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Industry 5.0 circular economy practices: Innovation management and its impact on sustainable development

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ABSTRACT

This study investigated the interaction between Industry 5.0, circular economy (CE) practices, and innovation management (IM) in promoting sustainable development (SD) within the industrial sector in Jordan. Data were collected through surveys of 50 companies and in-depth interviews with 15 participants and a mixed- methods approach were used. The results revealed a positive relationship between Industry 5.0 adoption, circular economy implementation and sustainable development outcomes, particularly in resource efficiency and environmental performance. While innovation management significantly influenced Industry 5.0 adoption and circular economy practices, it did not directly mediate the impact on sustainable development. The study concluded that innovation management frameworks need to be strengthened to overcome challenges and maximize sustainability benefits in the Jordanian industrial sector.

Contribution/Originality: The study addresses the role of Industry 5.0, CE and IM in promoting SD in the Jordanian industrial sector highlighting the importance of IM in adopting modern technologies and achieving sustainability despite challenges of costs and change resistance. It provides recommendations to support sustainable policies that contribute to achieving SD goals.

1. INTRODUCTION

1.1. Research Objectives and Hypotheses

Implementing Industry 5.0 with circular economy principles has become critically important, especially in terms of sustainable development over the last few years. Industry 5.0 integrates it with human factors or intelligent technologies while Industry 4.0 is based on advanced technologies. The idea behind the circular economy is to reduce the usage of resources as much as possible while promoting closed-loop systems. It is worth noting that industrial firms in Jordan still apply innovative measures that effectively promote environmental conservation and economic development. This research focuses on synthesizing Industry 5.0 technologies, circular economy, innovation management, and sustainable development of Jordan's industrial sector.

This research mainly examines Industry 5.0 technologies from a technology integration perspective by creating a systematic evaluation framework to integrate the circular economy and innovation management for the sustainable development of Jordan's industrial sector. In this regard, the area of Industry 5.0 technologies and the circular economy remains unanalyzed, mainly from analyzing the role of innovation management in mediating the relations between the elements to foster sustainable development within the Jordanian industrial sector. The following section outlines the research objectives highlighting the key goals that this study aims to achieve:

- To explore the integration of Industry 5.0 technologies with circular economy practices in major industrial companies in Jordan.
- To assess the role of innovation management as a mediating factor between Industry 5.0 technologies and circular economy practices.
- To assess the effectiveness of these combined strategies in enhancing sustainable development in Jordan's industrial market.

2. LITERATURE REVIEW

2.1. Theoretical Frameworks

2.1.1. Industry 5.0

Industry 5.0 combines advanced technology such as AI, IoT, and edge computing (not only intelligent things), which are human-centric and sustainable. It seeks to join between industrial systems that have high efficiency, adaptiveness, and collaboration and the creativity of humans and artificial intelligence (Soomro et al., 2024). In the 5th industrialization industry, the interaction between machines and people is beneficial not only from a productivity aspect but also in reducing resource use and environmental burden. It is consistent with sustainable objectives (Martini, Bellisario, & Coletti, 2024). This new era makes it possible to innovate faster, taking practices that will make errors less prone in sectors like manufacturing and supply chains. Industry 5.0 promotes the circular economy's goal of reducing waste and further consolidating resource reuse by facilitating collaboration between humans and intelligent systems (Fraga-Lamas, Lopes, & Fernández-Caramés, 2021). Similarly, Industries 5.0 integrates human-centred processes that effectively support social and environmental goals by ensuring industries satisfy the demand for ethical and sustainable practices (Atif, 2023).

However, the human-centric approach needs further critical evaluation to understand how industries can maintain such practices in a rapidly evolving technological landscape, particularly in terms of employee adaptation and societal impacts.

2.2. Circular Economy

The circular economy model seeks to democratize the traditional take, make, use and then dispose of it linear 'take, make, use and dispose' systems by aiming for sustainable systems focused on resource reuse, recycling, or waste reduction (Turner, Oyekan, Garn, Duggan, & Abdou, 2022). The emergence of the circular economy, supported by contemporary technology like blockchain, artificial intelligence, and the Internet of Things has increasingly become more encouraged through the industry 5.0 framework (Kannan, Amiri, Shaayesteh, Nasr, & Mina, 2024). Blockchain technology is the critical transition impact that brings transparency to the supply chains and helps companies monitor resource utilization and recycling activities more efficiently. The resulting responsibility supports a closed-loop system where waste is limited and resource savings are optimal (Kannan et al., 2024). Businesses have also adopted circular economy practices including green innovation which is an approach to investing in eco-friendly technologies to reduce environmental effects (Harasis, Helalat, Alhelalat, & Aqrabawi, 2024). Fraga-Lamas et al. (2021) emphasize that these advancements permit such industries to minimize their carbon footprint and shift to a more sustainable operation that responds to global sustainability goals.

2.3. Innovation Management

The fundamental goal of Industry 5.0 which emphasizes IM is to promote sustainable and human-centric technological developments to create efficient and environment-friendly industrial scenarios (Alheet, Hamdan, &

Areiqat, 2024). IM uses artificial intelligence, the Internet of Things, and blockchain technologies to optimize processes and SD (Santiago, Scavarda, Caiado, Santos, & Nascimento, 2024). For instance, blockchain facilitates CE practices by offering decentralized, safe resource recycling and waste management networks (Kannan et al., 2024). Furthermore, open and green innovation is encouraged through IM wherein an environment of open collaboration among industries, governments and academia is encouraged to ensure sustainable practices (Shi, Liu, & Mahmood, 2024). However, challenges including high implementation costs and a lack of skilled personnel are necessary for these tactics to be successful. As companies increasingly embrace the CE, IM is a vital instrument for attaining financial gains as well as social and environmental objectives (Kannan et al., 2024).

2.4. Sustainable Development

Industry 5.0 is closely intertwined with advanced technologies such as AI, IoT, and edge computing which contribute to resource efficiency and reduce development's environmental impact. Industry 5.0 aligns with broader sustainability goals by promoting human-centric industrial processes to avoid economic growth, leaving society and the environment behind (Martini et al., 2024). Corporate social responsibility (CSR) promotes business involvement in practices that result in net benefit to society and the environment (Santiago et al., 2024). CSR initiatives are often demonstrated through emission reduction, improvement of recycling processes, and application of CE principles that minimize waste and resource consumption (Jarrar, Barrena, Foncubierta, & Al-Hyari, 2024). These efforts must pave the way to more competitive industries that contribute to long-term sustainability goals while staying operational and resilient (Atif, 2023). For this reason, Industry 5.0 puts development on a path that encompasses the need for profitable development and social and environmental responsibility (Zuriegat, 2024).

2.5. Technologies of Industry 5.0

A fundamental technology of Industry 5.0 is AI, IoT, and edge computing which make industrial processes more efficient, sustainable, and human-centred. AI has another significant influence as it helps improve decision-making, reduces the use of time in executing recurrent assignments and is crucial in predicting maintenance in intelligent manufacturing systems. Such a change allows industries to emphasize invention and effectiveness and minimize human mistakes and time depletion (Martini et al., 2024). IoT enables real-time data gathering with interoperability among machines. This integration guarantees smooth interaction among industrial systems that remain critical for the CE providing insights into resource usage and waste generation (Fraga-Lamas et al., 2021). Moreover, edge computing enhances the speed of processing by ensuring that computation is made closer to where data is generated, hence consuming less power, something that Industry 5.0 supports concerning the goal of environmental conservation when it comes to the use of power (Fraga-Lamas et al., 2021).

Terms like green IoT, edge AI, and intelligent manufacturing are essential in making the sustainability goals of Industry 5.0 a reality. Green IoT is concerned with reducing energy consumption in IoT devices to support environmental conservation (Fraga-Lamas et al., 2021). Likewise, edge AI refines the critical strength of AI in handling data at a different scale since the intense computational load and impact on the environment to enable the central processing of data is not necessary (Shi et al., 2024).

Blockchain application also enhances CE by proving accountability and origin of resources, timely tracking of personnel recycling activities and reduced wastage. Blockchain technology promotes secure, decentralized data management, and enhances the effectiveness of CE practices by providing greater visibility in supply chains (Kannan et al., 2024).

2.6. Innovation Management, Industry 5.0 and Circular Economy Practices

Innovation management is crucial in bridging Industry 5.0 technologies and CE practices by fostering the integration of sustainable and human-centric innovations within industrial processes. It helps organizations use new technologies, like AI, IoT, and blockchain to optimize supply and demand, cut wastage, and so on. IM ensures that businesses focus on profit and contribute to environmental sustainability and societal well-being by aligning these technologies with CE principles. This integration ensures ultimate sustainability and reinvention of industries besides solving global ecological concerns (Kannan et al., 2024; Santiago et al., 2024).

However, integrating blockchain technology with CE principles particularly in manufacturing presents considerable challenges. Regulatory issues, high prices and relatively new technology make it difficult to employ blockchain for resource tracking, waste management and product enlightenment in some supply chains. These issues are like those that are now recognized. However, the problem of a shortage of qualified personnel for implementing and further managing blockchain systems is another challenge in using blockchain as a tool for promoting the principles of CE (Kannan et al., 2024). Therefore, if blockchain is to be properly used to assist sustainable behaviors, these obstacles must be removed. Strategies such as open and green innovation are critical to overcoming these challenges and driving the adoption of CE practices. Open innovation promotes the concept of cross-industry, cross-government and cross-academic partnership in sharing knowledge and resources to improve sustainable innovations. Green innovation involves investment in environmentally sustainable technologies and processes needed to shift toward a CE (Atif, 2023; Shi et al., 2024). These strategies are pivotal in integrating Industry 5.0 technologies with CE practices for sustainable industrial growth.

From the CE perspective, Industry 5.0 is an essential solution to global environmental problems as it encourages the recycling, reusing, and repairing processes. The circular economy replaces the conventional linear model which is considered a "take-make-dispose model" with a system in which several processes ensure reuse, thus minimizing waste (Turner et al., 2022). Industry 5.0 and CE practices align closely with sustainability goals, encouraging companies to innovate to reduce their environmental footprint while increasing operational resilience (Kannan et al., 2024).

Human-oriented approaches should be integrated into Industry 5.0 as effectively. From the human need aspects, Industry 5.0 encompasses human-centred approaches to industrial processes and, thus, the development of sustainable technologies for long-term human growth (Atif, 2023). This approach not only fortifies processes on operational levels but also develops industries' capacity to deliver global sustainability requirements for economic, environmental and social purposes (Fraga-Lamas et al., 2021).

2.7. Sustainable Development, Industry 5.0 and Circular Economy

Industry 5.0 affects sustainable manufacturing development by incorporating human factors and complicated technologies for productivity which are joined with sustainable development. Manufacturing in Industry 5.0 improves the utilization of diverse technologies including AI and IoT to cut expenses towards resource use and carbon footprints. This situation results in maintaining sustainable development as technologies developed for business needs consider human and social values in addition to concentrating on quantitative value. Starting from Industry 5.0, according to Martini et al. (2024) and Atif (2023), there is a shift from embracing profitability mainly to showing value-focused targets that also embrace the social and eco-environmental outcomes as well as dwelling on the alignment of industrial processes with sustainable development goals.

Here, the concept of CSR assumes a critical role in circular economy transitions occurring in supply chain management (SCM) because it motivates companies to engage in sustainable practices favorable to the environment and society. Thus, CSR makes ethics essential to business, ensuring the base of its operations is met and transparent using resources rationally and respecting society's interests. This integration helps companies to transition towards CE practices by rethinking product design, resource utilization, and waste management (Rumman, Alsmairat, Alshawabkeh, & Al-Abbadi, 2024). Corporate social responsibility (CSR) activities, including the decrease of emissions and improvement of recycling, support corporate objectives and the goals of the CE as a reflection of sustainable development for years to come (Santiago et al., 2024).

Several essential premises must be considered to ensure the integration of CE objectives and sustainable development. Life cycle assessment (LCA) and circular supply chain management help reduce wastage and resource utilization. CSR and CE ideas in the context of sustainable supply chain management show that industries can remain sustainable, profitable, and efficient (Santiago et al., 2024).

The literature emphasizes the pivotal role of Industry 5.0 technologies in transforming industrial practices and advancing sustainable development goals (SDGs). Industry 5.0 is characterized by the integration of human capabilities with advanced technologies, enabling more efficient, adaptable, and sustainable production systems. The resource-based view (RBV) theory provides a valuable framework for understanding how organizational resources, such as human capital, technology, and knowledge can be leveraged to achieve a competitive advantage in a rapidly evolving industrial landscape (Barney, 1991). In the context of Industry 5.0, RBV highlights the significance of unique technological capabilities such as artificial intelligence (AI), big data analytics (BDA), the Internet of Things (IoT), machine learning (ML), and blockchain (BC) in enhancing operational efficiency and fostering sustainability (Oladapo, Olawumi, & Omigbodun, 2024).

Industry 5.0 technologies can be grouped into the following three categories: extensions of existing technologies (e.g., industrial robots, blockchain, and IoT), revolutionary technologies (e.g., AI and humanoid robots), and adaptive technologies (e.g., cognitive robots and smart energy management systems). These technologies are closely tied to circular economy (CE) practices which focus on reducing waste and optimizing resource use through approaches like recycling, remanufacturing, and eco-design. Research shows that the integration of Industry 5.0 technologies with CE practices enhances sustainable supply chain performance, driving positive environmental, social, and economic outcomes (Le & Ikram, 2022).

Despite these advancements, a gap exists in the literature concerning the integration of Industry 5.0 technologies with CE principles to boost sustainable performance. Several existing research have focused on Industry 4.0, leaving an underexplored area regarding the synergistic impact of Industry 5.0 on CE practices and sustainable performance (Chen, 2019). This gap highlights the need for further studies to explore how Industry 5.0 technologies can support CE initiatives, offering insights into their potential to advance sustainability in the manufacturing sector.

2.8. Challenges and Future Directions

Integrating Industry 5.0 with circular economy practices faces several challenges, mainly technological barriers, lack of expertise, and regulatory hurdles. Some challenges are inherent to technologies. For instance, the relative infancy of some technologies such as the blockchain or AI in particular settings constrains their implementation. Moreover, there are challenges that industries undergo in attracting the human resource skilled to manage the new technologies efficiently. Moreover, circular economy transition regulations necessitated by sustainable practices are not well developed or are disjointed, thus posing difficulty in adoption among business entities (Atif, 2023; Kannan et al., 2024). These challenges must be surmounted to fully realize the technologies that underpin Industry 5.0 and the circular economy.

Future trends of sustainable digitization are emerging as more humanitarianized manufacturing systems. These systems pay attention to development in technology as well as the welfare of people in producing better and more robust environments. Green IoT and edge AI are anticipated to provide an extra layer of intelligence to enhance resource utilization efficiency and reduce the environmental impacts of manufacturing (Fraga-Lamas et al., 2021; Martini et al., 2024). Real-time decisions of such technologies enhance energy efficiency aligning with Industry 5.0 and the circular economy (Abu Rumman & Al-Abbadi, 2023).

The specific, actionable steps to integrate Industry 5.0 into circular economy principles are to invest in technologies, build expertise in technologies and advocate for supportive regulations. Finally, industries, governments, and academic institutions' cooperation in promoting open innovation can create a model where sustainable practice integration is encouraged. Businesses can better align with sustainability goals and fully leverage the potential of Industry 5.0 in supporting circular economy practices by addressing these challenges (Fraga-Lamas et al., 2021; Kannan et al., 2024).

3. METHODOLOGY

This study employs a mixed methods research design, integrating quantitative and qualitative approaches to explore the relationship between Industry 5.0 technologies, CE practices, IM, and their collective impact on SD in Jordan's industrial sector. The selection of Industry 5.0, CE, IM, and SD variables addresses critical gaps in the sector's ability to enhance competitiveness and capture greater market share, both domestically and internationally.

Jordan's industrial sector operates within a broader economic environment that has demonstrated resilience among regional challenges. According to the World Bank Group (2024) Jordan's real Gross Domestic Product (GDP) grew by 2.7% in 2023 driven by robust manufacturing growth and strong performance in key sectors such as agriculture and services. The manufacturing industry has the potential to lessen these difficulties by utilizing cutting-edge technologies and innovation to increase productivity and improve sustainability. The variables selected for this study are aligned with these pressing needs. Industry 5.0, which emphasizes human-centric technologies, drives operational efficiencies while CE practices aim to reduce waste and optimize resource use in line with Jordan's fiscal consolidation goals and sustainable growth targets. IM acts as the vital component that unifies these strategies and permits their strategic implementation throughout the industrial sector to accomplish SD. Additionally, this study aims to close the empirical gap in research by looking at how these variables intersect in the Jordanian setting and offering useful information to business executives and policymakers.

The focus on Jordan's industrial sector is further supported by recent economic data. According to the World Bank Group's (2024) report, unemployment has slightly decreased while it remains high at 21.4%, with limited labor force participation, particularly among women and youth. Regional trade disruptions also emphasize how important it is to increase local sector competitiveness to reduce dependence on vulnerable trade routes. This study aims to provide a comprehensive understanding of how Industry 5.0, CE practices, and IM can collectively address these challenges and foster SD by combining quantitative and qualitative methods.

The target population includes 100 medium-to-large industrial firms in Amman representing diverse manufacturing sub-sectors. These firms were selected due to their significant role in driving the Jordanian national economy and their readiness to adopt advanced technologies and sustainable practices. Purposive sampling was employed to select key decision-makers, innovation officers and sustainability experts with a quantitative sample size of 50 respondents and a qualitative sample of 15 interviews. While the qualitative phase expands and validates the results from the quantitative research, this technique guarantees a fair representation of strategic perspectives and operational insights.

The sample size of 15 respondents for the qualitative phase and 50 industrial companies for the quantitative phase was selected in accordance with accepted research practices in industrial studies. According to Sekaran (2003) a sample size of 30 to 50 respondents is typically sufficient to achieve meaningful results in industrial sector surveys, provided the sample reflects the diversity and variability of the population under study. The chosen sample size of 50 industrial companies for the quantitative phase and 15 respondents for the qualitative phase aligns with established research methodologies in industrial studies. Sekaran (2003) states that as long as the sample accurately represents the diversity and heterogeneity of the population being studied, a sample size of 30 to 50 respondents is usually adequate to produce significant results in surveys conducted in the industrial sector. Furthermore, Sekaran (2003) suggests that qualitative interviews can reach saturation at 15 to 20 participants beyond which no new information is typically uncovered. According to the World Bank Group's (2024) report, this sample size is adequate for exploring the relationship between Industry 5.0 technologies, CE practices, IM, and SD given the current transformation of Jordan's industrial sector.

This methodological approach ensures that the findings will be statistically valid and rich in contextual insights providing a comprehensive understanding of how these key factors contribute to SD in Jordan's industrial sector. Moreover, the selection of these variables addresses critical areas for growth and competitiveness, making the research particularly relevant given the expanding Jordanian economy and the sector's need to adapt to both local and global challenges.

3.1. Research Design

The mixed methods design provides a more holistic view of the phenomena. The quantitative part is based on surveying Industry 5.0, circular economy, innovation management connection and the impact of implementing circular economy practices. The qualitative aspect consists of face-to-face and telephonic semi-structured interviews focusing on how these elements are implemented and how the Jordanian industrial firms regard them. This research design complements the research objectives of investigating these elements and evaluating their practices incorporated in their various forms and usages from strategic and organizational viewpoints.

3.2. Sampling Strategy

The sampling technique used in this study is the purposive in both the quantitative and qualitative stages of data collection targeting top managerial elites of Jordanian industrial firms. Such people include management personnel, innovation officers and others. Almost everyone in the organization knows Industry 5.0 and the circular economy. Regarding the quantitative survey, the number of respondents is 50 which ensure that quantitative tests can be effectively conducted while staying within the study's scope. In the qualitative phase, 15 face-to-face semi-structured interviews will be conducted to obtain sufficient depth with the respondents. The data saturation theory determines participants for the qualitative interviews to increase the study's efficiency since interviews will not produce further information.

The involvement of human participants in this research has been conducted in full compliance with ethical and scientific standards. Al-Ahliyya Amman University where the authors of the study are affiliated and ensures adherence to ethical guidelines by issuing an official letter to the relevant authority in the study's target population. This process guarantees the integrity of the research, respects the rights and confidentiality of participants, and upholds the highest standards of academic and ethical responsibility. The study was approved by the Institutional Review Board at Al-Ahliyya Amman University, Jordan, on July, 2024 (Ref. No SR-F17-14-001-Eng, Rev.a).

3.3. Data Collection

3.3.1. Quantitative Data Collection

Fifty major industrial companies' employees in Amman, Jordan will be required to complete the survey. The survey will feature Likert scale questions that will be used to establish the level of Industry 5.0, circular economy and the contribution of innovation management towards sustainable development. This approach ensures that data critical to the analysis of relationships between key variables are obtained in a standardized manner across respondents.

3.3.2. Qualitative Data Collection

The qualitative supplement consists of interviews with 15 respondents from the aforementioned industrial enterprises. Such interviews will focus on the participants' informed insights regarding the perceived prospects/ liabilities of Industry 5.0 and the circular economy. The type of interview design preserves certain subjects of discussion while offering the respondents more leeway which is crucial for the individualized experiences of these people.

3.4. Data Analysis

3.4.1. Quantitative Analysis

Descriptive analysis of survey data will involve the application of t-tests in SPSS to compare Industry 5.0 adoption practices and circular economy practices as well as innovation management for sustainable development. The t-test is suitable for this paper because it identifies the means differences between two groups, for example, adopters and non-adopters of Industry 5.0 technologies. This paper assesses the validity of the posited hypotheses concerning the variables under study.

We will perform structural equation modeling in SPSS AMOS to establish the relationship of innovation management as a mediator variable between industry 5.0 and sustainability, circular economy and sustainability. The independent variables are Industry 5.0 and circular economy, the mediator variable is innovation management, and the dependent variable is sustainability. Figure 1 represents the Structural Equation Model (SEM) created in SPSS as follows:

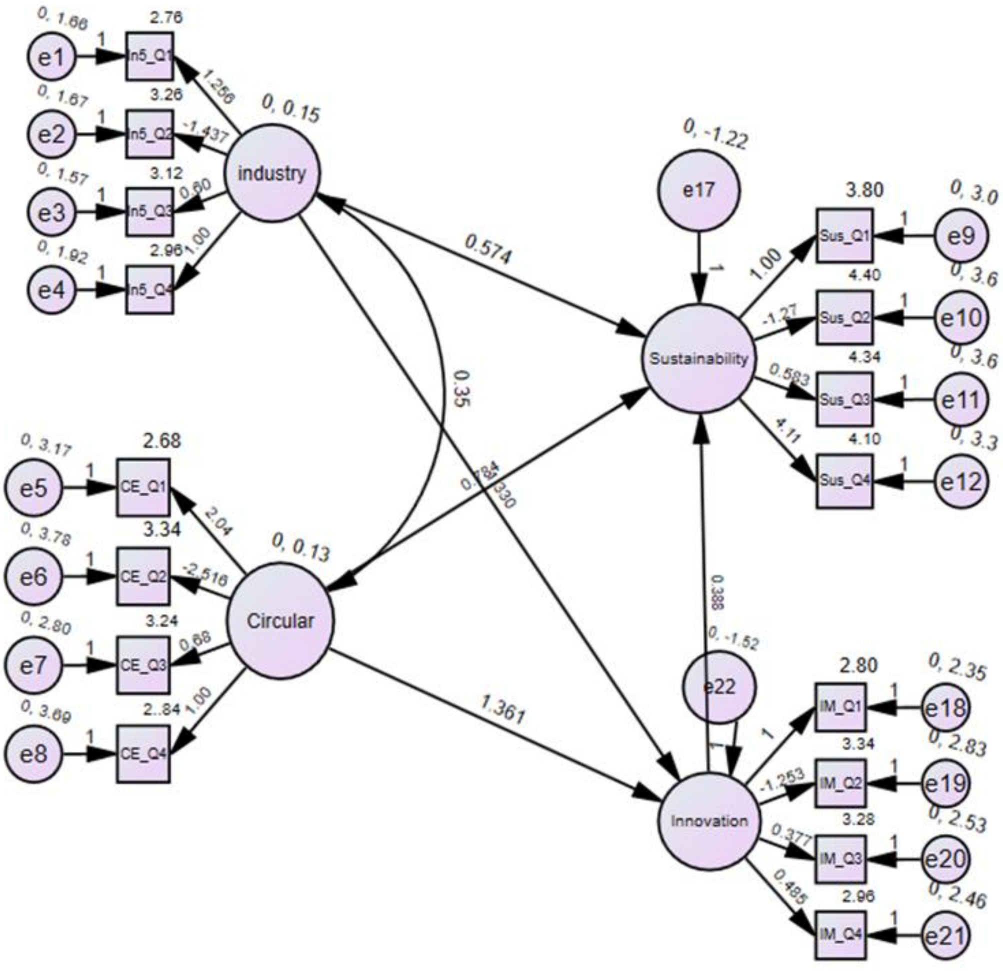

Figure 1. SEM for significance testing of innovation management as a mediator.

3.4.2. Qualitative Analysis

The interview information will be processed thematically. This method allows patterns and themes that occur frequently in the qualitative data to be selected. In thematic analysis, the interview transcripts are coded, specific themes are identified and the relationship of these themes with the research questions is established. This approach will afford a more affluent and enhanced understanding of how IM drives the integration of Industry 5.0 and circular economy elements and how these foster sustainable development in Jordan.

3.5. Justification for Research Design

The mixed methods design is justified as it offers both breadth and depth allowing for triangulation of findings. The quantitative phase provides a comprehensive view of the phenomena under study whereas the second phase is more profound and examines participants' experiences. The purposive sampling increases the reliability of the findings since respondents will possess relevant knowledge. The sample of respondents chosen for the survey is large enough for data analysis in the quantitative component and for reaching data saturation in the qualitative component. Regarding data collection, Likert scale surveys can be easily used to get standard measurements of the most essential variables. At the same time, semi-structured interviews enable free stemming regarding complex aspects like innovation and sustainability. Using both t-tests to analyze quantitative data and thematic analysis for qualitative data guarantees the exploration of statistical trends and data and the prevalence of critical themes in the interaction between Industry 5.0 and circular economy and sustainable development.

3.6. Limitations

This study has certain limitations, i.e., a small sample was used. Although 50 survey respondents and 15 interviews helped get information, more samples will enhance the credibility of the findings. Furthermore, purposive sampling has been criticized for being biased since the participants are chosen instrumentally and from a specific background concerning the topic under study. Lastly, a possible limitation of the survey and interview data is standard method variance since the data were self-reported, and some participants might provide favorable responses because of the desirability of the concepts being measured. It is essential to view these drawbacks when analyzing the results of this study.

3.7. Statistical Analysis

The results of the statistical analysis are shown in Table 1 which summarizes the hypotheses tested, the methods used to analyze them, the statistical results obtained, and the conclusions drawn regarding their support. Table 2 presents the results of a structural equation model (SEM) analysis focusing on the relationships between different variables.

Table 1. Testing hypotheses: relationships between industry 5.0, circular economy, innovation management, and sustainable development.

Hypothesis	Test conducted	Results	Conclusion
H1: Industry 5.0 is positively related to sustainable development.	Independent t-test between industry 5.0 score (>= 4.0 and < 4.0) and sustainable development score.	$t = 3.743$ and $p < 0.001$	Supported (Significant and positive relationship)
H2: Circular economy is positively related to sustainable development.	Independent t-test between circular economy score (>= 4.0 and < 4.0) and sustainable development score.	$t = 2.788$ and $p = 0.008$	Supported (Significant and positive relationship)
H3: Innovation management is positively related to sustainable development.	Independent t-test between innovation management score (>= 4.5 and < 4.5) and sustainable development score.	$t = 5.610$ and $p < 0.001$	Supported (Significant and positive relationship)
H4: Industry 5.0 is positively related to innovation management.	Independent t-test between industry 5.0 score (>= 4.5 and < 4.5) and innovation management score.	$t = 6.645$ and $p < 0.001$	Supported (Significant and positive relationship)
H5: Circular economy is positively related to innovation management.	Independent t-test between circular economy score (>= 4.5 and < 4.5) and innovation management score.	$t = 4.177$ and $p < 0.001$	Supported (Significant and positive relationship)
H6: Innovation management positively mediates the relationship between industry 5.0 and sustainable development.	Regression analysis with an interaction term.	Interaction term is not significant ($p<0.001$).	Supported
H7: Innovation management positively mediates the relationship between circular economy and sustainable development.	Regression analysis with interaction term.	Interaction is not significant ($p<0.001$).	Supported

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Table 2. Regression weights: (Group number 1 – default model) (SEM AMOS SPSS).

Dependent variables	Path direction	Independent variables	Estimate	SE.	CR.	P	Label
Innovation	<---	Industry	1.330	0.455	2.922	0.003	par_14
Innovation	<---	Circular	1.361	0.525	2.592	0.010	par_15
Sustainability	<---	Innovation	0.388	0.116	3.357	***	par_16
Sustainability	<---	Industry	0.574	0.223	2.579	0.010	par_17
Sustainability	<---	Circular	0.784	0.291	2.693	0.007	par_18
Industry5_Q4	<---	Industry	1.000				
Industry5_Q3	<---	Industry	0.600	0.223	2.687	0.007	par_1
Industry5_Q2	<---	Industry	-1.437	0.432	-3.324	***	par_2
Industry5_Q1	<---	Industry	1.256	0.384	3.273	0.001	par_3
CircularEco_Q4	<---	Circular	1.000				
CircularEco_Q3	<---	Circular	0.680	0.293	2.320	0.020	par_4
CircularEco_Q2	<---	Circular	-2.516	0.873	-2.883	0.004	par_5
CircularEco_Q1	<---	Circular	2.041	0.708	2.885	0.004	par_6
Sustain_Q1	<---	Sustainability	1.000				
Sustain_Q2	<---	Sustainability	-1.270	0.413	-3.071	0.002	par_7
Sustain_Q3	<---	Sustainability	0.583	0.215	2.709	0.007	par_8
Sustain_Q4	<---	Sustainability	0.411	0.169	2.429	0.015	par_9
InnoMgmt_Q1	<---	Innovation	1.000				
InnoMgmt_Q2	<---	Innovation	-1.253	0.331	-3.783	***	par_11
InnoMgmt_Q3	<---	Innovation	0.377	0.123	3.072	0.002	par_12
InnoMgmt_Q4	<---	Innovation	0.485	0.148	3.266	0.001	par_13

Note: *** means p-value is less than 0.001.

3.8. Analysis of Innovation as a Mediator between Industry 5.0 and Sustainability, Circular Economy and Sustainability

The following paths are statistically significant as indicated by their p-values:

- Innovation <--- industry (estimate = 1.330, p = .003): This suggests that industry has a significant and positive effect on innovation.
- Innovation <--- circular (estimate = 1.361, p = .010): Circular economy also positively influences innovation.
- Sustainability <--- innovation (estimate = 0.388, p < .001): Innovation positively impacts sustainability, indicating that higher innovation leads to improved sustainability.
- Sustainability <--- industry (estimate = 0.574, p = .010): Industry positively influences sustainability.
- Sustainability <--- circular (estimate = 0.784, p = .007): Circular economy has a significant positive effect on sustainability.

Significant relationships emerge between key variables (a finding that experts consider the most vital relationship between industry, circular, and innovation. In particular, the regression estimates for innovation of 1.33 and 1.361 demonstrate the strong influence of industry and circular. These regression coefficients allow us to know that for a unit increase in industry and circular, innovation increases by 1.33 and 1.361 units, respectively. P-values of .003 for industry and .010 for circular indicate that the effects are not just chance but statistically significant for both relationships. The significance of these p-values below the conventional 0.05 cut-off demonstrates that industry and circular is a strong and direct driver of innovation within the model. Besides these direct effects, the model shows that sustainability is increased by innovation, industry and circular. These relationships have regression weights of 0.388, 0.574, and 0.784, and the first suggests that sustainability is somewhat determined by innovation and more so by industry and circular. How they contribute to this weight are circular, which had the most substantial effect on sustainability, industry, and then innovation. The p values below .05 further emphasize the importance of these variables in determining sustainability outcomes. Overall, the model emphasizes the crucial and substantive roles that industry and circular play in stimulating both innovation and sustainability and further supports the use and importance of these variables in explaining the effects on variables examined.

The fitness of the model is described as follows:

3.9. Model Fit Summary

Table 3. CMIN.

Models	NPAR	CMIN	DF	P	CMIN/DF
Default model	52	80.139	100	0.928	0.801
Saturated model	152	0.000	0	1.000	0.000
Independence model	32	188.585	120	0.000	1.572

Table 4. Baseline comparison.

Models	NFI Delta1	RFI rho1	IFI Delta2	TLI rho2	CFI
Default model	0.575	0.490	1.224	1.347	1.000
Saturated model	1.000	1.000	1.000	1.000	1.000
Independence model	.000	0.000	0.000	0.000	0.000

Table 5. Parsimony-adjusted measures.

Models	PRATIO	PNFI	PCFI
Default model	0.833	0.479	0.833
Saturated model	0.000	0.000	0.000
Independence model	1.000	0.000	0.000

Table 6. NCP.

Models	NCP	LO 90	HI 90
Default model	0.000	0.000	2.826
Saturated model	0.000	0.000	0.000
Independence model	68.585	35.195	109.910

Table 7. FMIN.

Models	FMIN	F0	LO 90	HI 90
Default model	0.403	0.000	0.000	0.014
Saturated model	0.000	0.000	0.000	0.000
Independence model	0.948	0.345	0.177	0.552

Table 8. RMSEA.

Models	RMSEA	LO 90	HI 90	PCLOSE
Default model	0.000	0.000	0.012	1.000
Independence model	0.054	0.038	0.068	0.331

Table 9. AIC.

Models	AIC	BCC	BIC	CAIC
Default model	184.139	193.853	445.38	497.38
Saturated model	304.000	332.396	1067.63	1219.63
Independence model	252.585	258.563	413.35	445.35

Table 10. ECVI.

Models	ECVI	LO 90	HI 90	MECVI
Default model	0.925	1.025	1.039	0.974
Saturated model	1.528	1.528	1.528	1.670
Independence model	1.269	1.101	1.477	1.299

Table 11. HOELTER.

Models	HOELTER 0.05	HOELTER 0.01
Default model	309	338
Independence model	155	168

Table 12. Summary of model contributions.

Minimization	0.109
Miscellaneous	0.751
Bootstrap	0.000
Total	0.860

The results of the model fit analysis reveal an excellent fit across various indices. Specifically, the Chi-Square Minimum (CMIN) value of 80.139 (p = 0.928) as Table 3 presents and the Chi-Square Minimum Value divided by Degrees of Freedom (CMIN/DF) ratio of 0.801 suggest that the model fits well with no significant discrepancies between the observed and implied covariance structures. The Root Mean Square Error of Approximation (RMSEA) value of 0.000 (90% CI: 0.000–0.012) as shown in Table 8 further confirms the model's adequacy as it falls well below the commonly accepted threshold of 0.05 indicating a close fit to the data. Additionally, the p-value for the Chi-square test ($p > 0.05$) reinforces this conclusion showing no significant differences in covariance structures, thereby supporting the model's overall validity. Table 4 presents the Comparative Fit Index (CFI) value of 1.000 is exceptional, reflecting that the model outperforms the baseline null model and suggests a strong fit. Table 9 presents the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values also indicate a good balance between model fit and complexity with the default model showing lower values compared to both the independence and saturated models. Table 5 presents the parsimony-adjusted indices Parsimony Ratio (PRATIO) (0.833), Parsimony-Adjusted Normed Fit Index (PNFI) (0.479), and Parsimony-Adjusted Comparative Fit Index (PCFI) (0.833) highlight that the model achieves optimal fit without unnecessary complexity.

Table 6 presents the Non-centrality Parameter (NCP) is a statistic used in model fit assessments, especially in chi-square- based tests. It provides an indication of how much the observed data deviates from the hypothesized model. Table 7 presents a goodness-of-fit measure used to evaluate how well the model fits the data. A lower FMIN value indicates a better fit of the model to the data. Moreover, Table 10 presents the Expected Cross-Validation Index (ECVI) value of 0.925 which is closer to the ideal value of 1.0 supports the conclusion of a well-fitting model while Table 11 presents the Hoelter Critical N (HOELTER) indices (309 at p = 0.05 and 338 at p = 0.01) indicate that the sample size is adequate for model estimation. These indices indicate that the model provides an accurate and robust representation of the data without the need for further revisions or adjustments. The results suggest a high level of fidelity between the model and the observed data aligning well with the theoretical constructs under investigation. Table 12 summarizes the contributions of various components within the model. The minimization component contributes 0.109 while the miscellaneous component has a significantly higher contribution of 0.751. The bootstrap component does not contribute to the model with a value of 0.000. The total contribution of all components amounts to 0.860.

3.10. Qualitative Analysis Results

The results of the interviews after conducting a thematic analysis are as follows in Table 13 which summarizes the perspectives of respondents regarding Industry 5.0 adoption, challenges, circular economy practices, innovation management and their impact on sustainable development. It also highlights the mediating role of innovation management.

Table 13. Summary of respondents' perspectives on Industry 5.0 adoption, challenges, circular economy practices, innovation management, and sustainable development.

Theme	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5
Industry 5.0 adoption	Adopted smart manufacturing and AI, challenges with workforce training.	Partially adopted, using IoT and plans for AI integration.	Fully integrated industry 5.0, significant benefits seen in efficiency.	Adoption in progress. IoT is being prioritized.	No full adoption yet, considering innovative technology upgrades.
Challenges in industry 5.0	Resistance to change and cost issues.	Need for specialized skills and high costs.	Overcame initial cost barriers, still facing resistance.	Budget constraints and lack of skilled personnel.	Uncertain ROI leads to hesitation in adoption.
Circular economy practices	Fully implemented, focusing on waste reduction and recycling.	Focus on recycling and aims to introduce closed-loop systems.	Strong focus on reusing materials and reducing waste.	Some recycling but no full circular economy practices yet.	Recycling is the primary practice, and plans for more integration.
Innovation management	A key driver of new technology adoption.	Helps integrate Industry 5.0 and circular economy practices.	Plays a significant role in optimizing sustainability practices.	Innovation management is weak, but plans for improvement.	Low emphasis on innovation management.
Impact on sustainable development	Significant improvement in sustainability and positive impact on the company's CSR.	Some improvements in resource efficiency but not fully sustainable.	Improved environmental and economic sustainability.	Limited sustainability gains, but circular economy adoption is helping.	Still early to see significant impacts on sustainability.
Mediating role of innovation management	Innovation management enhanced industry 5.0 and sustainability outcomes.	Mediates the relationship by enabling better circular economy integration.	Critical for connecting Industry 5.0 technologies with sustainable practices.	Not yet effective in mediating Industry 5.0 and sustainability.	Low priority on innovation, so limited moderation effect seen.

4. RESULTS AND DISCUSSION

4.1. Summary of Quantitative Results

The results of the quantitative analysis are as follows:

The quantitative analysis showed a positive correlation between Industry 5.0, circular economy and sustainable development. By looking at the table of the independent t-test analyses, it was found that the results showed more positive differences and that companies with higher Industry 5.0 scores (>=4.0) had higher SDS scores ($t = 3.743$, $p < 0.001$). Just like the substantially high CE scores, companies (score of 4 and above) had significantly higher SD scores ($t = 2.788$ and $p = 0.008$). This result implies that the industry 5.0 technologies and skills and circular economy practices improve sustainable development within industrial practicing firms. Moreover, there was a positive correlation between the innovation management and sustainable development mean with organizations with a higher mean score in innovation management having improved sustainability ($t = 5.610$, $p < 0.001$).

Other results revealed even more significance showing that innovation management has a central contribution to the advancement of Industry 5.0 and the deployment of circular economy strategies. Businesses that selected higher numbers of Industry 5.0 components also had significantly higher mean scores for innovation management ($t = 6.645$, $p < 0.001$) supporting the proposition that innovation management skills can enable organizations to bring in complex technologies. Similarly, the companies that obtained higher results for circular economy practice also obtained better scores for innovation management ($t = 4.177$; $p < 0.001$). Nevertheless, moderation analysis demonstrated that innovation management did not significantly influence the relationship between Industry 5.0 or circular economy and sustainable development, as the coefficients of the interaction terms were not crucial in both cases. Therefore, although IM was protocoled as directly associated with these practices, the mediating effect was not verified.

4.2. Summary of Qualitative Analysis

The results of the qualitative analysis are as follows:

Industry 5.0 Adoption: Some organizations have embraced some of Industry 5.0 while others are in transit experiencing hitches like costs and workforce resistance to change.

Circular Economy Practices: It has been found that most stakeholders have some form of circular economy management, in general, recycling and waste minimization, but accurate closed-loop designs remain limited.

Innovation Management: This role plays a significant role in organizations incorporating Industry 5.0 and circular economy strategies but some organizations lack robust innovation management.

Sustainable Development: The sustainability returns achieved by the respondents who have embraced Industry 5.0 and the circular economy have positively impacted resource efficiency and environmental returns.

4.3. Discussion of Results in Light of Objectives and Literature

The synthesis of qualitative and quantitative data provides rich insights into the role of Industry 5.0, circular economy, and innovation management in achieving sustainable development in Jordan's industrial context. An analysis of the quantitative results indicated that Industry 5.0 was significantly associated with sustainable development and that the circular economy was significantly related to sustainable development. The quantitative results also tend to be supported by the qualitative data since most respondents pointed out the opportunities of Industry 5.0 technologies, including AI and IoT, to improve resource utilization and minimize resources and energy loss. The qualitative interviews identified a similar trend as the quantitative data but also showed practical barriers that were not identified, including resistance to change and costs. Although these challenges do not eliminate the benefits of implementing the new technologies, they show that implementing them at a new scale has difficulties.

Innovation management appeared to be a significant factor in quantitative and qualitative analyses. Qualitatively, all innovation management categories positively correlated with sustainable development, confirming that it is crucial to manage innovation to enhance the implementation of Industry 5.0 technologies and CE. The qualitative data worked in affirming this, whereby we noted that several respondents said that innovation management was a significant contributing factor towards the efficiency of implementation. However, certain firms responded that they had inefficient innovation management that compromised the improvement of Industry 5.0 and the circular economy. The fact that there are differences between high and low innovation management means that while the trend for sustainable results is present; its achievement depends on the management of innovation inside the company.

However, the moderation analysis in the quantitative data supported the hypothesis that innovation management offers a buffer for the correlation between Industry 5.0 and circular economy with sustainable development. There was some support for this relationship also in the qualitative data. Research respondents discussed innovation management as a direct effect rather than a mediator. Compared with the contingency theory, where innovation management was considered a vital contingency variable that amplifies or reduces the impact of Industry 5.0 or circular economy practices, their mediating effect was less evident. This consideration raises the idea that innovation management may be more influential as a first-order rather than a second-order factor that changes the influence of other variables on sustainable initiatives.

When compared, these findings were consistent with the research objectives which shed light on the state of applying Industry 5.0 and circular economy principles in Jordanian firms. The positive relationships found in the quantitative analysis fulfil the first two objectives: focusing on the interaction between Industry 5.0 and the circular economy concept and the possibility of stimulating sustainable development. However, the last and third research questions that addressed the mediating effect of innovation management received relatively less support from the current analysis. While innovation management was identified to have an essential influence on adopting such practices, the finding showed that its mediating effects were not significant. The results correspond to the prior literature that advocates for Industry 5.0 and circular economy for attaining sustainability objectives (Atif, 2023; Kannan et al., 2024). The presented qualitative findings and, specifically, the difficulties of adoption serve as enriching applications for literature. In contrast, literature presents plentiful theoretical advantages of overlapping adoption but does not manifest practical ones. Similarly, based on the literature, innovation management was found to play a pivotal role in influencing technology adoption. However, this study reveals the need to understand how it happens and the contexts surrounding its process within various organizations.

Despite the extensive literature on these main topics, gaps remain in addressing the synergy between Industry 5.0, CEPs, and sustainable performance. The present study bridges this gap by emphasizing how Industry 5.0 capabilities, when combined with circular practices, enable organizations to achieve long-term Sustainable Development Goals (SDGs). The study highlights the theoretical relevance of the resource-based view (RBV), which posits that unique and inimitable capabilities such as those provided by industry 5.0 technologies, can secure a competitive advantage (Barney, 2001; Epelbaum & Martinez, 2014). Industry 5.0 technologies underscore integrating human expertise with advanced technologies to achieve enhanced efficiency and sustainability. Data from the Jordanian manufacturing sector confirms this framework, showcasing industry 5.0 technologies' potential to improve operational efficiency and establish competitive advantages while achieving SDGs. This study provides a foundation for advancing the understanding of Industry 5.0 technologies' role in sustainable industrial transformation by addressing these theoretical and practical gaps.

Therefore, it is argued that adopting Industry 5.0 and circular economy strategies substantially supports SD and that the innovation management approach has a predominant role, although not moderation. Nonetheless, the challenges that have been highlighted show that to remove those barriers that inhibit the full exploitation of these sustainable developments by Jordanian industrial companies, more focused efforts need to be employed.

5. CONCLUSION AND RECOMMENDATIONS

This research focuses on adopting Industry 5.0 technologies, CE, and IM in Jordan's industrial environment to evaluate the levels of sustainable development. The quantitative findings supported the positive correlation between Industry 5.0 and circular economy with sustainable development. The literature supported both Industry 5.0 and circular economy as possible ways to support sustainability. To a large extent, the firms adopting these practices were found to have considerably improved sustainable performance measures, especially regarding environmental sensitivity and resource use. Another critical enabler was innovation management, directly linked to improving sustainable practices due to funding-enhanced technologies. Although hypothesizing that innovation management would mediate Industry 5.0/ circular economy and sustainable development, the regression analysis findings support this statement. The results mean that though innovation management is an essential direct exercise, it affects the strength of the relationship between those variables.

The data collected supplemented these findings and portrayed the implementation of Industry 5.0 technologies and circular economy solutions. Respondents highlighted factors including cost, resistance from the workforce, and lack of skilled personnel which limited the perfect implementation of the above strategies. However, it is essential to remark that for those companies that implemented Industry 5.0 and principles, positive impacts on performance with an emphasis on sustainability were highlighted. Moreover, innovation management was mentioned often as a solution to how these challenges were met, as it offered the framework required to manage change and nurture sustainable innovations.

Organizations must integrate innovation management as a strategic driver. This integration not only addresses existing barriers but also fosters a culture of continuous improvement and adaptability. Jordanian industries can position themselves as leaders in sustainability, leveraging advanced technologies and resource-efficient practices to achieve long-term environmental and economic resilience.

5.1. Future Research Recommendations

For Jordanian industries to meet the full potential of benefits related to Industry 5.0 and circular economy practices, industries must overcome the following challenges: first, capability development is required to address the nature of organizations, precisely the requirements of the workforce in terms of their readiness to achieve higher technologies. The idea is to develop specific training activities to create awareness of Industry 5.0 technology and the circular economy, eliminating the negative attitude towards change and enhancing the implementation's impact. Moreover, these favorable policies may incite further practice of these activities through financial subsidies or tax exemptions for companies developing sustainable activities.

The results also imply that firms must enhance the innovation management process further to be effective. It can be noted that despite innovation management not being a mediator between polytechnic and traditional universities concerning quantitative analysis, the qualitative study showed that a robust innovation management mechanism is imperative for the successful implementation of innovations, including new technology. Organizations must work on nurturing innovation-capable cultures and approaches supporting cross-organizational communication and learning functionality.

Moreover, subsequent studies should examine the sustainability effects of these practices in broader, longer-reaching terms using larger samples and involving other industries. The research will assist in corroboration of the results of this study and provide additional information on the precise deployment of Industry 5.0 and the principles of Circular Economy in the various industry sectors. It is also essential to examine the extent to which policy can stimulate stakeholder engagement in sustainable practices – this may act as the critical enabler to the sustainable development goals outlined for Jordan.

To promote the implementation of Industry 5.0 and circular economy principles in Jordan, government policies should focus on providing financial and training incentives to companies to accelerate the adoption of these sustainable technologies. It is also important to enhance public-private sector collaboration and provide the necessary support to educational institutions to train the workforce on these innovations. In addition, sustainability criteria should be included in industrial policies and incentives should be provided to companies that contribute to achieving environmental and social goals. These steps will contribute to achieving effective sustainable development and promoting innovation across industrial sectors in Jordan.

5.2. Theoretical and Practical Implications

The present work extends the current knowledge of Industry 5.0, circular economy, and innovation management underlining their applicability to sustainable development at the industrial level. Conceptually, this research contributes to knowledge regarding the role of Industry 5.0 technologies like AI, IoT, and circular economy practices in delivering environmental and economic sustainability. It also emphasizes innovation management as an enabler of these practices and reaffirms the value of the subject concerning performing technological and organizational change. However, this study also questions the assumption of the continuum proposition in which innovation management is postulated to act as a mediator between the two extremes. These insights pave the way for future research to extend the understanding of the complexity of the innovation processes surrounding sustainability initiatives.

From a practical perspective, the study provides somewhat tangible recommendations for industry managers and policymakers. For Industry 5.0 and circular economy adoption in organizations, innovation management forms the core practice for successful uptake due to operational challenges like cost and worker resistance. The study also suggests that there is merit in developing capacities to support utilizing these innovations because training avails most of the technologies. It is, therefore, essential to embrace the establishment of favorable structures guiding and facilitating exceptional environmental and industrial management, thus achieving overall environmental and economic benefits for industries in Jordan and other countries.

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Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
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Appendix 1. Qualitative questionnaire.

Appendix 1 presents qualitative questionnaire.

The following questionnaire uses a Likert scale (1 = Strongly Disagree, 5 = Strongly Agree) to measure the relationships between Industry 5.0, Circular Economy, Innovation Management, and Sustainable Development as outlined in the hypotheses.

Section 1: Demographics

1. Company Name: ___________________________
2. Position in the company: ___________________________
3. Number of employees in the company: ___________________________
4. How long has the company been operating? (Years): ___________________________

Section 2: Industry 5.0

1. Our company has adopted intelligent technologies (e.g., AI, IoT) to enhance industrial processes.
2. Industry 5.0 technologies help us integrate human-centric solutions into our operations.
3. Using Industry 5.0 technologies has improved our efficiency and reduced operational waste.
4. Our employees are trained to work with Industry 5.0 technologies effectively.

Section 3: Circular Economy

5. Our company promotes recycling and reusing resources throughout the production process.
6. Adopting circular economy practices has reduced our reliance on raw materials.
7. Our company has implemented closed-loop systems to minimize waste generation.
8. Circular economy practices have positively impacted our environmental sustainability.

Section 4: Innovation Management

9. Our company actively engages in innovation management strategies to improve processes.
10. Innovation management has enhanced the integration of new technologies like Industry 5.0.
11. Innovation management has facilitated the adoption of circular economy practices.
12. Our company has developed new products/services due to innovation management.

Section 5: Sustainable Development

13. Industry 5.0 technologies have positively contributed to our company's sustainable development.
14. Circular economy practices have supported our company's long-term sustainability goals.
15. Innovation management has been critical in our sustainable development strategy.
16. Our company's practices have led to positive environmental, economic, and social outcomes.

Appendix 2. Quantitative interview questionnaire.

Appendix 2 presents quantitative interview questionnaire.

Industry 5.0:

- How has your company adopted Industry 5.0 technologies?
- What challenges have you encountered in integrating these technologies into your operations?

Circular Economy:

- Can you describe the circular economy practices implemented in your company?
- How have these practices impacted your company's sustainability efforts?

Innovation Management:

- How does innovation management support the adoption of Industry 5.0 and circular economy practices in your company?
- Can you share an example of how innovation management has driven sustainability initiatives?

Sustainable Development:

- In what ways have Industry 5.0 and circular economy practices contributed to your company's sustainable development goals?
- What improvements would you suggest to enhance their impact on sustainability?

Mediating Role of Innovation Management:

- How do you see innovation management influencing the relationship between Industry 5.0, circular economy, and sustainable development?
- Can you describe any specific initiatives where innovation management played a key role?