Circular Economy Integration in the Gold Jewelry Supply Chain through Sustainable Industry 4.0 Practices

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The gold jewelry production sector in developing countries is faced with increasing challenges to becoming sustainable and competitive. While the adoption of Industry 4.0 technologies and principles based in Circular Economy (CE) can improve efficiencies and traceability, they are currently not widely adopted. This research identifies and ranks twenty significant barriers to applying Sustainable Industry 4.0 (S-OSCM4.0) through a Fuzzy Delphi Fuzzy DEMATEL methodology. Notable affecting drivers include high costs of technology, lack of management commitment, and limited digital readiness. The outcomes of the research create a cause–effect model that will support managers and policymakers as they develop specific actions for the sustainable digital transformation of the gold jewelry supply chain.

Keywords: Fuzzy Delphi, Fuzzy Dematel, Sustainable Supply Chain, Gold Ornament Manufacturing, Circular Economy, Industry 4.0, Fuzzy Dematel.

1. Introduction

Global value chains are exposed to the pressure on many fronts reducing resources, uncertain markets and the rising sustainability demands. To address these issues, Industry 4.0 (I4.0) technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), cyber-physical systems, and blockchain, are changing the way we are making products, logistics, and utilizing resources (Hettiarachchi et al., 2022; Awan et al., 2022). Together with the principles of Circular Economy (CE), these digital tools are an effective means to leave wasteful, linear systems and adopt closed-loop value chains, which utilize resources better, reduce wastes, and respect ethical norms (da Silva et al., 2022; Mantravadi et al., 2025; Bartekova et al., 2022; Liu et al., 2022; Wynn et al., 2022). Gold jewelry business in the developing markets such as India is a good case to study how digital and circular entities can collaborate. It is a labor- and material-intensive industry that is heavily dependent on high-value raw materials, labor-intensive artisan craftsmanship, as well as on a complicated system of supply chains with numerous intermediaries (Raut et al., 2023; Tenuta et al., 2024; Hindle, 2024; Antinarelli Freitas, 2024; Fioravanti, 2021; Thammaraksa et al., 2017). The industry is facing ongoing sustainability issues, including inefficient energy consumption, lack of traceability of materials, and ethical sourcing (Lin, 2024; Smith et al., 2024; Reynolds, 2024; Chatzipanagi et al., 2022). The deep cultural meaning and economic importance of the industry do not prevent it. The additional features of Sustainable Industry 4.0 (S-I4.0), including blockchain-based traceability, AI-optimised design, and the production of digital twins can aid in solving these problems, making work more transparent, accountable, and efficient across the lifecycle of a product. Such technologies can facilitate sourcing materials in a more responsible way, help make better decisions using real-time data, and align the sector with such global sustainability purpose as the United Nations Sustainable Development Goals (SDGs) that require responsible consumption and sustainable innovation (Jiang et al., 2023; Nair and Hussain, 2025). By so doing, the integration of I4.0 and CE provides a viable solution to the future of digitalizing the gold jewelry supply chain into a circular system. Industry 4.0 is also one of the primary facilitators of circular transitions that assist industries to move towards more regenerative systems rather than linear production. The I4.0 technologies enable real-time data capture, predictive data, and feedback loops which will be instrumental in controlling the material flows more efficiently and the time in which products will remain in usability (Hettiarachchi, Seuring and Brandenburg, 2022; Godinho et al., 2022; Albaladejo et al., 2023). Smart manufacturing enhances flexibility, traceability, and efficiency-inates, which are essential to circular activities (Nascimento et al., 2019; Nascimento et al., 2019). In particular, blockchain can be used to improve ethical sourcing through checking the origin of materials, and IoT and AI can be used to enhance recycling, remanufacturing, and waste recovery (Schmidt and Muller, 2024; Abid et al., 2024). Such technologies may support the use of digital product passports and methods to trace recycled gold, smarter production planning all of which increase the level of transparency and responsible resource utilization in the gold jewelry supply chain (Albaladejo et al., 2023; Khanna, Kuik & Ban, 2025). But in third world economies, the implementation of CE and I4.0 is not an easy task. They are fragmented institutions, low digital readiness, poor infrastructure, inadequate financial and policy backing (Rafifing et al., 2024; Srikanth et al., 2025). There are numerous small and medium enterprises (SMEs) that are unable to access advanced digital tools, and the skills required to utilize them, which provides an obstacle to sustainable change. To make the integration of CE and I4.0 successful, they need to align the digital innovation to the sustainability objective and implement it with the help of a powerful leadership, qualification, and empowering policies (Godinho Godinho et al., 2022; Khanna et al., 2025).

1.1 Research Gaps and Problem Definition

Although the connection between Industry 4.0 and sustainability is widely examined in the mainstream manufacturing (Islam, Hossain and Ornob, 2024; Hettiarachchi, Seuring and Brandenburg, 2022), the traditional, craft-based manufacturing industry such as gold jewelry manufacturing lacks research. Sustainable Industry 4.0 as a combination of CE principles with digital transformation is a well-established theoretical concept with a less-developed practical side of implementation, especially in developing countries, where digital penetration is not even, technological capabilities are low, and institutional support is low (The Circular Economy and Industry 4.0: Synergies and Challenges, 2022; Industry 4.0 and Circular Economy in Emerging Markets: Evidence of SMEs in India, 2023). Past research (Khanna, Kuik and Ban, 2025; Trevisan et al., 2021) identifies the role of digitalization in fostering circularity, yet the value chain in the gold jewelry sector presents distinctive problems: the informal nature of supply chains, reliance on craftsmanship, and its fragmented traceability and similar issues make it challenging to implement on a large scale (Circular Systems of Economy: Values Creating Value - Jewellery Business, 2021). Consequently, we do not have an all-encompassing idea of what contributes to or detracts the integration of CE and I4.0 in this industry. Despite the recent literature highlighting the significance of digital traceability, eco-design, and supply chain transparency (Exploring How Digital Technologies Enable a Circular Economy of Products, 2023), the key success factors and the relationship between various barriers to one another is poorly understood (Technology Integration to Promote Circular Economy Transformation of the Garment Industry, 2023). This research paper seeks to address such gaps by answering the following research questions

1. What can be done to ensure integration of the gold jewellery value chain into the Chain of Circular Economy by means of digital transformation?
2. What management, institutional and technological conditions affect a successful implementation of Sustainable Industry 4.0 practices?

1.2 Barriers Identification

The flow methodology based on PRISMA ensured the quality of the methods and clarity in the search of the relevant literature to use in this research. As shown in (Table 1), In initial search in Google Scholar, Scopus, MDPI, Springer Open, and ScienceDirect was done using the keywords Circular Economy, Industry 4.0, Sustainable Supply Chain, Gold Jewelry, Fuzzy Delphi, and Fuzzy DEMATEL to find 200 articles. After the removal of duplications and screening of the title and abstract, 162 articles were left to screen the first round, with 70 articles being filtered out due to the lack of relevance to the context of the CE-I4.0 integration and manufacturing sustainability. 92 full-text papers were then filtered based on methodological and contextual fitness, and 40 articles were filtered based on the lack of empirical or analytical fit to the context of the Fuzzy Delphi-Fuzzy DEMATEL framework. The qualitative synthesis was done using the last 52 studies to develop the foundation on which 20 potential barriers to the implementation of Circular Economy and Sustainable Industry 4.0 in the gold jewelry supply chain were determined. Experts' consultation confirmed these barriers to have eight causal and twelve effect determinants. The PRISMA methodology was systematized and made it comprehensive, minimized selection bias, and boosted the validity of the barrier identification and validation process, thereby increasing the strength of the mixed-method study framework. And the collected barriers of circular economy in the gold ornament manufacturing mentioned in the Table 2.

Table 1 *Process for the Selection of Articles*

Stage	Process	Records	Notes
Identification	Articles collected using keywords from Google Scholar, Scopus, MDPI, Springer Open, Science Direct	200	Based on CE, Industry 4.0, sustainability, jewelry supply chain
Screening	Removed duplicates and non-relevant abstracts	162	Excluded 70 irrelevant studies
Eligibility	Full-text review based on methodological fit	92	Excluded 40 due to poor CE–I4.0 linkage
Inclusion	Final studies used for developing and validating barriers	52	Fuzzy Delphi and Fuzzy DEMATEL applied

Table 2 *Barriers of Circular economy in the Gold Ornament Manufacturing*

CB1	Lack of sustainability awareness
CB2	Weak circular-economy adoption
CB3	High cost of sustainable technologies
CB4	Absence of lifecycle assessment tools
CB5	Poor waste-recovery infrastructure
CB6	Limited renewable resource use
CB7	Low consumer demand for ethical jewelry
CB8	Inadequate digital infrastructure
CB9	Cybersecurity and data-privacy risks

CB10	Fragmented data flow and weak transparency
CB11	Conservative organizational culture
CB12	Low R&D and innovation investment
CB13	Lack of change-management capability
CB14	Insufficient leadership commitment
CB15	Skill shortages in digital and green practices
CB16	Resistance from traditional craftsmen
CB17	Low supplier transparency and alignment
CB18	Weak inter-firm collaboration networks
CB19	Financial constraints for SMEs
CB20	Policy and institutional gaps

2. Methodology

2.1 Fuzzy Delphi Method for Barrier Validation

We used the Fuzzy Delphi Method (FDM) to screen and confirm the barriers that we already identified based on the consensus of the experts, and this method assumes that the expert is correct in assessing the significance of various factors (Kuo and Chen, 2008). We requested professionals to place the ratings of the importance of each of the barriers in simple language terms such as very low, low, medium, high, and very high. Because individuals tend to think in such qualitative terms and give their views in these terms as opposed to numerical values, we transformed their responses into triangular fuzzy numbers (TFNs). In this way, we managed to pool the ambiguity and subjectivity of the human judgment. We also made a number of evaluation sessions until the experts have reached a stable point in their views. We determine the threshold value (a) to identify the barriers to be retained in the next step of the analysis based on the Fuzzy DEMATEL, which meant that a barrier was retained in the next step if it had a defuzzified mean score above this threshold (Kumar et al., 2023). This validation process was important as it allowed us to disregard the factors that either were not significant enough or were redundant and allow us to have a more transparent, precise, and easier to interpret model (Hettiarachchi et al., 2022). The combination of professional judgment and fuzzy logic provided the FDM with a solid method of sifting the barriers and establishing a strong base on which to explore the causal relationship among them in the next analysis.

2.2 Fuzzy Dematel Analysis

We applied the Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) to determine the relationship between the validated barriers in their impact on one another. We did so because it is especially effective at showing the interrelationships and feedback loops, which are present in complex systems such as the gold jewelry supply chain. In comparison to less complex approaches, DEMATEL not only measures the strength of the influence of one factor on another but also demonstrates their direction, thus allowing us to understand which barriers influence others and which are their results (Godinho et al., 2022). During this step, we requested experts to rate the extent to which each barrier affects the rest of the barriers. They made fuzzy linguistic scales used such terms as no influence, low influence, medium influence and so on which we transformed to fuzzy numbers. This translation was significant since it enabled us to deal with the vagueness that exists in the judgment of people in nature. We have placed these assessments in a direct-relation matrix and have normalized this to enable us make a fair comparison of all the variables. There, we computed the total-relation matrix, which does not only consider the direct-effects between barriers but also the indirect-effects course that take place as the effects propagate through the system (Godinho et al., 2022). In order to simplify the work with the results, we transformed the fuzzy values into clear and precise numbers with the help of a method known as the centroid method (Daraba et al., 2024). This furnished us with two significant measures to each barrier: Prominence (D + R), the information about the general centrality or significance of a barrier in the system; Relation (D - R), whether to identify a barrier as more of a cause or an effect. When the value is positive, it implies that the barrier is more likely to be a cause of other problems and when it is negative, it is more likely to be an outcome of other problems. The next step was to plot these findings in a cause-effect diagram, that is, visually represent what all the barriers are related to each other and how they are hierarchical. This diagram is very handy as it aids us to look at it and see immediately which are the root causes that need to be addressed by all means and which ones are symptoms that would improve as soon as we tackle the underlying drivers. In the end, this discussion provides us with a precise roadmap on the areas that we should concentrate our efforts on in case we intend to apply Circular Economy and Sustainable Industry 4.0 principles in the gold jewelry industry.

Table 3 *Triangular Fuzzy Numbers*

Linguistic terms	Influence Score	Triangular fuzzy number		
No influence	0	(0.000	0.000	0.25)
Very low influence	1	(0.000	0.25	0.500)
Low influence	2	(0.250	0.5	0.750)
High influence	3	(0.500	0.75	1.000)
Very high influence	4	(0.750	1	1.000)

Step 1 Construct the Initial Direct-Relation Matrix
Experts assess the influence of factor *i* on factor *j* using linguistic terms (No Influence, Very Low influence, Low influence, High influence, very high influence). Each linguistic term is represented as a triangular fuzzy number (TFN) as shown in **(Table 3)**

$$\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \quad (1)$$

Where l_{ij} : $lower\ bound, m_{ij}: most\ likely\ (mean) value, u_{ij}\ upper\ bound$
The initial direct relation matrix is

$$\tilde{X} = [\tilde{x}_{ij}]_{n \times n} \quad (2)$$

Step 2 Normalize the Fuzzy Direct-Relation Matrix
Compute the normalization coefficient:

$$S = \max_i \sum_{j=1}^{n} u_{ij} \quad (3)$$

Then normalize each element:

$$\tilde{Z} = \frac{\tilde{X}}{S} \quad (4)$$

So, each element becomes:

$$\tilde{Z}_{ij} = \left(\frac{l_{ij}}{S}, \frac{m_{ij}}{S}, \frac{u_{ij}}{S}\right) \quad (5)$$

Step 3: Compute the Total Relation Matrix
The fuzzy total relation matrix is:

$$\tilde{T} = \tilde{Z}(I - \tilde{Z})^{-1} \quad (6)$$

I = Identity matrix
$(I - \tilde{Z})^{-1}$ = Fuzzy matrix inverse

Step 4 Defuzzification
Convert each fuzzy number $\tilde{t}_{ij} = (l_{ij}, m_{ij}, u_{ij})$to a crisp value using the centroid method

$$t_{ij} = \frac{l_{ij} + m_{ij} + u_{ij}}{3} \quad (7)$$

Thus, we obtain the **crisp total relation matrix** $T = [t_{ij}]$.
Step 5: Derive the Cause–Effect Relationships (Table 3)

$$D_i = \sum_{j=1}^{n} t_{ij} \text{ (sum of row i — the influence given by factor i)}$$
$$R_i = \sum_{j=1}^{n} t_{ij} \text{ (sum of column i — the influence received by factor i)}$$

Then:

- $D_i + R_i$→ *Prominence* (overall importance of factor *i*)
- $D_i - R_i$→ *Relation* (positive = cause, Négative = effect

Step 6: Cause–Effect Diagram Fig 2

- X-axis $D_i + R_i$(prominence)
- Y-axis $D_i - R_i$(relation)

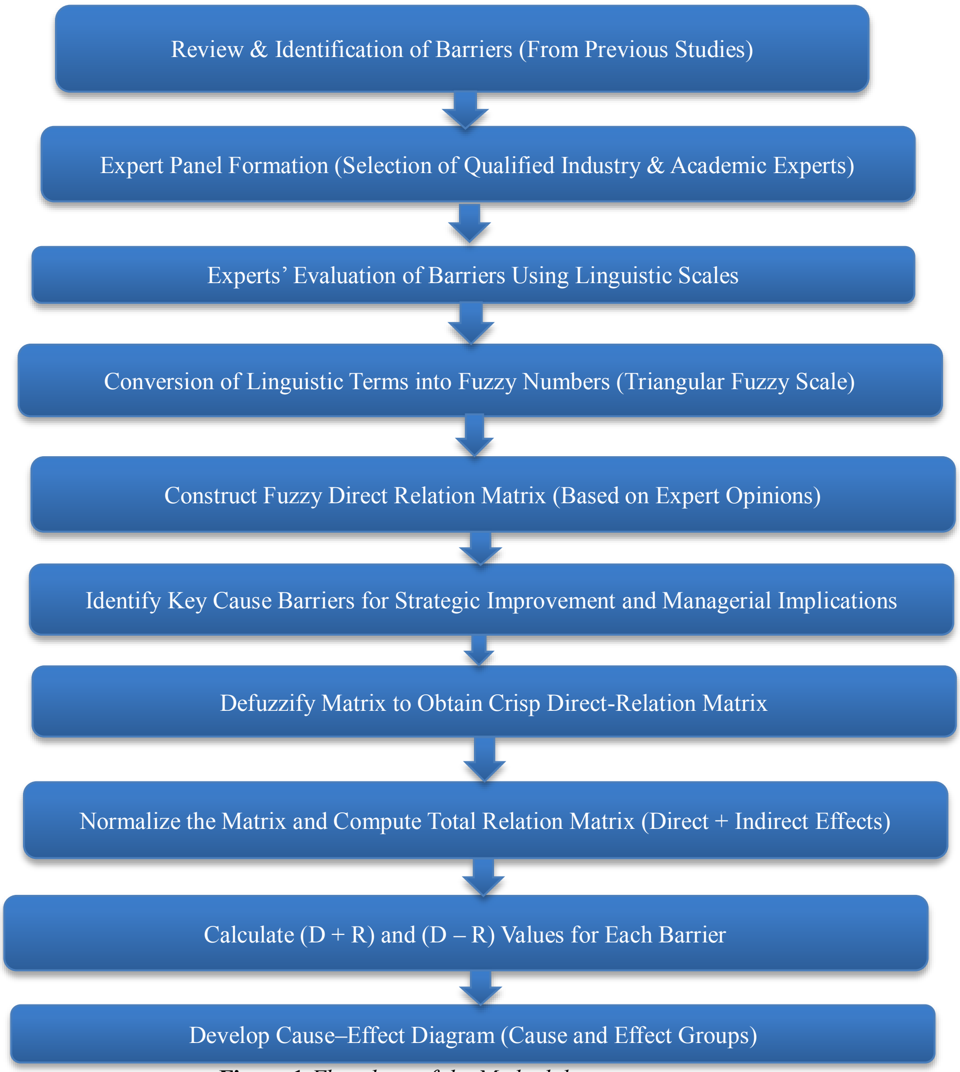

Figure 1 *Flowchart of the Methodology*

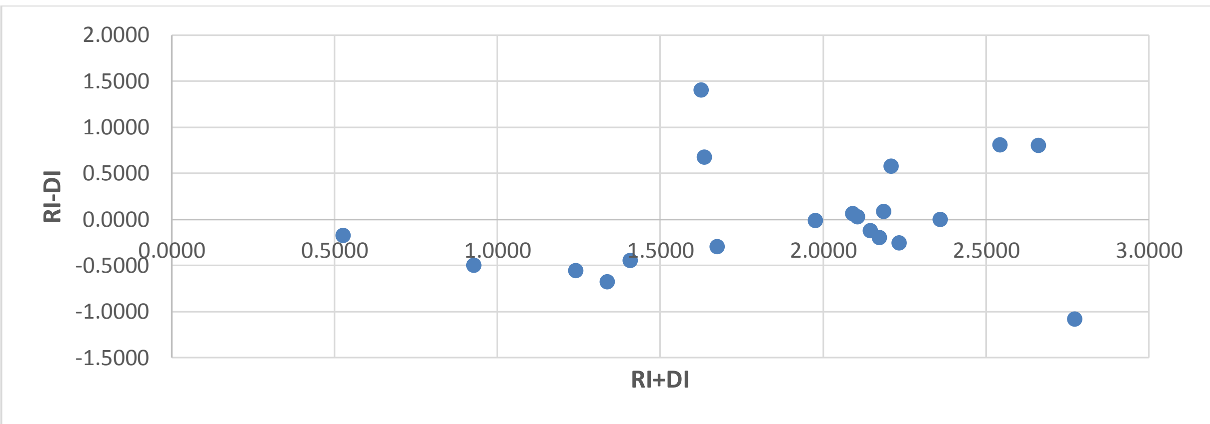

Figure 2 *Cause and Effect Relation*

Table 4 *Cause–Effect Relationship*

Barriers	RI	CI	RI+CI	RI-CI	Identify
CB1	1.5118	0.1155	1.6273	1.3963	Cause
CB2	0.8446	1.9292	2.7738	-1.0846	Effect
CB3	0.6865	0.9893	1.6758	-0.3029	Effect
CB4	0.9788	0.9989	1.9777	-0.0201	Effect
CB5	0.3271	1.0120	1.3391	-0.6848	Effect

CB6	0.4782	0.9310	1.4092	-0.4529	Effect
CB7	0.2122	0.7168	0.9290	-0.5046	Effect
CB8	1.1532	0.4841	1.6373	0.6691	Cause
CB9	0.1727	0.3547	0.5274	-0.1820	Effect
CB10	1.0743	1.0190	2.0933	0.0553	Cause
CB11	1.3917	0.8193	2.2110	0.5724	Cause
CB12	1.0098	1.1371	2.1469	-0.1273	Effect
CB13	1.0651	1.0419	2.1070	0.0232	Cause
CB14	1.7299	0.9330	2.6629	0.7969	Cause
CB15	1.1773	1.1833	2.3606	-0.0060	Effect
CB16	0.3402	0.9020	1.2422	-0.5618	Effect
CB17	0.9861	1.1885	2.1745	-0.2024	Effect
CB18	0.9863	1.2484	2.2347	-0.2622	Effect
CB19	1.1328	1.0550	2.1878	0.0779	Cause
CB20	1.6724	0.8721	2.5445	0.8003	Cause

3. Result and Discussion

Fuzzy Delphi-Fuzzy DEMATEL analysis of the twenty key barriers to implementing Sustainable Industry 4.0 (S-I4.0) and Circular Economy (CE) principles in the gold jewellery supply chain was performed. Out of these, eight barriers, including CB1, CB8, CB10, CB11, CB13, CB14, CB19, and CB20 were categorized as causal and the rest of these twelve barriers as effect barriers, As says in **Table 4**. The analysis showed that the strongest reasons were Lack of sustainability awareness (CB1), Inadequate digital infrastructure (CB8), Fragmented data flow and weak transparency (CB10), Conservative organizational culture (CB11), Lack of change-management capability (CB13), Insufficient leadership commitment (CB14), Financial constraints for SMEs (CB19) and Policy and institutional gaps (CB20). These causal determinants all lead to the development of downstream barriers, including High cost of sustainable technologies (CB3), Absence of lifecycle assessment tools (CB4), Limited use of renewable resources (CB6) and Low supplier transparency and alignment (CB17). The findings show that the managerial, institutional, and infrastructural issues are major obstacles to the digital and circular transformation of the gold jewellery industry and not the technological accessibility. The results highlight that the technological cost (CB3), leadership commitment (CB14), and digital preparedness (CB8, CB20) factor are the key driving barriers that affect the other dependent barriers such as weak collaboration (CB18), poor traceability (CB4), and low sustainability awareness (CB1). This result is consistent with the existing literature that singles out high technological expenditures, the lack of digital infrastructures, and the lack of managerial involvement as the key challenges in facilitating the adoption of CE and Industry 4.0, particularly in developing economies (Kumar et al., 2021; Garcia-Muina et al., 2019; Hennemann, 2022). Poor data sharing (CB10), poor resource utilization (CB6), and low R&D investment (CB12) are the downstream effects of the lack of digital readiness (CB8) and minimal leaders' engagement (CB14). Such interconnections imply that interventions on upstream factors can help lessen the degree of dependent barriers considerably. Furthermore, the lack of robust managerial commitment and strategic vision is one of the reasons the lack of successful implementation of circular and sustainable practices in traditional industries is still a problem. In reinforcing the implementation of S-I4.0 in the gold jewellery supply chain, one should work on mitigating the causal barriers that have been dominant. This involves investing in the digital infrastructure, upgrading leadership and competencies in change management, and establishment of enabling financial and policy environment to support SMEs. The policymakers ought to do so by creating an enabling environment that encourages cooperation, information sharing and innovation within the supply chain. With these root causes resolved, the industry will be able to create a more digitally-integrated and sustainable future based on the concepts of a circular economy.

4. Managerial Implication

Fuzzy Delphi- Fuzzy DEMATEL analysis results can give a number of key managerial implications that can be used to facilitate the uptake of Sustainable Industry 4.0 (S-I4.0) and the Circular Economy (CE) in the gold jewelry supply chain. Managers need to appreciate that unsuccessful digital infrastructure, absence of sustainability consciousness, weak managerial dedication, disjointed information circulation and inadequate policy models are the fundamental causal prohibitors that affect the majority of downstream issues. Theoretically, a commitment and vision towards leadership are paramount in ensuring sustainability transformation, thus, the top management should institutionalize sustainability objectives in the business strategy and devote enough funds and human resources to develop digital capabilities. The digital infrastructure, automation, and data integration technologies can play a vital role in minimizing information fragmentation and quality traceability and transparency throughout the supply chain nodes. Collaborative networks should be established to bring together SMEs, through which they can share technological resources, training and best practices toward digital adoption due to the financial and technological constraints. Financial incentives, tax benefits and digital literacy programs should be developed by policymakers and industry associations to lower the barriers to entry of technologies that are sustainability based, (Caiado et al, 2025). Besides, managers should consider embracing structured change management programs that will help them to counteract resistance in conservative organizational cultures and build training programs that will empower digital preparedness and sustainability orientation among workers. Leaders can promote successful communication, data sharing and alignment throughout the supply chain by helping build a culture of innovation and responsibility. Weak traceability and ineffective collaboration should be countered by the implementation of the lifecycle assessment tools, integration of renewable materials, and supplier sustainability auditing. Managers are also to establish cross-industry collaborations, as well as use digital twins and IoT-connected traceability systems to obtain the real-time visibility and optimization of processes. Through upstream causal factors, the strategic approach will have a multiplier effect of removing barriers that are dependant, and a more agile, transparent, and circular value chain of gold jewelry will be achieved. Finally, a sustainable success is based on the synergistic convergence of leadership vision, digital infrastructure, financial empowerment, and collaborative policymaking, which, in turn, will make the gold ornament manufacturing industry turn into a digitally empowered and circular production ecosystem.

5. Theoretical Implication

In theory, the results of the Fuzzy Delphi-Fuzzy DEMATEL analysis can add value to the developing discourse surrounding Sustainable Industry 4.0 (S-I4.0) and Circular Economy (CE) integration by developing a causal-effect relationship that promotes the interdependence of managerial, institutional and infrastructural impediments in the traditional manufacturing setting such as the gold jewelry sector. This work builds on the current literature on sustainability and digital transformation by illustrating that the shift to a circular and digital production process is not only highly technological but also has a strong foundation in the organizational behavior, leadership culture, and institutional preparedness. In theory, it highlights systems thinking approach in the socio-technical paradigm, in which digital infrastructure, human capabilities, and regulatory frameworks are dynamically interacting to determine CE adoption. The recognition of causal barriers including poor digital infrastructure, sustainability ignorance, and deficiency in leadership commitment offers a theoretical basis to the future models of the relationship between technological preparedness and sustainability-oriented organizational change. In addition, it facilitates the resource-based perspective (RBV) and dynamic capabilities theory, which implies that companies need to develop internal strength, leaders flexibility, and digital strengths to turn external sustainability challenges into strategic benefits. Strategically as a managerial insight, this theoretical insight suggests that leadership commitment acts as a mediating construct between institutional enablers and technological adoption and organizational learning and collaboration as reinforcing loops that increase systemic resilience. The results also contribute to institutional theory by showing how the lack of policy and disjointed governance structures impede the normative and coercive forces necessary to diffuse CE in developing economies. Therefore, the managers ought to understand these theoretical observations as a guideline to develop a unified framework to balance digital innovation with socio-organizational adaptability. The model is conceptually sound in that the corrective interventions at the root level of managerial and infrastructural will produce cascading beneficial impacts on the outcome of sustainability dependency. Thus, this study enhances the theoretical combination of sustainability transition models with Industry 4.0 maturity concepts and provides a good base on which scholars and practitioners can develop hybrid models that advance the principles of a circular economy, theories of digital transformation, and strategic management based on leadership development of sustainable industrial evolution.

6. Conclusion

The current study has adopted an integrated Fuzzy Delphi-Fuzzy DEMATEL approach in order to derive the ranking of barriers in the adoption of S-I4.0 and CE practices in the gold ornament manufacturing sector. Lack of leadership commitment, inadequate digital infrastructure, and inadequate policy support are ranked as some of the main causative barriers, leading to dependent problems such as low transparency and poor teamwork. The identification of such root causes would increasing the sustainable transformation through institutional reinforcement, building digital capabilities, and strategic leadership initiatives.

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