems. This paper also looks at the Ecoelligent manufacturing ability to spur sustainability, thus making valuable contributions towards optimizing sustainable supply chains for more eco-efficient and competitive and environment-friendly operations.

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