Integrated Industry 4.0, Circular Economy, and Low-Carbon Management Framework: Implications for Sustainability Performance in the Manufacturing Sector

Luay Jum'a[a], Issa Hazaimeh[a], Muhammad Ikram[b*], Zulkaif Ahmed Saqib[c]

[a] *Department of Logistic Sciences, Business School, German Jordanian University, Amman, 11180 Jordan*

[b] *School of Business Administration, Al Akhawayn University in Ifrane, Avenue Hassan II, P.O. Box 104, 53000 Ifrane, Morocco*

[c] *School of Civil Engineering, Chengdu University of Technology, Chengdu, Sichuan, China*

Abstract

This study examines the integrated impact of low-carbon management practices (LCMPs), Industry 4.0 (I4.0), and circular economy practices (CEPs) on the triple bottom line of manufacturing firms. A conceptual framework incorporating both direct and indirect relationships is developed and theoretically grounded in the resource-based view (RBV) and dynamic capabilities theory (DCT). Data were collected using a structured online survey administered to senior managers in production, procurement, operations, logistics, and supply chain functions, resulting in 286 valid responses. The hypothesized relationships were empirically tested using Partial Least Squares Structural Equation Modeling (PLS-SEM). The results indicate that I4.0 technologies have a strong and significant positive effect on LCMPs, which subsequently enhance economic and social performance. CEPs are found to directly and positively influence environmental, economic, and social performance. However, the direct relationship between I4.0 and CEPs is not statistically significant, and CEPs do not mediate the relationship between I4.0 and sustainability outcomes. Further the findings highlight LCMPs as a critical mechanism through which digital transformation translates into sustainability performance, while revealing limited integration between I4.0 and circular economy initiatives. This study contributes theoretically to sustainability literature and provide practical guidance for managers seeking to align digital transformation with low-carbon and circular strategies.

Keywords*:* Circular economy and low carbon; environmental performance; integrated industry 4.0 and low-carbon framework; environmental performance; sustainable development

1. Introduction

Peremptorily, protection of the environment has become critical due to the accelerated degradation of ecological systems and the unsustainable exploitation of natural resources to meet increasing societal demands (Agyabeng-Mensah et al., 2021; Khan et al., 2025). Environmental degradation poses a systemic global threat by undermining long-term economic development, social welfare, and ecological stability (Björklund et al., 2012; Cheng et al., 2024). Empirical evidence indicates that carbon dioxide (CO_2) constitutes a substantial share of global greenhouse gas emissions, intensifying climate-related risks for economies and supply chains worldwide (Luo et al., 2024). This growing body of evidence has heightened global awareness of climate change and reinforced the urgency for coordinated organizational and policy-level responses (Kazancoglu et al., 2021; Khan et al., 2022). Consequently, sustainability has evolved from a compliance-driven concern into a strategic imperative for firms, particularly within environmentally intensive supply chains (Magazzino et al., 2022; Khan et al., 2022).

Supply chains, particularly in manufacturing, are under heightened examination due to their considerable environmental externalities. Manufacturing activities significantly contribute to carbon emissions, resource depletion, and waste generation, requiring the implementation of low-carbon management practices (LCMPs) to reduce environmental impacts while maintaining operational performance (Ambekar et al., 2019; Nenavath, 2025). To respond effectively, firms are reconfiguring their supply chains toward greater intelligence, flexibility, and transparency, thereby enabling more systematic implementation of LCMPs across production and logistics processes (Ambekar et al., 2019). However, achieving such transformation requires not only operational adjustments but also strategic alignment between technological, organizational, and sustainability-oriented initiatives.

Industry 4.0 (I4.0) technologies have emerged as a critical enabler of this transformation by digitally integrating supply chain actors through real-time data exchange, automation, and advanced analytics (Nascimento et al., 2024). Prior studies demonstrate that I4.0 technologies can directly reduce carbon emissions through process optimization, predictive maintenance, and energy-efficient operations (Hettiarachchi et al., 2022; Pant & Palanisamy, 2025), while also enhancing eco-innovation and sustainable supply chain performance (Khan et al., 2023). Nevertheless, the effectiveness of digitalization in achieving sustainability outcomes remains contingent upon complementary managerial practices. Lean production systems, flexible supply chains, and adaptive operational strategies are required to translate digital capabilities into tangible environmental and social benefits (Flynn & Traver, 2013). At the same time, the high economic costs associated with sustainability-driven investments continue to constrain adoption, particularly in developing economies and resource-limited manufacturing contexts (Flynn & Traver, 2013; Gawusu et al., 2022).

The circularity has emerged as a systemic strategy to tackle resource scarcity and environmental degradation, particularly in underdeveloped and emerging regions, alongside the ongoing digital transformation (Bhawna et al., 2024; Burke et al., 2023). Circular economy practices (CEPs) aim to improve financial, environmental, and social performance by promoting recycling, reuse, remanufacturing, and product life extension across supply chains (Burke et al., 2023; Hettiarachchi et al., 2022). Emerging evidence suggests strong complementarities between I4.0 technologies and CEPs, as digital tools such as IoT, big data analytics, and automation facilitate traceability, closed-loop logistics, and green procurement (Khan et al., 2022; Singh et al., 2025; Zhang et al., 2024). Moreover, technological revolutions have been shown to accelerate the transition toward green and circular economic systems (Khan et al., 2025). Despite these theoretical synergies, the empirical findings remain fragmented and inconclusive.

This fragmentation is particularly evident in developing-country manufacturing contexts, such as Jordan. Jordan faces mounting pressure to meet international climate commitments under the Paris Agreement while simultaneously attracting sustainable investments and expanding access to green financing (Alnadi et al., 2024; Ogiemwonyi & Eneizan, 2025). Although leading manufacturing firms in sectors such as textiles, pharmaceuticals, mining, food, and aviation have increasingly adopted I4.0 technologies, CEPs, and LCMPs (Cuevas-Pichardo et al., 2025), these initiatives are often implemented in isolation. Many firms deploy I4.0 primarily to enhance efficiency and competitiveness, without systematically aligning digitalization with circular economy objectives and low-carbon strategies (Burke et al., 2023; Hettiarachchi et al., 2022; Pant & Palanisamy, 2025). Consequently, sustainability outcomes remain suboptimal, and firms struggle to realize the full potential of integrated sustainability transformation (Mardani & Saberi, 2024).

Prior studies have examined I4.0, CEPs, and LCMPs individually, limited empirical research has investigated their integrated and synergistic effects on the triple bottom line, particularly through direct and mediating mechanisms in manufacturing firms operating in developing economies (Cuevas-Pichardo et al., 2025; Pant & Palanisamy, 2025). Existing empirical work largely adopts fragmented analytical lenses, focusing on isolated sustainability initiatives rather than their interdependencies and co-evolution within complex supply chain systems (Mardani & Saberi, 2024; Nenavath, 2025). Moreover, the literature provides insufficient theoretical explanation of how firms can strategically align and reconfigure these initiatives over time to respond to dynamic environmental, regulatory, and market pressures, particularly under conditions of uncertainty and resource constraints (Abbasi & Choukolaei, 2023; Cheng et al., 2024). This gap constrains both theoretical advancement and managerial guidance, underscoring the need for a more integrated, capability-oriented, and dynamic perspective on sustainability transformation in manufacturing supply chains.

This study examines the direct and mediating relationships among I4.0, CEPs, and LCMPs in shaping the triple bottom line performance of manufacturing firms. Specifically, it addresses the following research questions:

RQ1: Does digitalization (I4.0) improve the triple bottom line performance of manufacturing firms under the direct and indirect effects of CEPs and LCMPs?

RQ2: How does I4.0 influence the adoption of LCMPs and CEPs in manufacturing firms?

The study is theoretically grounded in the resource-based view (RBV) and dynamic capabilities theory (DCT). RBV explains how firms achieve competitive advantage by leveraging valuable and rare resources (Grant, 1991; Chacón et al., 2014), while DCT extends this logic by emphasizing the firm's ability to integrate, reconfigure, and renew resources in rapidly changing environments (Teece, 2007). In this research, I4.0 technologies, CEPs, and LCMPs are conceptualized as interrelated dynamic capabilities that enable firms to sense environmental pressures, seize sustainability opportunities, and transform operational routines accordingly.

This research presents several significant implications. This study theoretically advances the literature on sustainability and supply chains by proposing an integrated RBV–DCT framework. It elucidates the interplay between digitalization, circular economy practices, and low-carbon management in the development of dynamic capabilities that enhance sustainable performance. Practically, the findings provide managers and policymakers with actionable insights on how to strategically align I4.0 investments with CEPs and LCMPs to overcome fragmented implementation and achieve long-term economic, environmental, and social benefits. Overall, the study responds directly to fill an important gap in the literature by demonstrating why integrated sustainability capabilities not isolated initiatives are essential for manufacturing firms seeking resilience and competitiveness in increasingly uncertain and sustainability-driven markets.

The manuscript is organized into several sections. Section 2 outlines the literature review, including the proposed hypotheses and the conceptual model. Section 3 outlines the methodology, which includes factor analysis, the data collection process, and hypothesis testing. Section 4 presents the study's findings. Section 5 outlines the discussions and implications of the study's outcomes. Section 6 presents the conclusion, including limitations and directions for future research.

2. Literature Review:

2.1 Circular Economy Practices (CEPs):

The circular economy represents a significant shift in our relationship with the environment (Cuevas-Pichardo et al., 2025). Implement closed-loop energy and material systems, avert resource depletion, and promote sustainable development among individuals, communities, and society (Ogiemwonyi & Eneizan, 2025; Suthagar & Mishra, 2025). CEPs represent a forward-thinking economic approach that emphasizes the management of waste cycles, addressing challenges associated with resource scarcity and waste disposal (Zhang et al., 2024). This is a notable alternative to the linear economic model, which stresses resource efficiency through a circular strategy for environmental and economic advantages (Dohale et al., 2023). All supply chain components must work together to switch from linear to circular production (Jum'a et al., 2025). The CEPs' business model emphasizes waste reduction, reapplication, recycling, and resource recovery (Nobili & Cappellaro, 2021; Sorensen & Baerenholdt, 2020).

The accomplishment of CEP's objectives depends on the collaborative efforts of all stakeholders in the supply chain, with policymakers playing a crucial role (Souza et al., 2024). External influences encompass public policies and market dynamics (both opportunities and threats), technological advancements, and stakeholder engagement, whereas internal influences relate to organizational resources, competencies, and capabilities (Schulz et al., 2019). In the literature, several necessary steps for the effective attainment of a CEP have been verified (Schulz et al., 2019; Sorensen & Baerenholdt, 2020). Activities are divided into five groups. During the "Take" phase, firms must refrain from employing hazardous and unsustainable materials, choose raw materials and suppliers that adhere to rigorous environmental policies, incorporate a significant proportion of recoverable materials, and maintain transparency in their processes and products.. Efficient manufacturing, renewable energy, sustainable design, and zero-waste production minimize environmental impacts during the "Make" phase. In collaboration with stakeholders, the "Distribute" phase enhances stock management, routes, and space for both forward and reverse logistics to promote sustainability. Companies employ green marketing strategies to engage sustainable market segments throughout the product-use phase by highlighting their ecological advantages, such as eco-labeling and zero-waste certifications, to their intended customer demographic. In the recovery stage, businesses must implement strategies for resource reuse or recycling, thus reducing the resource cycle within the economy.

2.2 Low-carbon management practices (LCMPs)

Over the past decade, global greenhouse gas emissions have changed conventional supply networks (Ambekar et al., 2019). LCMPs focus on energy usage and carbon emissions, essential for operational excellence and environmental sustainability (Abbasi & Choukolaei, 2023). Monitoring and regulating emissions across the supply chain maximizes benefits and minimizes downsides (Singh et al., 2025). Further, the concept of low-carbon plays a crucial role for SCM in LCMPs, emphasizing a holistic approach to planning, monitoring, and reducing carbon emissions across every stage of the supply chain, including material sourcing, product design, production plants, transportation, and delivery (Bhawna et al., 2024; Cuevas-Pichardo et al., 2025; Ogiemwonyi & Eneizan, 2025). The implementation of low-carbon public procurement, the generation of low-carbon energy, and the production of products with minimized life cycle emissions are crucial components of LCMP (Shaharudin et al., 2019). To reduce negative ecological impacts, it is crucial to examine the entire life cycle of a product during its design stage (Gao et al., 2025), select renewable or recyclable materials, and lessen reliance on carbon-intensive resources (Peng et al., 2022; S. Wang et al., 2024).

The production method incorporates enhanced efficiency, technological advancements, deliberate material selection, and life cycle management to reduce emissions (Sarkar et al., 2021). Low-carbon distribution emphasizes energy efficiency in warehousing and shipping, as well as eco-friendly packaging (Ng et al., 2022). The low-carbon logistics supply chain utilizes technology to enhance transportation efficiency and reduce emissions (Dohale et al., 2023; S. Wang et al., 2024). By implementing these supply chain measures, companies can significantly lower their carbon footprint and improve sustainability (Vegter et al., 2023).

2.3 Industry 4.0 (I4.0):

Olsen & Tomlin (2020) verified that I4.0 technology can revolutionize systems, operations, and competitive strategies. It presents a great opportunity to revolutionize supply chain and operations management (Souza et al., 2024). This connects to centralized systems capable of independently managing and making decisions regarding the manufacturing line (Cuevas-Pichardo et al., 2025). I4.0 allows strategic qualities including design-to-cost, servitization, and supply chain integration, demonstrating cutting-edge supply chain techniques (Ghadge et al., 2020; Mardani & Saberi, 2024). Garay-Rondero et al. (2020) created a cloud computing and cloud robotics supply chain model using virtual and physical elements.

The present framework aims to clarify the complex connections within the advanced supply chain, emphasizing its capacity to alleviate specific limitations linked to Industry 4.0. Scholars in the field of literature assert that innovative supply chain management solutions can enhance production by fostering larger, more flexible, and more efficient enterprises (Olsen & Tomlin, 2020). The potential of transformation in manufacturing through the adoption of innovative models that enhance efficiency existed (Jum'a et al., 2025). To alter processing, I4.0 technologies must be adopted (Hettiarachchi et al., 2022). Chavez et al. (2024) claimed that digital technologies boost process efficiency, task execution, and data collection and dissemination. Modern industrial technology is moving toward sustainable production, causing major changes (Souza et al., 2024). Consequently, I4.0 is pivotal to the evolution of modern sustainable production systems.

2.4 Hypothesis Development

2.4.1 CEPs to I4.0

The relationship between circular economy practices and Industry 4.0 gained interest; however, their systematic integration is still inadequately examined (Malik et al., 2024). Emerging evidence indicates that CEPs and I4.0 can be mutually reinforcing when guided by coherent roadmaps, governance, and performance targets (Abdul-Hamid et al., 2020). For instance, Abdul-Hamid et al. (2020) show that policy- and strategy-led programs unlock I4.0 resources to develop circular consumer goods. Integrating I4.0 with CEPs has been associated with operational excellence in the supply chain (Alkhuzaim et al., 2021), whereas the gradual implementation of digital technologies improves companies' technical skills and leads to long-term environmental and economic benefits (Abdul-Hamid et al., 2020; Taddei et al., 2024). Realizing circularity, however, requires coordinated action among consumers, firms, and manufacturers (Gao et al., 2025; Souza et al., 2024). As sustainability pressures intensify, both I4.0 and circular economy agendas have become central to corporate transformation (Malik et al., 2024), with I4.0-enabled supply chains outperforming non-digital counterparts on operational, environmental, and economic metrics (Mardani & Saberi, 2024). Prior studies consistently underline I4.0's relevance for circularity (Ambekar et al., 2019; Cuevas-Pichardo et al., 2025), highlighting decision support and timely intelligence that improve efficiency and strategic management. Such integration is also viewed as an engine of broader economic development (Nobili & Cappellaro, 2021).

Long-term effects typically encompass cost reductions and revenue growth, even in the presence of potentially subdued short-term financial returns (Hettiarachchi et al., 2022).

Complementary technologies most notably blockchain can further enable circular value creation and support environmental and social sustainability within the digital economy (Alnadi et al., 2024; Nascimento et al., 2024). Accordingly, this study proposes the following hypothesis for empirical testing: H1. The adoption intensity of Industry 4.0 technologies is positively associated with the breadth and depth of circular economy practice implementation across the supply chain, which in turn enhances operational, environmental, and economic performance.

H1: I4.0 technology has a positive effect on the adoption of CEPs.

2.4.2 CEPs to Sustainability Performance

Firms need CEPs to improve their environmental, economic, and social sustainability. The circular economy promotes remanufacturing, recycling, and sustainable product creation to decouple economic growth from resource consumption (Nobili & Cappellaro, 2021; Singh et al., 2025). Circle product design promotes product remanufacturing and refurbishing, reducing raw material extraction and waste (Taddei et al., 2024). Sustainable procurement and manufacturing help firms reduce their environmental impact and dependence on limited natural resources (Batista et al., 2018; Maji & Haloi, 2025). Through emission reduction, landfill waste reduction, and energy efficiency, CEPs help preserve the environment (Morais & Silvestre, 2018). Consequently, a hypothesis is proposed:

From an economic perspective, CEPs improve resource productivity, reduce operational costs, and create new revenue opportunities through value retention strategies, such as refurbishment and product-service systems (Brydges, 2021). Circular procurement reduces costs by encouraging resource recovery, while closed-loop systems improve cost efficiency across the supply chain (Wanja & Achuora, 2020; Zaidi et al., 2019). Moreover, CE enables organizations to mitigate risks linked to variations in resource costs and regulatory requirements, thereby enhancing their financial outcomes and sustaining their competitive edge over time (Astarita et al., 2020; Leng et al., 2020). As a result, we maintain:

CEPs contribute to long-term social sustainability by fostering economic growth in the remanufacturing and recycling industries, bolstering local communities, and fighting for ecological fairness by reducing pollution and protecting our planet's natural resources (Astarita et al., 2020; Hettiarachchi et al., 2022; Morais & Silvestre, 2018). Furthermore, the adoption of CEPs within supply chains has the potential to enhance social responsibility by involving local communities in waste recovery initiatives and promoting inclusive business models (Jum'a et al., 2025). These initiatives enhance the firm's social license to undertake operational tasks that contribute to achieving sustainability objectives, including the Sustainable Development Goals. As a result, we suggest the following:

Research indicates that Industry 4.0 (I4.0) technologies enhance circularity, whereas CEPs have a direct effect on sustainability. I4.0 technologies facilitate closed-loop operations and resource optimization through precise monitoring, data-driven decision-making, and real-time management of production processes (Astarita et al., 2020; Jum'a et al., 2025). These abilities enable circular models in manufacturing, where material flow monitoring and product lifecycle management are essential. Evidence suggests that Industry 4.0 and the Circular Economy boost businesses' sustainability. Kamble & Gunasekaran, (2023) demonstrate that CE is not required for I4.0 installation, although I4.0 technologies highly encourage CE settings, which boost sustainability. According to 238

Indian manufacturing enterprises, CE mediates the relationship between I4.0 and all three sustainability dimensions (social, economic, and environmental).

According to Cuevas-Pichardo et al. (2025), a study of 338 Mexican firms found that CE mediates the link between I4.0 and sustainability results. Industry 4.0 and Circular Economy improve environmental quality, resource efficiency, and low-carbon transitions. I4.0 provides the digital platform for CE, whereas CE promotes sustainable development through technical improvements. Bag & Pretorius (2022) argued that this perspective can be enhanced by introducing a conceptual framework that integrates I4.0, sustainable manufacturing, and CE. Big data analytics and AI enable companies to reduce waste, break resource cycles, and improve industrial environmental and social conditions. Literature works suggest CE mediates I4.0-sustainability. I4.0 technologies establish the technology basis for circular projects by improving traceability, automation, and optimization. CE channels I4.0's benefits to improve sustainability. Based on theoretical reasoning and empirical evidence, hypotheses 6,7, and 8 are proposed and shown in Figure 1:

H2: I4.0 technology has a positive effect on LCMPs

H3: CEPs are positively associated with environmental performance.

H4: CEPs are positively associated with economic performance.

H5: CEPs are positively associated with social performance.

H6: CEPs play a positive intermediary role between Industry 4.0 and environmental performance.

H7: CEPs play a positive intermediary role between Industry 4.0 and economic performance.

H8: CEPs play a positive intermediary role between Industry 4.0 and social performance.

2.4.3 Low-carbon management practices and sustainability performance

LCMPs are increasingly significant in corporate sustainability strategies, particularly as organizations face growing regulatory, market, and societal pressures to decrease greenhouse gas (GHG) emissions (Ambekar et al., 2019). LCMPs encompass a wide range of strategic and operational initiatives, including carbon footprint assessments, eco-design, carbon-efficient manufacturing, and low-carbon logistics, all aimed at minimizing emissions throughout the product lifecycle (Luo et al., 2024; Shi et al., 2022). These practices enable companies to incorporate carbon efficiency into their corporate strategies and foster sustainable development, consequently enhancing long-term competitiveness and stakeholder value (Raza & Lin, 2022; C. Wang et al., 2024).

LCMPs improve resource efficiency, reduce industrial pollution, and ensure adherence to environmental regulations in the context of environmental sustainability. Companies can mitigate their environmental impact through the implementation of waste reduction strategies, the adoption of carbon-neutral logistics, and the utilization of renewable resources (Sharma et al., 2025). These practices contribute to the goals of ecological conservation by reducing emissions and easing the pressure on natural ecosystems (Shaharudin et al., 2019). Research findings demonstrate that the adoption of LCMPs improves environmental performance through systematic monitoring of emissions, recycling efforts, and careful use of materials (Jum'a et al., 2025; Ogiemwonyi and Eneizan, 2025). As a result, we suggest:

H9: LCMPs are positively associated with environmental performance.

LCMPs improve economic performance by fostering cost efficiency and profit generation through the optimization of energy use, minimizing waste disposal costs, and enhancing supply chain productivity (Ghosh et al., 2025; Maji & Haloi, 2025).

Incorporating carbon efficiency into core business operations allows companies to reduce risks associated with variable energy markets, carbon taxation, and environmental fines.

Furthermore, low-carbon strategies open doors to new, environmentally friendly markets, enhance brand reputation, and enable differentiation within increasingly sustainability-focused value chains (Shaharudin et al., 2019). The collective benefits significantly improve corporate competitiveness and revenue growth, particularly in sectors where consumers and investors prioritize low-carbon products and ethical production methods (Olekanma et al., 2024). As a result, we maintain:

H10: LCMPs are positively associated with economic performance.

Moreover, LCMPs foster ethical business practices and stakeholder involvement by promoting environmental accountability and transparency (Aragão & Jabbour, 2017). Organizations that reduce their carbon emissions improve air quality and promote community health, thus enhancing the overall quality of life for local inhabitants (Jum'a et al., 2025; Kannan et al., 2014). LCMPs align corporate actions with the expectations of customers, employees, and the broader community to promote greater ethical standards, accountability, and social involvement within organizations. Furthermore, clear reporting and proactive efforts to reduce emissions build stakeholder trust and enhance the firm's standing in society (Shaharudin et al., 2019). The findings highlight the positive impact of LCMPs on corporate social performance, leading to the following hypothesis:

H11: LCMPs are positively associated with social performance.

LCMPs enhance sustainability independently, although they achieve optimal efficacy when integrated with I4.0 technologies. Cyber-physical systems, artificial intelligence (AI), the internet of things (IoT), and big data analytics facilitate real-time monitoring, predictive analysis, and digital management of energy and emission metrics in Industry 4.0. Organizational capabilities lay the groundwork for the widespread adoption and improvement of LCMP (Jum'a, 2023). Recent empirical studies provide compelling evidence for this synergistic relationship. Tian et al. (2024) illustrate that the industrial intelligence concept is a crucial component of I4.0, it significantly lowers carbon emissions within the industrial sector. Their study illustrates how I4.0 technologies enhance carbon reduction through the modernization of industrial frameworks and the encouragement of technological progress. The authors highlight that these effects are particularly pronounced when paired with strong human capital, which amplifies the environmental influence of industrial intelligence. This confirms that while digitalization has its advantages, it produces even more significant environmental benefits when it enhances and facilitates the adoption of low-carbon practices.

Sharma et al. (2025) demonstrate that the crucial role of LCMPs in strengthening organizational resilience during the transformation driven by I4.0. Integration of external low-carbon supply chains, a key part of LCMP, mediates the relationship between I4.0 adoption and organizational resilience. This mediation is shaped by the environmental commitment of suppliers, highlighting the importance of integrating external stakeholders into a cohesive, low-carbon ecosystem. The findings support the idea that Industry 4.0 creates favorable conditions for the successful application of Lifecycle Management Practices (LCMP), ultimately enhancing sustainability results across different performance areas.

The implementation of I4.0 enables organizations to accurately monitor emissions, optimize energy strategies, create carbon-neutral products, and digitally manage low-carbon supply chains. The digital capabilities enhance the efficiency and reliability of LCMPs, establishing them as vital intermediaries in the relationship between digitalization in supply chains and sustainable performance. Consequently, we put forth the subsequent hypotheses:

H12: LCMPs play a positive intermediary role between I4.0 and environmental performance.

H13: LCMPs play a positive intermediary role between I4.0 and economic performance.

H14: LCMPs play a positive intermediary role between I4.0 and social performance.

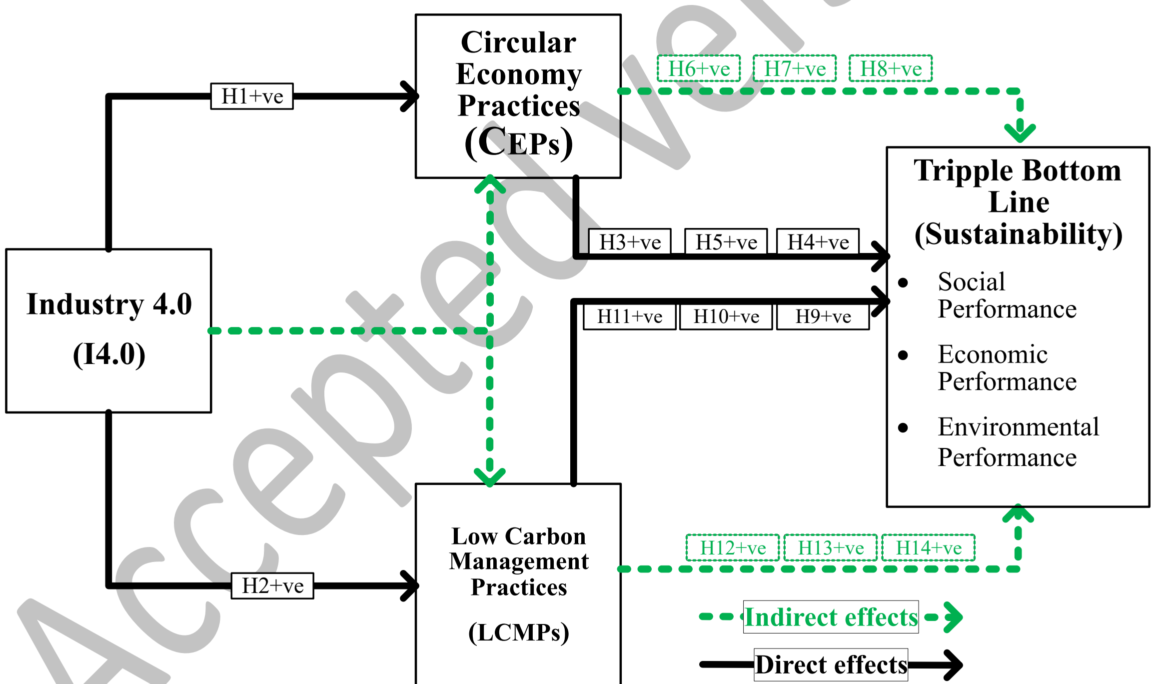

Figure 1: Conceptual model of study

3. Research Method:

3.1 Data administration:

This study examines a research population of supply chain experts working in Jordanian companies, specifically targeting individuals in upper management roles. The sample included participants from diverse industrial sectors, featuring a variety of job titles, including production managers, plant managers, operations managers, procurement managers, logistics managers, and supply chain managers. Purposive sampling, a sort of nonprobability sampling aim which allows researchers to choose cases (Saunders et al., 2019), that are likely to provide accurate and pertinent answers to research questions.

A data collection was conducted through an online questionnaire distributed via email and social media. This technique was adopted to increase response rates and accommodate the hectic schedules of the managers and specialists engaged in the study. Current work uses partial least squares structural equation modeling (PLS-SEM), which recommended for 100 samples (Hair et al., 2020). From August 2023 to March 2024, we collected 286 valid responses.

3.2 Measurement scale

The measurement items for the constructs included are derived from existing literature, as presented in Table 1. The I4.0 construct comprises five elements, based on the research from (Eslami et al., 2021; Xu et al., 2023). The construct CE practices was assessed by using 14 items adapted from (Benachio et al., 2020; Dey et al., 2022). LCMPs were evaluated using six items according to the literary works (Kannan et al., 2014; Sartal et al., 2020). The economic, environmental, and social performance was measured by 15 scale items, which were adapted from (Agrawal et al., 2022; Dey et al., 2022; Jum'a, 2023). The final questionnaire comprised two distinct sections, with demographic data collected in Section 1. Section 2 comprised scale items for all constructs, which were assessed using a five-point Likert scale ranging from 1 to 5, with 5 indicating higher agreement and 1 indicating disagreement.

Table 1. Construct and measurement items

Variables	Items	Measurement items	References

I4.0 (Industry 4.0)	I4.0T1	We utilize digital technologies (Industry 4.0) that uniquely identify items (e.g., products, packages, pallets).	(Eslami et al., 2021; Ghadge et al., 2020; Hettiarachchi et al., 2022)
	I4.0T2	We remotely monitor, track, and control supply chain activities using Industry 4.0 tools.	
	I4.0T3	We automate supply chain decisions by integrating Industry 4.0 digital solutions.	
	I4.0T4	We optimize our supply chain in real time through data provided by Industry 4.0 technologies.	
	I4.0T5	We generate and analyze large volumes of data via Industry 4.0 systems to inform decision-making.	
CE (Circular Economy) Practices	CEPr1	We assess suppliers based on their adherence to environmental regulations.	(Benachio et al., 2020; Dey et al., 2022; Saha et al., 2022)
	CEPr 2	We include environmental criteria when choosing suppliers.	
	CEPr 3	If we rely on nonbiodegradable materials, we endeavor to reuse, recycle, or remanufacture them.	
	CEPr 4	We have policies to cut down on raw material, water, or energy use during production.	
	CEPr 5	We strive to reduce environmental impact by maximizing resource efficiency.	
	CEPr 6	We incorporate renewable or sustainable energy sources for our production needs.	
	CEPr 7	We employ logistics optimization methods to improve vehicle capacity usage.	
	CEPr 8	We have solid reverse logistics processes to retrieve products customers no longer use	
	CEPr 9	We efficiently manage inventory, routing, and space throughout forward as well as reverse logistics.	
	CEPr10	We develop and maintain product designs aimed at extending product life and promoting reuse.	
	CEPr11	We inform customers about our environmental and social practices.	
	CEPrs 12	We recycle industrial byproducts (e.g., chemicals, oils, packaging, plastics) generated in our operations.	
	CEPrs 13	We have effective systems for reusing, recovering, and recycling materials.	
	CEPrs 14	We follow safe disposal procedures for equipment and chemicals at end-of-life.	
LCMPs (Low Carbon Management Practices)	LCMPs1	We consider ways to reduce carbon emissions at the product design phase.	(Jabbour et al., 2019; Sartal et al., 2020)
	LCMPs2	We upgrade or adopt manufacturing processes to lower carbon emissions.	
	LCMPs3	We utilize transportation methods that are efficient in terms of carbon emissions.	
	LCMPs4	We maintain (or plan to maintain) a structured environmental management system to reduce impacts and boost operational efficiency.	
	LCMPs5	We rely on low-carbon or carbon-free energy sources.	
	LCMPs6	We substitute carbon-intensive raw materials with eco-friendlier alternatives.	

EP (Economic Performance)	EcnP1	We have effectively lowered costs for purchasing materials.	
	EcnP2	We have seen a decrease in energy expenditure.	
	EcnP3	We have reduced fees tied to waste disposal.	
	EcnP4	We have boosted our return on investment (ROI).	(Agrawal et al., 2022; Jum'a et al., 2025; Saha et al., 2022)
	EcnP5	We have achieved increases in earnings per share (EPS).	
ENP (Environmental Performance)	EnrP1	We have reduced air pollution and emissions.	
	EnrP2	We have curbed the generation of waste (solid or water).	
	EnrP3	We have reduced reliance on toxic or harmful substances.	
	EnrP4	We have minimized the occurrence of environmental accidents.	
	EnrP5	We have enhanced energy savings through conservation and efficiency measures.	
SP (Social Performance)	SP1	We have improved the welfare and economic standing of our stakeholders.	
	SP2	We contribute to better health and safety within the community.	
	SP3	We take steps to lower adverse environmental impacts and risks posed to the public.	
	SP4	We have upgraded safety standards and health protections for our employees.	
	SP5	We have raised awareness and reinforced employee rights throughout the company.	

3.3 Descriptive statistics

Table 2 presents the details of the demographic data of respondents across various dimensions. The respondents predominantly represent the food industry (29.7%), followed by the packaging and paper industry (22.4%), pharmaceutical industry (16.8%), textile industry (19.9%), and mining industry (11.2%). With respect to company size, most respondents work in corporations with 100 or more employees (65.4%), while 22.4% come from medium-sized companies, and 12.2% from small businesses. At the job level, half of the respondents (50.0%) held middle management positions, whereas 19.9% held top management positions. The remaining respondents are split between supervisory-level (22.0%) and officer-level roles (8.0%).

Table 2: Descriptive stats of the respondents

Dimension	Category	Count	%

Industry sector	Mining industries	32	11.2%
	Food industries	85	29.7%
	Pharmaceutical industry	48	16.8%
	Packaging & paper industries	64	22.4%
	Textile Industry	57	19.9%
Company size	Larg firms (100 employees/>100)	187	65.4%
	Medium firms (20 employees/<100)	64	22.4%
	Small firms (< 20 employees)	35	12.2%
Job Level	Top management (Director, Chief, President)	57	19.9%
	Middle management	143	50.0%
	Supervisory level	63	22.0%
	Officer level	23	8.0%

4. Results

The analysis commences with descriptive statistics, assessing key measures including the mean, standard deviation, and skewness. The SEM-PLS process initiates with a multicollinearity assessment to identify strong correlations among exogenous constructs, followed by the removal of items exhibiting higher variance inflation factor (VIF) values. In the measurement model, reliability and validity are assessed through composite reliability, Cronbach's alpha, and the AVE. Discriminant validity is confirmed via the Fornell–Larcker criterion. Finally, the structural model is analyzed by bootstrapping to evaluate path relationships, beta values, and significance. PLS relies on nonparametric bootstrapping, commonly involving 5,000 resampling iterations. Each iteration recalculates estimates to produce t-values for path coefficients, which determine whether these coefficients differ significantly from zero (Hair et al., 2020). Figure 2 illustrates the SEM path diagram depicting the relationships among CMPs, I4.0, and CEPs concerning the triple bottom line.

4.1 Descriptive analysis

Table 3 shows that EcP has the highest mean at 3.96, indicating the strongest agreement among the constructs. This is followed by EnP, with a mean of 3.94, and SP, with a mean of 3.91, suggesting high levels of agreement. I4.0, CE and LCMP have slightly lower means of 3.77, 3.63 and 3.61, respectively, indicating somewhat lower levels of agreement than the other constructs do.

Table 3: Descriptive analysis result

Construct	Mean	Std. Deviation	Skewness	Std. Error	Kurtosis	Std. Error
I4.0T	3.77	0.63	-0.08	0.14	-0.46	0.29
CEPs	3.63	0.60	-0.34	0.14	-0.38	0.29
LCMPs	3.61	0.70	-0.42	0.14	0.12	0.29
EcnP	3.96	0.62	-0.49	0.14	0.56	0.29
EnrP	3.94	0.72	-0.84	0.14	1.55	0.29
SP	3.91	0.90	-0.79	0.14	1.59	0.29

4.2 Multicollinearity test

This study assessed multicollinearity to evaluate the strength of correlation among external factors. According to Hair et al. (2019), tolerance must be higher than 0.10, and the VIF should remain below 5 to confirm the absence of multicollinearity. As VIF values meet the criteria and multicollinearity was acceptable for further analysis, three CE items (1, 2, 4), three LCMP items (1, 4, 6), one environmental performance item (4), and two social performance items (4, 5) were excluded.

The two-stage structural equation modeling (SEM) technique employed both measurement and structural models. SmartPLS Version 4 served as the principal tool for data analysis (Hair et al., 2020). To implement SEM, factor analysis was conducted to assess the measurement of the statistical model.

4.3 Measurement model analysis

Factor analysis (FA) was conducted to check the validity and reliability of the data for the study framework. According to FA, convergence validity (CV) and discriminant validity (DV) approaches were used to verify the validity. The reliability was tested by using average variance extracted (AVE), composite reliability, factor loadings, and Cronbach's alpha values. As indicated by (Hair et al., 2020), Cronbach's alpha, composite reliability, factor loadings, and AVE values above 0.70. Table 4 demonstrates that the latent components of this study exhibited good convergent validity and reliability.

Discriminant validity (DV) and CV assessed data validity. DV was calculated by comparing the construct correlation coefficients to the square roots of AVE. Hair et al. (2020) posited that discriminant validity is confirmed when the square root of the average variances extracted for each construct surpasses the respective inter-construct correlations, as illustrated in Table 5. Table 5 also indicates that DV is confirmed when the HTMT value is significantly lower than the critical threshold of 0.9, thus affirming the validity of all model parameters. The FA validates the DV for all constructs.

Table 4: Composite Reliability

Scale Items	Mean	Standard deviation	Excess kurtosis	Skewness	Factor Loadings	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	VIF
CEPs1	4.329	0.845	5.965	-2.114	0.822***				2.865
CEPs10	4.332	0.820	5.645	-2.013	0.806***				2.704
CEPs11	4.314	0.863	5.750	-2.099	0.839***				3.06
CEPs12	4.300	0.843	5.777	-2.056	0.811***				2.652
CEPs13	4.343	0.830	6.010	-2.106	0.823***				3.106
CEPs14	4.361	0.851	6.054	-2.167	0.821***	0.962	0.964	0.668	3.073
CEPs2	4.350	0.845	6.175	-2.168	0.820***				2.939
CEPs3	4.339	0.847	5.989	-2.131	0.831***				3.103
CEPs4	4.386	0.833	5.664	-2.092	0.812***				2.89
CEPs5	4.361	0.842	5.750	-2.098	0.810***				2.83

CEPs6	4.346	0.818	5.834	-2.055	0.806***				2.869
CEPs7	4.343	0.826	5.512	-2.012	0.816***				2.963
CEPs8	4.354	0.862	6.146	-2.198	0.826***				3.339
CEPs9	4.389	0.816	5.598	-2.056	0.802***				2.688
EcnP1	3.896	0.732	2.080	-0.880	0.687***				1.516
EcnP2	3.825	0.949	-0.162	-0.675	0.916***				3.953
EcnP3	3.804	0.957	0.369	-0.878	0.893***	0.892	0.917	0.702	3.471
EcnP4	3.779	1.069	0.204	-0.869	0.868***				2.599
EcnP5	3.750	0.953	-0.098	-0.600	0.805***				2.073
EnrP1	4.236	0.708	3.048	-1.162	0.750***				1.811
EnrP2	4.311	0.712	0.753	-0.892	0.880***				3.334
EnrP3	4.279	0.737	3.303	-1.301	0.866***	0.862	0.899	0.642	3.043
EnrP4	4.289	0.796	2.747	-1.336	0.825***				1.824
EnrP5	4.243	0.740	-0.219	-0.636	0.666***				1.574
I4.0T1	3.600	0.690	3.590	-1.907	0.881***				2.868
I4.0T2	3.618	0.627	2.086	-1.589	0.878***				2.85
I4.0T3	3.568	0.667	3.130	-1.700	0.859***	0.916	0.919	0.748	2.456
I4.0T4	3.489	0.697	2.280	-1.458	0.877***				2.741
I4.0T5	3.536	0.691	2.807	-1.632	0.828***				2.257
LCMPs1	4.664	0.599	4.626	-2.010	0.873***				2.991
LCMPs2	4.668	0.604	4.621	-2.038	0.855***				2.65
LCMPs3	4.636	0.612	3.861	-1.847	0.852***	0.925	0.927	0.727	2.647
LCMPs4	4.675	0.546	1.192	-1.458	0.804***				2.209
LCMPs5	4.689	0.585	4.572	-2.060	0.865***				2.899
LCMPs6	4.657	0.570	2.079	-1.568	0.866***				2.809
SP1	3.861	0.857	0.340	-0.481	0.751***				1.6
SP2	3.818	0.861	1.108	-0.685	0.838***				1.886
SP3	3.886	0.850	1.219	-0.761	0.823***	0.837	0.859	0.605	1.882
SP4	3.889	0.823	1.232	-0.720	0.742***				1.626
SP5	3.918	0.835	1.222	-0.770	0.729***				1.603

Table 5: Discriminant validity

Heterotrait–Monotrait ratio of correlations (HTMT) criterion						
	CEPs	**EcnP**	**EnrP**	**I4.0T**	**LCMPs**	**SP**
CEPs	1					
EcnP	0.069	1				
EnrP	0.324	0.164	1			
I4.0T	0.047	0.398	0.145	1		
LCMPs	0.068	0.441	0.105	0.758	1	
SP	0.156	0.738	0.164	0.235	0.232	1
Fornell–Larcker Criterion						

	CEPs	EcnP	EnrP	I4.0T	LCMPs	SP
CEPs	**0.817**					
EcnP	0.063	**0.838**				
EnrP	0.31	-0.048	**0.801**			
I4.0T	-0.02	0.366	0.135	**0.865**		
LCMPs	-0.052	0.409	0.09	0.701	**0.853**	
SP	0.145	0.617	0.106	0.21	0.208	**0.778**

4.4 SEM analysis

SmartPLS conducted bootstrapping of its structural model using 5000 subsamples. Figure 2 illustrates that the R-squared value indicates the proportion of variance in the dependent variable that the model explains, thereby serving as an indicator of the model's explanatory power and overall robustness. According to Byrne (2013), the NFI should be 0.90 or greater; the closer the NFI is to 1, the better the fit. and the SRMR should be less than 0.09. On the basis of the model fit criteria, the PLS analysis yielded SRMR (0.047) and NFI (0.882) values are presented in Table 6, which indicate an acceptable fit for the model.

Table 6: Model fitness results

Index	Saturated model
SRMR-Standardized Root Mean Squared Residual	0.055
d_ULS-Unweighted Least Squares Discrepancy	2.488
d_G-geodesic distance	1.035
Chi-square	1496.282
NFI-Normed fit index	0.832

The SEM results provide mixed support for the proposed hypotheses. As shown in Table 7, H1 (I4.0 to CEPs) was not supported, with a negative path coefficient ($\beta = -0.02$), a T-value of 0.319, and a P-value of 0.75, indicating no significant relationship. Conversely, H2 (I4.0 to LCMPs) was strongly supported ($\beta = 0.701$, $T = 10.529$, $P < 0.001$), confirming a significant positive association. Regarding the effects of CEPs on sustainability outcomes, H3 (CEPs and Environmental Performance) was supported (β = 0.315, T = 6.491, P < 0.001), while H4 (CEPs and Economic Performance) was marginally significant (β = 0.085, T = 1.949, P = 0.05). H5 (CEPs → Social Performance) also showed a significant effect (β = 0.156, T = 2.293, P = 0.022). In terms of LCMPs, H9 (LCMPs and Environmental Performance) was not supported (β = 0.106, T = 1.571, P = 0.116). However, both H10 (LCMPs and Economic Performance) and H11 (LCMPs and Social Performance) were supported, with significant path coefficients (β = 0.414, T = 7.321, P < 0.001; β = 0.216, T = 3.847, P < 0.001, respectively).

Regarding the indirect effects, the mediating role of Circular Economy Practices (CEPs) in the relationship between Industry 4.0 and the sustainability dimensions (H6–H8) was not supported, as all T-values were below 1 and P-values exceeded 0.75, indicating no statistically significant mediation. The mediating role of Low-Carbon Management Practices (LCMPs) yielded varied results. Hypothesis 12 (I4.0 and LCMPs and Environmental Performance) was not supported (β = 0.074, T = 1.519, P = 0.129), indicating an insignificant indirect effect. Both H13 (I4.0 and LCMPs and Economic Performance) and H14 (I4.0 and LCMPs and Social Performance) received support, evidenced by strong T-values of 6.605 and 3.925, respectively, along with P-values < 0.001, indicating significant mediation effects.

Table 7: SEM model results

Direct hypothesis					
NO.	**Hypothesis**	**Effects**	**STDEV**	**T-values**	**P values**
H1	I4.0T-> CEPs	-0.02	0.064	0.319	0.75
H2	I4.0T-> LCMPs	0.701	0.067	10.529	0
H3	CEPs -> EnrP	0.315	0.049	6.491	0
H4	CEPs -> EcnP	0.085	0.043	1.949	0.05
H5	CEPs -> SP	0.156	0.068	2.293	0.022

H9	LCMPs -> EnrP	0.106	0.067	1.571	0.116
H10	LCMPs -> EcnP	0.414	0.056	7.321	0
H11	LCMPs -> SP	0.216	0.056	3.847	0
		Indirect hypothesis			
H6	I4.0T-> CEPs -> EnrP	-0.006	0.021	0.305	0.761
H7	I4.0T-> CEPs -> EcnP	-0.002	0.006	0.283	0.777
H8	I4.0T-> CEPs -> SP	-0.003	0.011	0.281	0.779
H12	I4.0T-> LCMPs -> EnrP	0.074	0.049	1.519	0.129
H13	I4.0T-> LCMPs -> EcnP	0.29	0.044	6.605	0
H14	I4.0T-> LCMPs -> SP	0.151	0.039	3.925	0

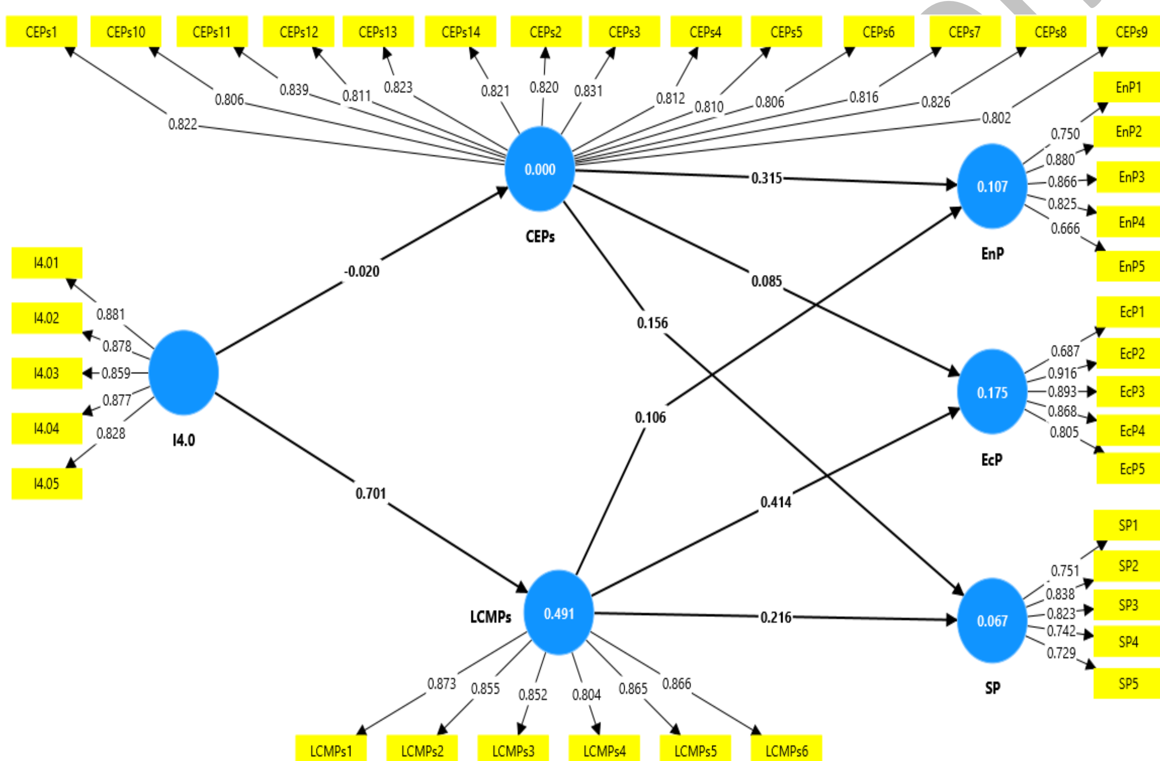

Figure 2: SEM path diagram

5. Discussion and Implications

This study investigates the complex interplay among Industry 4.0 (I4.0), Circular Economy Practices (CEPs), Low-Carbon Management Practices (LCMPs), and sustainability performance, offering nuanced insights into their direct and indirect relationships within the manufacturing sector.

Contrary to theoretical expectations and prior empirical evidence, the direct relationship between I4.0 and CEPs (H1) was not statistically significant. This finding diverges from earlier studies suggesting that I4.0 technologies enhance traceability, enable intelligent product design, and support data-driven circular strategies such as recycling, remanufacturing, and closed-loop production (Taddei et al., 2024). While such complementarities are well documented in advanced industrial contexts, the present result suggests that digitalization alone may be insufficient to trigger circular transformation in developing economies. One plausible explanation for this inconsistency lies in the uneven levels of digital maturity and organizational readiness across firms. Without coherent circular strategies, supportive institutional frameworks, or interoperable digital infrastructure, I4.0 investments may remain primarily efficiency-oriented rather than circularity-driven (Bag & Pretorius, 2022; Taddei et al., 2024). In this regard, I4.0 technologies may be deployed tactically rather than strategically, limiting their potential contribution to CEP adoption. This finding reinforces emerging arguments that circular outcomes require deliberate alignment between digital tools, managerial intent, and policy support rather than technological deployment in isolation.

In contrast, the relationship between I4.0 and LCMPs (H2) was strongly supported, corroborating prior empirical evidence (Sharma et al., 2025). This result underscores the instrumental role of industrial intelligence in enhancing energy efficiency, minimizing carbon emissions, and enabling real-time monitoring of carbon-intensive processes. Digital technologies facilitate predictive analytics, automated control systems, and data transparency, which are critical enablers of low-carbon operations. Consistent with Tian et al. (2024), the findings suggest that I4.0-driven innovation supports structural improvements in industrial systems and accelerates low-carbon transitions, particularly in developing economies where regulatory pressure is emerging but not yet fully institutionalized.

The study further confirms that CEPs exert a significant influence on environmental (H3), economic (H4), and social performance (H5). These results align with existing literature highlighting the multifaceted benefits of circular strategies, including waste and pollution reduction (Benachio et al., 2020), cost savings through improved resource efficiency (Batista et al., 2018), and positive social outcomes such as job creation and community development (Brydges, 2021; Morais & Silvestre, 2018). Although the economic impact was relatively modest compared to environmental and social outcomes, this pattern is consistent with the argument that the financial benefits of circularity often materialize gradually as circular systems mature (Agrawal et al., 2022). Thus, CEPs remain a foundational pillar of sustainability despite their uneven short-term economic returns. Interestingly, the mediating role of CEPs between I4.0 and sustainability outcomes (H6–H8) was not supported. This contradicts recent studies suggesting that circularity serves as a conduit through which digitalization enhances sustainability (Cuevas-Pichardo et al., 2025). The findings imply that, although I4.0 and CEPs independently contribute to performance, their interaction does not automatically generate synergistic effects. As argued by Souza et al. (2024), such synergy requires intentional integration at both strategic and operational levels, supported by cross-functional coordination and long-term investment in circular capabilities.

LCMPs were found to have a significant positive effect on economic (H10) and social performance (H11), but not on environmental performance (H9). This finding contrasts with studies emphasizing the direct environmental benefits of LCMPs through emission reductions and green logistics initiatives. However, the absence of a significant environmental effect may reflect implementation limitations, weak enforcement mechanisms, or inadequate carbon measurement systems within the studied context. As suggested by Jabbour et al. (2021) and Mardani and Saberi (2024), firms may adopt low-carbon initiatives primarily for economic efficiency or reputational considerations, while their environmental impact remains difficult to quantify due to fragmented monitoring and reporting practices.

Conversely, LCMPs significantly mediated the relationship between I4.0 and both economic (H13) and social performance (H14), supporting earlier findings that digitally enabled low-carbon integration strengthens supply chain resilience and corporate sustainability (Bhawna et al., 2024). These results are also consistent with Tian et al. (2024), who demonstrate that industrial intelligence fosters carbon-sensitive innovation and operational efficiency. However, the lack of mediation for environmental performance (H12) further reinforces the notion that environmental gains from LCMPs are constrained by execution gaps, limited digital sophistication, or weak carbon governance structures (Ghosh et al., 2025).

The findings present significant implications for Jordanian manufacturing firms within a developing economy that aims to modernize its industrial base, in accordance with the Economic Modernization Vision and the Jordan Climate and Development Report. The non-significant I4.0 and CEPs relationship highlights a persistent disconnect between digitalization and circularity. Although technologies such as IoT, big data, and AI hold transformative potential, their application to circular objectives remains underdeveloped in Jordan’s manufacturing sector (Kamble & Gunasekaran, 2023). Bridging this gap requires targeted training programs, subsidized digital tools, and innovation platforms that enable firms-particularly SMEs-to apply I4.0 technologies toward resource efficiency, product reuse, and waste minimization (Bag & Pretorius, 2022; Taddei et al., 2024).

The strong influence of I4.0 on LCMPs further emphasizes the enabling role of industrial intelligence in carbon reduction efforts. Digital solutions facilitate emissions monitoring, process automation, and predictive control, which are essential for transitioning toward low-carbon operations (Bhawna et al., 2024; Sharma et al., 2025). Policymakers should therefore prioritize green financing instruments, digital transformation grants, and regulatory frameworks that explicitly integrate I4.0 and LCMP objectives. Such initiatives are expected to enhance economic performance (EcP) through reduced energy and input costs (Ghosh et al., 2025), while simultaneously strengthening social performance (SP) by improving transparency and corporate accountability (Kannan et al., 2014).

Finally, the limited environmental impact of LCMPs and the weak mediating role of CEPs suggest the need for stronger governance mechanisms. Prior studies emphasize that effective low-carbon implementation requires standardized benchmarks, robust reporting systems, and sector-specific performance indicators (Peng et al., 2022). In Jordan, enforcing carbon disclosure regulations and developing tailored environmental metrics would enable firms to better link sustainability ambitions with measurable environmental outcomes. Moreover, the significant mediating role of LCMPs underscores their strategic relevance across supply chains. Supplier development programs, sustainability-oriented procurement standards, and environmental certification schemes could further embed low-carbon practices throughout industrial networks (Sharma et al., 2025). Overall, Jordan's transition toward sustainable industrial development requires a coherent policy framework that integrates I4.0 adoption, strengthens LCMP execution, supports CEP alignment, and ensures transparent assessment of EnP, EcP, and SP

5.1 Theoretical Implications

The findings of this study offer several important theoretical contributions to the literature on sustainable manufacturing, supply chain management, and digital transformation. First, the absence of a statistically significant relationship between Industry 4.0 (I4.0) and circular economy practices (CEPs) challenges the widely held assumption that digitalization inherently facilitates circularity. Rather than emerging as an automatic outcome of technological transformation, circularity appears to require intentional strategic alignment and organizational commitment, suggesting that CEPs should be conceptualized as a distinct organizational capability rather than a technological by-product. In contrast, I4.0 demonstrates a strong positive association with low-carbon management practices (LCMPs), and LCMPs, in turn, enhance both economic and social performance. This positions LCMPs as a core dynamic capability through which digital investments are translated into tangible sustainability outcomes. This pattern aligns with the view that IoT, AI, and real-time analytics enhance firms' adaptive operational capacity to monitor emissions, improve energy efficiency, and implement low-carbon strategies (Sharma et al., 2025).

The findings indicate asymmetric effects across the triple bottom line, enhancing theoretical comprehension of sustainability performance differentiation. LCMPs exhibit stronger effects on economic and social outcomes, whereas CEPs exert greater influence on environmental and social dimensions while demonstrating a comparatively modest impact on economic performance. These findings suggest that sustainability-oriented theories should explicitly distinguish between short-term, operations-focused gains associated with low-carbon strategies and the longer-term, system-level benefits generated through circular economy implementation. This distinction refines existing sustainability frameworks by acknowledging temporal and functional heterogeneity in performance outcomes (Ghadge et al., 2020).

The study enhances circular economy theorizing by presenting empirical evidence that CEPs positively affect sustainability performance across all three dimensions. This supports prior arguments that circular strategies enhance resource productivity, reduce waste, and generate broader sustainability value (Benachio et al., 2020). These results align with a holistic view of circularity in which firms improve sustainability by extending product lifecycles, reducing material dependency, and developing closed-loop supply chains (Agrawal et al., 2022). At the same time, the lack of a direct I4.0 and CEP relationship introduces an important theoretical nuance: technological adoption alone is insufficient to induce circular practices. Instead, effective circularity appears contingent upon complementary organizational capabilities, stakeholder coordination, and enabling institutional arrangements, thereby refining models that link digital technologies to sustainability-oriented practice change.

The mediating role of LCMPs between I4.0 and both economic and social performance contributes to theoretical understanding by establishing LCMPs as the key mechanism through which digitalization produces performance advantages. This finding encourages a reconceptualization of LCMPs not merely as operational or environmental routines but as strategic integrative mechanisms that connect digital infrastructure with sustainability outcomes. In doing so, the study strengthens the conceptual integration between I4.0 and environmental management theory, reinforcing the role of LCMPs as value-creating dynamic capabilities (Kannan et al., 2014).

The mediating role of LCMPs between I4.0 and both economic and social performance contributes to theoretical advancement by establishing LCMPs as the principal mechanism through which digitalization produces performance benefits (Homrich et al., 2018; Olsen & Tomlin, 2020). The findings illuminate how these constructs interact under non-ideal conditions, thereby enriching sustainability and operations theory with context-sensitive insights from under-researched settings and reinforcing the relevance of dynamic capability perspectives in emerging economies

5.2 Managerial Implications

The findings offer actionable and context-specific guidance for managers seeking to enhance sustainability through digital transformation, particularly within manufacturing firms operating in resource-constrained environments in Jordan.

First, the results clearly demonstrate that Industry 4.0 (I4.0) technologies do not automatically translate into Circular Economy Practices (CEPs). For Jordanian manufacturers many of which face capital constraints, fragmented supply chains, and limited digital maturity digitalization initiatives must therefore be accompanied by a clearly articulated circular roadmap. This roadmap should define measurable targets, KPIs, governance responsibilities, and dedicated budgets, while explicitly linking digital tools to circular outcomes including IoT-enabled tracking for product take-back systems, product lifecycle management platforms for reuse and recycled-content control, and digital twins to support remanufacturing and predictive maintenance. Without such strategic alignment, investments in I4.0 risk remaining efficiency-oriented rather than sustainability-driven.

Second, although I4.0 does not directly stimulate CEP adoption, managers can unlock its sustainability potential by embedding circular design principles into digital transformation programs from the outset. In the Jordanian manufacturing context this requires a shift from viewing digitalization as a purely operational upgrade toward treating it as a strategic enabler of resource productivity where firms often prioritize short-term cost efficiency. Managers should integrate requirements for product reuse, remanufacturing, modular design, and closed-loop systems into automation projects, enterprise data platforms, and advanced analytics initiatives. Firms that deliberately combine I4.0 capabilities with CEP objectives are more likely to improve material efficiency, reduce import dependency on raw materials, and build resilient competitive advantages in both domestic and export markets.

Third, given that CEPs positively affect environmental, economic, and social performance, circularity should be elevated to a core strategic priority within Jordanian manufacturing firms rather than treated as a peripheral environmental initiative. Managers should operationalize circular principles across procurement, production, and distribution by prioritizing sustainable sourcing, waste minimization, and reverse logistics. In a national context characterized by limited natural resources and rising energy costs, such practices can simultaneously enhance environmental performance, lower operating costs, and strengthen relationships with local communities, regulators, and international buyers increasingly demanding sustainable production standards.

Fourth, the findings underscore low-carbon management practices (LCMPs) as the primary mechanism through which I4.0 translates into sustainability performance. For manufacturing firms in Jordan, LCMPs should be treated as both operational and strategic instruments where energy intensity remains high and carbon pricing mechanisms are still evolving. Managers are encouraged to move beyond compliance-driven initiatives toward enterprise-level carbon accounting, real-time energy monitoring, and cross-functional emissions-reduction targets. Integrating LCMPs into core decision-making processes across operations, supply chain, finance, and IT functions can enhance cost control, improve risk management, and position firms more favorably for future environmental regulations and green financing opportunities.

Fifth, the relatively modest variance explained in social performance highlights the importance of organizational and human enablers alongside technological investments. In the Jordanian manufacturing sector managers should invest in targeted training programs, employee engagement initiatives, and transparent internal communication to foster acceptance of sustainability-oriented change where workforce skills gaps and resistance to change may constrain digital transformation. Strengthening organizational culture around sustainability can improve employee well-being, enhance retention, and reinforce corporate legitimacy in the eyes of external stakeholders.

Finally, given the central role of supply chains in Jordan's manufacturing ecosystem, managers should extend CEPs and LCMPs beyond firm boundaries through active supplier collaboration. This includes setting shared sustainability targets, embedding green procurement criteria into contracts, offering capability-building support to local suppliers, and adopting performance-linked incentives. Such collaborative approaches are particularly important in Jordan, where small and medium-sized suppliers often lack the resources to independently invest in digital or low-carbon technologies. By fostering supply chain-wide engagement, manufacturing firms can enhance resilience, reduce environmental risks, and accelerate progress toward national sustainability and industrial modernization objectives. Thus, these managerial implications are closely aligned with Jordan's Economic Modernization Vision, which emphasizes industrial competitiveness, digital transformation, energy efficiency, and sustainable growth as core pillars of national development

6. Conclusions

This study advances understanding of how digital transformation interfaces with sustainability by integrating Industry 4.0 (I4.0), Circular Economy Practices (CEPs), and Low-Carbon Management Practices (LCMPs) within a unified framework aimed at improving environmental (EnP), economic (EcP), and social performance (SP). Drawing on data from senior managers in production, procurement, operations, logistics, and supply chain roles within Jordanian manufacturing firms, the findings reveal a clear pattern. I4.0 exerts a strong positive effect on LCMPs, and LCMPs, in turn, mediate the relationship between digitalization and both EcP and SP. In contrast, the direct relationship between I4.0 and CEPs is not supported, challenging the assumption that digital adoption inherently leads to circularity. While CEPs positively influence EnP, EcP, and SP, LCMPs demonstrate stronger effects on EcP and SP and a weaker, non-significant association with EnP. Collectively, these results position LCMPs as the operational conduit linking digital capabilities to performance outcomes, while highlighting CEPs as system-level practices essential for comprehensive sustainability.

Despite these contributions, the study is subject to several limitations. First, the cross-sectional research design restricts the ability to capture lagged and cumulative effects, particularly those associated with CEPs, which often generate benefits over longer time horizons. Second, the focus on Jordanian manufacturing firms may limit the generalizability of the findings to other institutional and regulatory contexts. Third, reliance on perceptual survey data introduces the potential for common method bias, despite the use of established measurement and analytical techniques.

Future research could address these limitations by employing longitudinal designs to examine the dynamic and cumulative impacts of I4.0, CEPs, and LCMPs over time. Comparative studies across industries and countries would help assess the robustness of the proposed relationships and explore how regulatory regimes, cultural norms, and levels of digital maturity shape sustainability outcomes. The explanatory power of the model could be enhanced by incorporating additional antecedents, such as institutional pressures, green innovation capabilities, and organizational culture, particularly to better explain social performance. Moreover, qualitative or mixed-method approaches could provide deeper insights into managerial perceptions, capability gaps, and implementation barriers that hinder the effective alignment of digital transformation with circular and low-carbon strategies. Finally, future studies could examine moderating and mediating factors such as firm size, supply chain integration, and technological readiness to further refine understanding of how I4.0, LCMPs, and CEPs jointly drive sustainable transformation.

Competing interests: The authors declare that they have no competing interests.

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