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Blockchain-enabled circular economy: Rethinking waste management in global manufacturing

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Abstract

The transition toward a circular economy (CE) in global manufacturing is hindered by challenges such as limited traceability, fragmented waste flows, and lack of compliance enforcement. Blockchain technology, with its capabilities in transparency, immutability, and decentralization, presents a promising solution to address these gaps. This study develops a decision-oriented framework to evaluate blockchain-enabled strategies for circular waste management. Drawing on expert insights collected through a Delphi process and applying the Best-Worst Method (BWM) and TOPSIS, the research prioritizes strategic alternatives based on key criteria including traceability, regulatory compliance, and ease of integration. The results reveal that material traceability platforms and smart contracts for reverse logistics are the most viable blockchain applications for enhancing circularity. A case study in the electronics sector and sensitivity analysis further validate the robustness and applicability of the findings. This research contributes to both theory and practice by offering a structured, replicable model for aligning blockchain adoption with sustainable manufacturing goals.

Keywords: blockchain, circular economy, waste management, global manufacturing, multi-criteria decision making (MCDM).

1. Introduction

The global manufacturing sector remains a cornerstone of economic development but also stands as one of the most significant contributors to environmental degradation, resource depletion, and industrial waste (Štreimikienė et al., 2025). Traditional linear economic models characterized by the sequential flow of take, make, use, and dispose are increasingly criticized for their unsustainable nature. These models not only exacerbate ecological pressures but also limit the long-term resilience and competitiveness of manufacturing systems (Azmi et al., 2025). Consequently, there is growing consensus that a fundamental paradigm shift toward a circular economy

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(CE) is necessary, wherein material flows are redesigned to reduce waste and regenerate natural systems.

The circular economy aims to decouple economic growth from environmental harm by promoting closed-loop systems of production and consumption. In the manufacturing context, this involves extending product lifecycles, enhancing material reuse, and improving waste valorisation. Despite the theoretical promise, the practical realization of circular strategies in global manufacturing remains limited and uneven. Barriers such as a lack of transparency, data silos, inadequate verification mechanisms, and low stakeholder trust hinder effective circular waste management. These barriers are particularly salient in global supply chains, where traceability and accountability across multiple tiers and jurisdictions remain complex and poorly coordinated (Streimikiene & Bathaei, 2025).

Recent technological advancements, especially blockchain technology, offer novel mechanisms to overcome these systemic challenges. Blockchain, as a decentralized, immutable, and transparent ledger system, has the potential to support circular economy objectives by enabling secure and real-time tracking of material flows, automating waste recovery processes via smart contracts, and incentivizing sustainable behavior through token-based systems (Streimikis, 2025). In the context of waste management, blockchain can facilitate traceability of waste streams, verify the authenticity of recycling practices, and integrate end-of-life product handling into upstream design and production stages. This makes it an ideal candidate to operationalize circularity within manufacturing ecosystems.

However, the integration of blockchain into circular waste management practices is still in its infancy. Current scholarly work is largely conceptual, with limited empirical investigation into how blockchain can be effectively applied in complex, real-world manufacturing environments. Moreover, there is a lack of structured decision-making frameworks that can guide stakeholders especially manufacturers, policymakers, and supply chain actors in evaluating the feasibility, relevance, and impact of blockchain applications in this domain. Most existing studies either focus narrowly on technological features or offer fragmented insights without providing comprehensive strategic or managerial guidance (Krisciukaitiene & Bathaei, 2025).

This reveals a critical research gap: despite the theoretical alignment between blockchain capabilities and circular economy principles, there is no robust, integrated framework for evaluating how blockchain can specifically enhance waste management practices in global manufacturing. There is a pressing need for an interdisciplinary approach that combines technological assessment with sustainability criteria and decision-making tools to identify context-relevant strategies for blockchain adoption in waste systems.

To address this gap, this study is guided by the following research objectives:

- To identify and classify the key enablers and barriers of blockchain adoption for circular waste management in global manufacturing.
- To develop a comprehensive framework integrating blockchain capabilities with circular economy principles for waste traceability, recovery, and reuse.

- To apply a multi-criteria decision-making (MCDM) approach (e.g., Best-Worst Method or TOPSIS) to evaluate and rank blockchain-based waste management strategies based on expert input and sustainability performance indicators.
- To derive practical implications and policy recommendations for industries and governments seeking to implement digital innovations in circular manufacturing systems.

Accordingly, this study seeks to answer the following research questions: What are the main drivers and inhibitors influencing the adoption of blockchain for waste management in global manufacturing? How can blockchain functionalities (e.g., traceability, smart contracts, transparency) be aligned with circular economy objectives in waste systems? What decision-making framework can be employed to prioritize blockchain-based strategies for sustainable waste management? What are the implications of blockchain-enabled circularity for manufacturers, supply chains, and environmental policy?

By integrating these questions into a structured research design, the study aims to bridge the existing theoretical-practical divide and contribute both methodologically and substantively to the growing field of sustainable manufacturing. The outcomes will support the development of a digital circular economy by offering empirically grounded, context-sensitive, and decision-oriented insights. In doing so, this research will benefit a wide range of stakeholders, including manufacturing firms, supply chain partners, technology providers, and environmental regulators, all of whom are under increasing pressure to achieve sustainability through innovation.

2. Literature review

The literature on sustainable manufacturing has evolved significantly over the past two decades, reflecting an increasing awareness of the environmental consequences of industrial production and the limitations of linear economic models. At the center of this evolution lies the concept of the circular economy (CE), which emphasizes regenerative systems where materials and energy are continuously cycled back into the value chain. Numerous studies have emphasized the CE's potential to reduce waste, conserve resources, and foster sustainable development. In manufacturing, CE principles translate into practices such as product life extension, remanufacturing, material recycling, and closed-loop supply chains. However, operationalizing these strategies at scale remains a formidable challenge (Bathaei et al., 2025; Camilleri, 2019; Štreimikienė et al., 2024).

One of the persistent barriers to implementing circular models in global manufacturing is the lack of transparency and traceability across extended supply chains. The complexity and globalization of manufacturing networks hinder visibility into the life cycle of products and materials, making it difficult to monitor compliance with CE practices such as proper sorting, reuse, or end-of-life recovery (Bathaei et al., 2021). Traditional data systems, often centralized and siloed, are insufficient to provide the level of granular and secure information needed to track circular flows effectively. This creates both technical and governance obstacles that impede circular waste management initiatives, particularly in resource-intensive sectors like electronics, textiles, and automotive manufacturing (Streimikis et al., 2024).

Blockchain technology has emerged as a promising tool to overcome these limitations. As a decentralized ledger that allows immutable and transparent record-keeping, blockchain can provide secure verification of product origin, composition, usage, and disposal. Scholars have highlighted blockchain's potential to enhance supply chain visibility, foster trust among actors, and support the automation of circular transactions through smart contracts. For example, smart contracts can be used to trigger automated take-back programs or deposit-refund schemes once certain conditions like product returns or material recycling are fulfilled. This technological integration could create a more seamless and accountable waste management process across multiple supply chain tiers (Bathaei et al., 2022).

Furthermore, blockchain can play a pivotal role in supporting reverse logistics, which is a cornerstone of CE practices in manufacturing. Reverse logistics involves the processes by which products and materials are moved from consumers back to producers for reuse, remanufacturing, or recycling. Studies by Makoondlall-Chadee et al. (2021) demonstrate how blockchain can record each step in the reverse flow, ensure data integrity, and validate environmental claims. In waste-intensive industries, such as electronics (e-waste), blockchain can be used to track hazardous components, verify recycling practices, and ensure compliance with environmental standards. This functionality is particularly valuable given the increasing regulatory scrutiny and consumer demand for product transparency and responsible disposal (Makoondlall-Chadee et al., 2021).

Despite the growing body of literature on blockchain and CE, few studies provide integrated decision-making frameworks for selecting and implementing blockchain-based strategies in waste management. Existing work tends to either emphasize the technological potential of blockchain in isolation or focus on theoretical CE models without addressing the practical complexities of implementation in manufacturing. For example, while Fernandez-Vazquez et al. (2022) propose blockchain as a means of enhancing transparency in sustainable supply chains, they fall short of offering methodological guidance for prioritizing among competing use cases or evaluating technological readiness (Fernandez-Vazquez et al., 2022). Similarly, the work of Siegfried et al. (2022) offers a taxonomy of blockchain applications in CE but lacks empirical validation across diverse manufacturing sectors (Siegfried et al., 2022).

Additionally, there is a notable gap in the literature concerning the use of Multi-Criteria Decision-Making (MCDM) methods to assess blockchain applications in the circular economy. MCDM techniques, such as the Analytic Hierarchy Process (AHP), Best-Worst Method (BWM), and TOPSIS, have been widely used in sustainability assessments, supply chain strategy selection, and technology adoption studies. These methods allow for systematic evaluation of alternatives based on both qualitative and quantitative criteria. However, their application in the context of blockchain-enabled CE particularly for waste management in manufacturing remains underexplored. Integrating MCDM methods with expert input could provide actionable insights into the feasibility, scalability, and impact of blockchain solutions in circular systems.

Another under-addressed issue in the literature is the role of contextual factors, such as regulatory environments, industry-specific dynamics, and firm size, in shaping the success or failure of blockchain initiatives for waste management (Wang et al., 2024). While blockchain's technical functionalities are often discussed in generic terms, their adoption in practice is mediated by institutional readiness, digital infrastructure, and stakeholder collaboration. For instance, large multinational manufacturers may have the capacity to invest in blockchain integration and train staff, while small and medium-sized enterprises (SMEs) may face significant barriers due to limited resources or lack of interoperability with existing systems. Understanding these contextual variables is essential for tailoring blockchain-based CE strategies to different manufacturing environments (Singh & Kumar, 2024).

Finally, although there are numerous pilot projects and conceptual models linking blockchain and CE, the empirical evidence base remains weak. There is a pressing need for real-world case studies that examine the implementation process, identify challenges, and document outcomes of blockchain integration in circular waste systems (Kumar & Chopra, 2022). Without such empirical grounding, it is difficult to generalize best practices or formulate policy recommendations. This underscores the necessity of developing a research agenda that combines conceptual modeling with stakeholder input and empirical validation through case studies or industry surveys (Storey et al., 2023).

In summary, while blockchain is increasingly recognized as a technological enabler of circular economy practices in manufacturing, the literature lacks comprehensive, empirically validated, and decision-oriented studies that address its application in waste management. There is a need to move beyond conceptual discussions and develop robust analytical frameworks that incorporate MCDM techniques, account for contextual differences, and provide practical pathways for blockchain implementation. This study seeks to fill this gap by offering a systematic evaluation model that bridges blockchain innovation and circular waste management in the global manufacturing sector. To synthesize the insights from the existing body of literature and to establish a theoretical foundation for this study, a conceptual framework is proposed to illustrate the dynamic interrelationship between blockchain technology, circular economy principles, and waste management within the global manufacturing context (see Figure 1). This framework serves as a visual synthesis of how emerging technologies can address structural inefficiencies in industrial waste systems by aligning technological capabilities with sustainability imperatives.

As shown in Figure 1, the framework positions Circular Waste Management at the center of three interdependent domains. On one side, the Circular Economy contributes guiding principles such as waste reduction, resource efficiency, and lifecycle extension. These principles define the strategic objectives of waste management systems that aim to shift from linear to circular material flows. On the opposite side, Global Manufacturing represents the domain in which industrial waste is generated, driven by high resource consumption and complex, internationalized supply chains. Between these two spheres, Blockchain Technology functions as a technological enabler, offering mechanisms such as traceability, decentralization, and smart contracts to bridge information gaps and reinforce accountability.

The interaction of these domains culminates in a new model of Blockchain-Enabled Circular Waste Management, characterized by traceability of material flows, verification of recycling and reuse practices, and improved transparency across extended value chains. This framework not only clarifies the theoretical alignment between blockchain and CE principles but also highlights the operational dimensions such as smart reverse logistics, data integrity, and automated compliance that are critical for transforming waste into resource value.

Importantly, this framework identifies the current research gap: although existing studies have explored blockchain and CE in isolation or at a conceptual level, few have integrated them into a decision-oriented model capable of guiding practical implementation in manufacturing waste systems. The proposed framework thus sets the stage for the next phase of this research, which will operationalize these linkages through a structured multi-criteria evaluation process. In the following section, this framework will guide the selection of evaluation criteria, stakeholder inputs, and methodological design using MCDM tools.

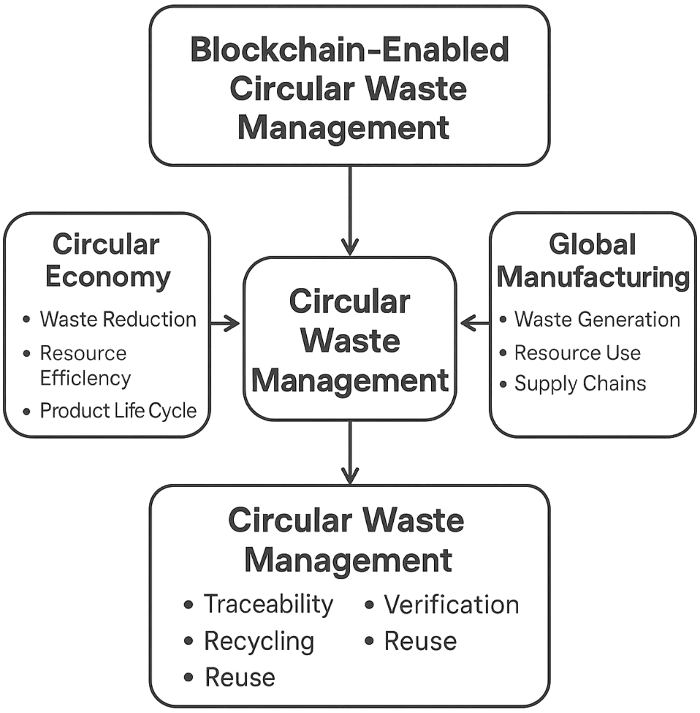

Figure 1. Research framework

3. Methods

This study employed a mixed-methods exploratory design, integrating expert consultation and multi-criteria decision-making (MCDM) techniques to evaluate and prioritize blockchain-enabled strategies for circular waste management in global manufacturing. The methodology was structured into four sequential phases: (1) problem definition and literature synthesis, (2) expert panel selection and data collection, (3) criteria identification and application of MCDM methods, and (4) validation and sensitivity analysis.

Phase 1: Problem Definition and Literature Synthesis. The research began with an in-depth review of academic literature and industrial reports on circular economy (CE), blockchain technology, and waste management in the manufacturing sector. This phase aimed to define the scope of the study and identify initial decision criteria and relevant strategic alternatives. The synthesis of the literature informed the development of the conceptual framework and established a theoretical foundation for empirical analysis.

Phase 2: Expert Panel Selection and Data Collection. A panel of 18 experts was recruited using purposive sampling. Participants were selected from three domains: (1) academia (with expertise in blockchain, sustainability, or circular economy), (2) industry (particularly professionals in manufacturing, digital supply chains, and waste systems), and (3) policy and technology advisors (with roles in environmental regulation or digital innovation). The selection criteria included academic publication record, years of practical experience, and institutional affiliation.

Experts were contacted through institutional email invitations, academic networks, and professional associations related to blockchain and sustainability. The two-round Delphi process was conducted. The expert panel included individuals with an average of 12 years of professional experience in academia, industry, or policy. Most held doctoral degrees and had published in high-impact journals related to sustainability, manufacturing, or emerging technologies. The expert panel represented a diverse range of countries including Lithuania, Germany, Malaysia, Australia, and the Netherlands. Industrial sectors covered included electronics manufacturing, automotive, packaging, and digital supply chain services. This diversity ensured a broad understanding of blockchain applicability across global manufacturing contexts.

Each expert received a formal invitation along with an informed consent form. Data were collected through a two-round Delphi process. In the first round, participants responded to open-ended questions to identify key enablers, barriers, and potential blockchain applications in circular waste systems. In the second round, experts reviewed a refined list of criteria and strategic options and provided rankings based on perceived importance and feasibility. Consensus was achieved through iterative feedback.

Phase 3: Criteria Identification and MCDM Application. Based on the Delphi results, a final list of evaluation criteria was established. These criteria included: traceability, cost-effectiveness, ease of integration, environmental impact, data security, scalability, and regulatory compliance. To prioritize these criteria, the Best-

Worst Method (BWM) was employed. This method required each expert to identify the most and least important criteria and make pairwise comparisons using a numerical scale. An optimization model was applied to determine the optimal weights for each criterion while minimizing inconsistency (Rezaei, 2015).

Following the determination of criterion weights, the study evaluated a set of blockchain-based waste management strategies (e.g., smart contracts for reverse logistics, token-based recycling incentives, material tracking platforms). These alternatives were ranked using the TOPSIS method to assess their relative performance against the weighted criteria. The combined use of BWM and TOPSIS ensured both consistency in weight elicitation and precision in alternative prioritization.

Phase 4: Validation and Sensitivity Analysis. To validate the practical relevance of the findings, a case study approach was employed in the electronics manufacturing sector. Real-world data on waste flows, digital infrastructure, and supply chain practices were used to simulate the application of the top-ranked blockchain strategies. In addition, a sensitivity analysis was conducted to test the robustness of the ranking outcomes under varying weight scenarios. This involved systematically altering the weights of key criteria (e.g., increasing the importance of "regulatory compliance") and observing how these changes influenced the final rankings.

All participants were fully informed about the nature and purpose of the study. Anonymity and confidentiality were ensured throughout the data collection and analysis process.

4. Results

This section presents the findings from the expert-based evaluation of blockchain-enabled circular waste management strategies in global manufacturing. The results are reported in three stages: (1) finalized criteria and their weights (via BWM), (2) ranking of strategic alternatives (via TOPSIS), and (3) insights from the case study and sensitivity analysis.

4.1. Evaluation Criteria and Weighting (BWM Results)

The Best-Worst Method (BWM) was applied to determine the relative importance of the evaluation criteria derived from expert input. After pairwise comparisons and model optimization, the following criteria weights were obtained (Table 1).

The results indicate that traceability emerged as the most critical criterion, reflecting the need for transparent and verifiable tracking of materials in circular supply chains. Regulatory compliance was the second most important, highlighting the growing role of digital tools in meeting environmental and waste legislation. Data security received the lowest weight, suggesting that while important, it is not yet a decisive factor in strategy evaluation for many experts.

Table 1
BWM Results

Criterion	Weight
Traceability	0.278
Regulatory Compliance	0.198
Ease of Integration	0.154
Cost-Effectiveness	0.132
Environmental Impact	0.101
Scalability	0.079
Data Security	0.058

4.2. Ranking of Blockchain-Based Strategies (TOPSIS Results)

Five blockchain-based strategies were evaluated using the weighted criteria:

- Smart Contracts for Reverse Logistics
- Blockchain-Enabled Material Traceability
- Token-Based Recycling Incentive Systems
- Decentralized Waste Verification Platforms
- Product Lifecycle Smart Labels (Digital Twins)

Using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the following rankings were obtained (Table 2).

Table 2
TOPSIS results

Strategy	Closeness Coefficient	Rank
Material Traceability Platform	0.872	1
Smart Contracts for Reverse Logistics	0.811	2
Token-Based Recycling Incentives	0.729	3
Digital Twins for Product Lifecycle	0.664	4
Decentralized Waste Verification Systems	0.593	5

The Material Traceability Platform was ranked highest due to its strong alignment with the most critical criteria—traceability and compliance. Smart Contracts for Reverse Logistics ranked second, appreciated for automating complex return flows and enforcing regulatory obligations. Lower-ranked strategies, while innovative, were perceived to face greater challenges in integration and scalability.

To enhance clarity, the results from the BWM and TOPSIS analyses are presented in Table 1 and Table 2, respectively. Table 1 summarizes the relative importance of criteria, with traceability and regulatory compliance receiving the highest weights. Table 2 displays the ranking of blockchain strategies based on the TOPSIS method.

4.3. Case Study Insights and Validation

The top two strategies were further validated using a case study in the electronics manufacturing sector. The analysis showed that material traceability platforms allowed firms to track rare-earth metals across suppliers and recyclers, improving both operational control and compliance with EU Waste Electrical and Electronic Equipment (WEEE) regulations. Similarly, smart contracts were shown to reduce administrative delays in take-back systems and increase the efficiency of closed-loop logistics.

The implementation challenges identified included initial investment costs, lack of blockchain literacy among suppliers, and limited policy incentives in non-EU contexts. Nonetheless, pilot deployments confirmed the technical feasibility and potential return on investment for large manufacturers.

4.4. Sensitivity Analysis

To test the robustness of the strategy rankings, a sensitivity analysis was performed by adjusting the weights of the top three criteria. Even with a 15–20% shift in individual weights, the ranking of the top two strategies remained unchanged, indicating high stability of the results. In contrast, the ranking of lower-ranked alternatives showed slight variability depending on whether cost or integration ease was prioritized.

This confirms that the top-ranked strategies are consistently preferred across plausible scenarios, enhancing the reliability of the findings for real-world application.

5. Discussion

The findings of this study offer several important insights into the integration of blockchain technology within circular waste management systems in global manufacturing. By combining expert-driven prioritization with robust multi-criteria decision-making methods, the research provides empirical clarity on which blockchain-based strategies are most viable, why they are preferred, and how they may be effectively implemented.

The prioritization of material traceability platforms and smart contracts for reverse logistics as the most effective blockchain strategies confirms theoretical expectations raised in the literature (Bekrar et al., 2021; Centobelli et al., 2022). These applications directly address the key bottlenecks in circular economy implementation—namely, the lack of visibility across supply chains and the difficulty of enforcing compliance in reverse logistics. As highlighted in previous works, traceability enhances accountability and transparency, while smart contracts provide automated enforcement mechanisms for circular practices, reducing dependency on centralized authorities.

Furthermore, the relative importance assigned to criteria such as traceability, regulatory compliance, and ease of integration aligns with findings from (Razak et al., 2023), who argue that the effectiveness of digital technologies in sustainability transitions is mediated by institutional compatibility and operational feasibility. Interestingly, data security, often emphasized in blockchain discussions, received the lowest weight, suggesting that while it remains relevant, practitioners are more concerned with immediate operational and compliance outcomes than with cryptographic robustness in early adoption stages.

For practitioners in manufacturing industries, the results offer a clear roadmap for prioritizing blockchain investments. The top-ranked strategies material traceability and smart contracts are not only technologically feasible but also strongly aligned with current policy trends, such as the EU Green Deal and extended producer responsibility (EPR) frameworks. These findings suggest that firms seeking to improve their circularity performance should begin by implementing blockchain solutions that provide auditable traceability and automated compliance management.

The findings also carry implications for technology providers and startups developing blockchain solutions. Rather than developing generic blockchain tools, there is clear value in creating industry-specific platforms that address traceability in recycling, closed-loop logistics, and product end-of-life management. Moreover, the high ranking of these applications provides validation for pilot testing and eventual scale-up in resource-intensive sectors such as electronics, textiles, and automotive manufacturing.

This study contributes to the emerging body of interdisciplinary research at the nexus of blockchain technology, circular economy, and sustainable supply chain management. While previous studies have explored these domains independently or conceptually, this research integrates them through a quantified, decision-oriented framework, enabling both comparison and prioritization of blockchain strategies.

The use of the Best-Worst Method (BWM) and TOPSIS together represents a novel methodological contribution. This hybrid approach combines the strength of expert-based judgment aggregation with a robust mathematical ranking of strategic alternatives. Furthermore, the study contributes empirical evidence to support claims about blockchain's enabling role in sustainability, a domain still dominated by theoretical and exploration work.

Despite its contributions, the study has several limitations. First, the use of expert judgment, while valuable, may introduce subjective bias. Although the Delphi method was employed to reduce variability and achieve consensus, broader stakeholder inclusion particularly among small and medium-sized enterprises (SMEs) and regulators would enhance representativeness. Second, the scope of blockchain strategies evaluated was necessarily limited to those most prominent in current discourse. Future studies could expand this to include emerging applications such as decentralized identity for compliance tracking or AI-integrated blockchain platforms.

Another limitation of the study is the omission of blockchain's environmental footprint, especially regarding the energy intensity of consensus algorithms like Proof-of-Work. Future studies should evaluate the trade-offs between blockchain-enabled traceability and the energy use associated with different blockchain architectures.

The case study validation, while useful for contextualizing findings, was limited to the electronics manufacturing sector. Application of the model across other industries (e.g., food processing, construction, pharmaceuticals) would be valuable to test the generalizability of the results. Moreover, the environmental impacts of blockchain itself particularly energy consumption, were not explicitly considered, though they remain a relevant concern.

Future research could integrate lifecycle assessment (LCA) or environmental cost metrics to assess the ecological footprint of blockchain-based waste management systems, especially considering the energy consumption of various blockchain consensus mechanisms.

Future research could build on this study by conducting longitudinal assessments of blockchain adoption in circular waste systems to understand how these technologies evolve over time in different industrial contexts. Additionally, comparative studies across countries or regulatory regimes could uncover how legal and policy environments shape the effectiveness of blockchain strategies in enabling circularity. Finally, integrating life cycle assessment (LCA) and cost-benefit analysis with the MCDM framework would provide a more holistic assessment of blockchain's value proposition in circular manufacturing systems.

6. Conclusions

This study explored the strategic integration of blockchain technology into circular waste management systems within the global manufacturing sector. Motivated by the urgent need to address inefficiencies in linear production models and the challenges of implementing circular economy (CE) principles, the research proposed a conceptual and decision-oriented framework that evaluates blockchain applications using expert input and multi-criteria decision-making (MCDM) methods.

By engaging a diverse panel of experts through a structured Delphi process and applying the Best-Worst Method (BWM) and TOPSIS, the study systematically identified and ranked blockchain strategies based on their alignment with CE objectives. The results clearly indicated that material traceability platforms and smart contracts for reverse logistics represent the most viable and impactful solutions for supporting circularity in waste systems. These strategies were found to strongly contribute to enhanced traceability, regulatory compliance, and operational efficiency—criteria deemed most critical by experts.

Studying contributes both theoretically and practically. Theoretically, it advances the discourse on digital enablement of sustainability transitions by offering a quantified, empirically grounded framework that connects blockchain technology to circular manufacturing. Practically, it provides stakeholders including manufacturers, technology developers, and policymakers with actionable guidance on where to focus investment and policy support. In particular, the findings support the development of blockchain-based solutions tailored to industrial waste systems, especially in sectors with high environmental externalities.

Nonetheless, the study acknowledges certain limitations. The reliance on expert judgment introduces subjectivity, and the case validation focused on a single industry. Broader empirical testing across different sectors, geographies, and regulatory environments would strengthen the generalizability of the framework. Moreover, further integration of environmental impact metrics, such as blockchain energy consumption, remains a necessary complement to future assessments.

In summary, blockchain offers substantial potential to enable transparent, accountable, and efficient circular waste management in global manufacturing. However, its implementation must be carefully aligned with strategic priorities, stakeholder capabilities, and contextual constraints. The proposed framework lays a foundation for such alignment, providing a strategic tool for advancing sustainable industrial transformation in the era of digital innovation.

References

Azmi, A. N. A., Alimin, N. S. N., & Bathaei, A. (2025). Mitigating machinery's environmental impact in palm oil plantations for enhanced business performance. *International Journal of Industrial Management, 19*(1), 10 - 21. https://doi.org/10.15282/ijim.19.1.2025.12090

Bathaei, A., Awang, S. R., & Ahmad, T. (2021, 28/07/2021). An overview of organizational performance and total quality management. *Journal of Review in Science and Engineering*.

Bathaei, A., Awang, S. R., & Ahmadc, T. (2022). Evaluate and Rank Iranian Automobile Companies Based on Agile Supply Chain with Using Fuzzy TOPSIS.

Bathaei, A., Awang, S. R., Štreimikienė, D., & Ahmad, T. (2025, %03/%17). Agility sustainable supply chain in automobile industry. *Technological and economic development of economy, 31*(2), 619–638. https://doi.org/10.3846/tede.2025.23231

Bekrar, A., Ait El Cadi, A., Todosijevic, R., & Sarkis, J. (2021). Digitalizing the closing-of-the-loop for supply chains: A transportation and blockchain perspective. *Sustainability, 13*(5), 2895.

Camilleri, M. A. (2019). The circular economy's closed loop and product service systems for sustainable development: A review and appraisal. *Sustainable development, 27*(3), 530-536.

Centobelli, P., Cerchione, R., Del Vecchio, P., Oropallo, E., & Secundo, G. (2022). Blockchain technology for bridging trust, traceability and transparency in circular supply chain. *Information & Management, 59*(7), 103508.

Fernandez-Vazquez, S., Rosillo, R., De la Fuente, D., & Puente, J. (2022). Blockchain in sustainable supply chain management: an application of the analytical hierarchical process (AHP) methodology. *Business Process Management Journal, 28*(5/6), 1277-1300.

Krisciukaitiene, I., & Bathaei, A. (2025). Developing a tailored sustainable supply chain framework for dairy SMEs in Lithuania using Best-Worst Method. *Transformations and Sustainability, 1*(1), 43-62. https://doi.org/10.63775/sv982x31

Kumar, N. M., & Chopra, S. S. (2022). Leveraging blockchain and smart contract technologies to overcome circular economy implementation challenges. *Sustainability, 14*(15), 9492.

Makoondlall-Chadee, T., Goolamally, N. P., Coolen, P. V. R., & Bokhoree, C. (2021). Sustainable tourism, technology and Internet 4.0: opportunities and challenges for small Island developing states. *2021 IoT Vertical and Topical Summit for Tourism*, 1-4.

Razak, G. M., Hendry, L. C., & Stevenson, M. (2023). Supply chain traceability: a review of the benefits and its relationship with supply chain resilience. *Production planning & control, 34*(11), 1114-1134.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega, 53*, 49-57.

Siegfried, N., Rosenthal, T., & Benlian, A. (2022). Blockchain and the Industrial Internet of Things: A requirement taxonomy and systematic fit analysis. *Journal of Enterprise Information Management, 35*(6), 1454-1476.

Singh, A. K., & Kumar, V. P. (2024). Integrating blockchain technology success factors in the supply chain of circular economy-driven construction materials: An environmentally sustainable paradigm. *Journal of Cleaner Production, 460*, 142577.

Storey, V. C., Lukyanenko, R., & Castellanos, A. (2023). Conceptual modeling: topics, themes, and technology trends. *ACM Computing Surveys, 55*(14s), 1-38.

Streimikiene, D., & Bathaei, A. (2025, %05/%01). Evaluating and ranking quality education for sustainable development in the Baltic States: A multi-criteria decision-making approach using Eurostat data. *Transformations and Sustainability, 1*(1), 12-29. https://doi.org/10.63775/vq29r460

Štreimikienė, D., Bathaei, A., & Streimikis, J. (2024). Evaluating Agri-Environmental Indicators for Land Use Impact in Baltic Countries Using Multi-Criteria Decision-Making and Eurostat Data. *Land, 13*(12), 2238. https://www.mdpi.com/2073-445X/13/12/2238

Štreimikienė, D., Bathaei, A., & Streimikis, J. (2025). Enhancing Sustainable Global Supply Chain Performance: A Multi-Criteria Decision-Making-Based Approach to Industry 4.0 and AI Integration. *Sustainability, 17*(10), 4453. https://www.mdpi.com/2071-1050/17/10/4453

Streimikis, J. (2025). Comparative assessment of circular economy performance in the Baltic States using MCDM methods. *Transformations and Sustainability, 1*(1), 30-42. https://doi.org/10.63775/pcxj8p61

Streimikis, J., Bathaei, A., & Štreimikienė, D. (2024). Sustainability assessment of the agriculture sector using best worst method: Case study of Baltic states. *Sustainable development, 32*(5), 5611-5626. https://doi.org/https://doi.org/10.1002/sd.2993

Wang, Z., Yu, L., & Zhou, L. (2024). Navigating the blockchain-driven transformation in industry 4.0: Opportunities and Challenges for Economic and Management Innovations. *Journal of the Knowledge Economy*, 1-43.