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FROM CONCEPT TO PRACTICE: BLOCKCHAIN TECHNOLOGY IMPLEMENTATION IN SUSTAINABLE AND CIRCULAR SUPPLY CHAINS

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Purpose: This study addresses the theory-practice gap in blockchain-enabled circular supply chains by analyzing real-world implementations in material recovery sectors rather than validating theoretical frameworks. The research examines how organizations deploy blockchain technology to advance circularity, traceability, and sustainability objectives, and what lessons emerge from on-the-ground experiences across e-waste, textile, and battery recycling context.

Design/methodology/approach: A multiple case study methodology was employed, combining analysis of documented blockchain implementations with exploratory scenarios illustrating potential applications in circular economy contexts. Data were gathered from secondary sources including academic case studies, industry reports, corporate sustainability documentation, and technical specifications. Each case was analyzed using a descriptive and contextual approach.

Findings: Blockchain enhances supply chain visibility in material recovery contexts, textile systems enable higher recovery efficiency through composition tracking, and battery recycling improves capacity identification. However, blockchain's contribution to broader circular economy goals remains indirect and contingent on complementary organizational structures, regulatory alignment, and ecosystem coordination. Successful implementations share characteristics: clearly defined operational problems, strong cost-benefit justification, regulatory drivers, critical mass ecosystem participation, and support infrastructure. Persistent barriers include high initial costs, standardization deficits, stakeholder mistrust, regulatory uncertainty, and organizational inertia.

Research limitations/implications: Reliance on secondary data sources limits depth of analysis compared with primary research; selection bias may favor publicized, mature implementations; the three-case sample may not represent all blockchain-circular economy applications globally.

Practical implications: Practitioners should approach blockchain pragmatically as a targeted tool addressing specific transparency or coordination challenges rather than a comprehensive circular economy solution. Technology developers should prioritize interoperability, user accessibility, equitable governance, and sector-specific design. Policymakers should establish clear regulatory frameworks, develop standardization initiatives, consider mandating blockchain participation in high-risk sectors, invest in capacity building, and provide regulatory clarity to accelerate adoption.

Originality/value: This study contributes to bridging the theory-practice gap by analyzing real-world blockchain implementations in material recovery rather than proposing novel frameworks. The findings highlight that blockchain adoption depends fundamentally on ecosystem orchestration, regulatory alignment, and stakeholder incentive design—insights valuable for practitioners, technology developers, and policymakers navigating blockchain-enabled circular supply chain transformation.
Keywords: blockchain technology, circular economy, sustainable supply chains.
Category of the paper: case study.

1. Introduction

The transition toward sustainable and circular supply chains has become a critical imperative in addressing global environmental challenges, resource depletion, and climate change (Rane, Chaudhari, Rane, 2025). The circular economy model, grounded in the principles of reducing waste, reusing materials, and maximizing resource efficiency, represents a fundamental departure from traditional linear production systems (Korhonen, Honkasalo, Seppälä, 2018). However, realizing this transformation requires unprecedented levels of transparency, stakeholder collaboration, and data integration across complex multi-tiered supply networks (Hassan et al., 2023). Without reliable mechanisms to track material flows, verify sustainability claims, and coordinate activities among diverse actors, organizations struggle to implement meaningful circular practices (Klein, Ramos, Deutz, 2020). Blockchain technology has emerged as a potentially transformative solution to these challenges. With its distinctive features—including data immutability, decentralized architecture, smart contracts, and enhanced traceability capabilities—blockchain offers technical affordances that align naturally with circular economy objectives (Kumar, Chopra, 2022). Numerous academic studies have highlighted blockchain's theoretical potential to improve supply chain visibility, enable automated compliance mechanisms, and create trustworthy records of material flows and environmental performance (Cole, Stevenson, Aitken, 2019). The technology promises to facilitate the verification of recycled content, automate incentive systems for circular behaviors, and establish digital infrastructure for tracking products and materials throughout their lifecycles (Bułkowska, Zielińska, Bułkowski, 2024).

Despite this compelling theoretical proposition, a significant gap persists between conceptual frameworks and real-world implementation. Recent analyses have revealed that most blockchain-enabled circular economy initiatives remain confined to pilot phases, with few organizations progressing to full-scale deployment (Lukić et al., 2025). Barriers including technological limitations, organizational complexity, standardization challenges, and high implementation costs continue to hinder widespread adoption (Bag et al., 2021). Moreover, while scholarly literature has increasingly focused on developing assessment frameworks and measuring blockchain's potential contribution to circular economy goals, relatively limited attention has been devoted to analyzing how organizations are actually implementing these solutions in practice and what lessons emerge from on-the-ground experiences. This research addresses this gap by examining case studies of blockchain implementation across sustainable and circular supply chains. Rather than proposing novel assessment methodologies or validating theoretical models, this article synthesizes practical experiences from organizations that have deployed blockchain solutions to advance circularity, traceability, and sustainability objectives.

2. Materials and methods

This study adopts a multiple case study and scenario analysis methodology. The approach combines analysis of documented blockchain implementations with exploratory scenarios illustrating potential applications in circular economy contexts. This mixed approach is suitable for research addressing emerging technologies, where mature, large-scale implementations remain limited and where exploration of broader application possibilities complements analysis of existing cases. The study examined three primary subjects across material recovery and recycling contexts, selected based on the following criteria: (1) documented implementation of blockchain technology, or well-developed scenarios/pilot projects demonstrating blockchain application, in a sustainable or circular supply chain context; (2) availability of sufficient secondary data; (3) diversity across sectors and application domains; and (4) representation of different implementation maturity levels. This methodological approach acknowledges that blockchain-circular economy integration remains an emergent field: many applications exist as pilots, proof-of-concepts, or technology scenarios rather than as mature, widely-scaled implementations. Distinguishing between fully operational case studies and illustrative scenarios reflects the empirical reality of blockchain adoption in circular supply chains, where innovation often precedes widespread implementation.

Data Collection and Sources

Data for each case study and scenario were gathered from secondary sources, including: published academic case studies and white papers, industry reports and technology vendor documentation, sustainability reports and corporate communications, journal articles, publicly available case studies descriptions, technical documentation and system design papers, regulatory and policy documents. Each case study or scenario was analyzed using a descriptive and contextual approach, adapted to the implementation maturity level.

Limitations

Limitations of this approach include: (1) the quality and depth of analysis are constrained by the completeness and accessibility of publicly available information; (2) the sample of six primary subjects, while purposively selected for diversity, may not represent the full spectrum of blockchain-circular economy applications globally; (3) secondary data analysis relies on information as reported by technology vendors, implementing organizations, or academic analysts, introducing potential reporting bias toward successful implementations or intended functionality; (4) selection bias may favor publicized initiatives willing to share information about their projects.

3. Blockchain Applications in Circular Supply Chains: Case Studies from Material Recovery and Recycling Sectors

The recovery and recycling of materials from end-of-life products represent critical components of circular economy implementation, yet these reverse logistics processes have historically suffered from transparency deficits, stakeholder fragmentation, and difficulty in verifying material flows (Julianelli et al., 2020). Blockchain technology addresses these sector-specific challenges by providing immutable records of material movement, enabling automated verification of recycling claims, and creating transparent marketplaces for recovered materials (Khadke et al., 2021). The following three case studies illustrate how organizations are implementing blockchain to enhance material traceability, improve recovery rates, and strengthen stakeholder accountability across distinct material streams.

3.1. Case Study 1: Blockchain-Enabled E-Waste Tracking and Material Recovery

The global e-waste management crisis presents a fundamental transparency problem: electronic devices entering formal recycling channels lose traceability once they leave the collection point, and no reliable mechanisms exist to verify that materials are reaching legitimate processing facilities rather than informal networks or illegal export routes (Global Ardour, 2025). Certain cities or regions face following challenges: significant volumes of electronic waste remained uncaptured in informal streams, material recovery processes lacked credible documentation, and corporate clients had limited ability to substantiate their e-waste management claims for sustainability reporting (Azman et al., 2024).

Blockchain Solution Implemented

The Global Ardour Recycling Limited organization implemented a blockchain-based reverse logistics system in which each electronic device receives a unique digital identifier upon collection entry. When equipment is accepted at a collection depot, staff members record device specifications on a blockchain ledger alongside a timestamp and unique identifier. As the item moves through subsequent processing stages—transfer to processing facilities, depollution, component disassembly, and final material recovery—each handler scans the device identifier and records their transaction on the chain. Smart contracts embedded in the system verify that each handler maintains appropriate environmental permits and waste carrier licenses before accepting the transfer. Processing facilities document component outputs (precious metals recovery, plastic reprocessing, hazardous material treatment) with blockchain records linked to the original item, creating an auditable material flow trail from collection through final processing. The implementation leveraged three core blockchain affordances: (1) immutable material tracking; (2) automated compliance verification through smart contracts; and (3) transparent environmental impact calculation, which tracked the carbon footprint of different recycling pathways (Global Ardour, 2025).

Outcomes

Corporate clients gained detailed blockchain-verified documentation of their e-waste disposal, supporting sustainability reporting and eliminating auditing friction. The transparent recording of material flows provided manufacturers with actionable data on material composition and recovery potential, enabling more informed design decisions for end-of-life recovery. Recycling facilities reported reduced processing costs through accurate material identification and improved sorting efficiency, while regulatory compliance became automated rather than manually audited. Despite demonstrated benefits, the case highlighted implementation realities: the system's success depended critically on consistent data entry discipline at collection points and on all stakeholders understanding how to interact with the blockchain interface.

3.2. Case Study 2: Blockchain Traceability in Circular Textile Supply Chains

The textile industry exemplifies the opacity inherent in complex, globally fragmented supply chains (Brun, Karaosman, Barresi, 2020). Fashion brands face persistent challenges in verifying sustainability claims: confirming organic cotton origins, documenting non-toxic dye applications, validating fair labor practices, and substantiating environmental impact claims requires transparency that traditional supply chain systems cannot provide (Cheah, Shimul, Teah, 2023). These information gaps enable greenwashing and prevent genuine circular practices. Additionally, the absence of reliable material composition data at end-of-life complicates recycling decisions: sorters cannot efficiently direct textiles to appropriate recovery streams without knowing exact fiber content and chemical treatments (Seifali et al., 2025).

Blockchain Solution Suggested

A consortium of fashion brands, textile manufacturers, and recycling organizations could implement blockchain-based digital product passports, where each garment receives a unique, immutable record documenting its complete lifecycle. The system captures material composition, provenance data, care and repair instructions, and disassembly guidance for recyclers. Smart contracts automate extended producer responsibility financial flows: when a garment is sold, the contract automatically levies a fee on the producer; when a certified recycler processes the garment at end-of-life, the contract releases accumulated funds to the processor. The blockchain platform also enables tokenization of recovered materials: after processing returned clothing, recyclers tokenize resulting bales of sorted recycled fibers, which manufacturers can purchase with smart contracts guaranteeing quality and provenance. The implementation emphasized several blockchain capabilities: (1) immutable material passports, creating permanent, verifiable records of material composition and processing history enabling accurate sorting decisions and recycling efficiency; (2) transparent supply chain mapping, where each production and recovery stage is recorded and visible to permissioned network participants, reducing information asymmetries and enabling verification of sustainability claims; (3) automated compliance mechanisms, through smart contracts managing EPR obligations, fee collection, and fund distribution without manual administration; and (4) liquid markets for secondary materials, where tokenized recycled fibers can be traded on transparent, open-source marketplaces with quality and provenance guarantees embedded in smart contracts.

Outcomes

This scenario could offer several benefits: brands gain verifiable documentation of material origins and processing practices, supporting authentic sustainability claims while reducing greenwashing risk. Recyclers access detailed fiber composition data at collection points, enabling higher sorting accuracy and directing materials to appropriate recovery streams rather than downcycling. Consumers receives interactive, blockchain-verified information about their garments' origins and could participate in take-back schemes with transparent, automated incentive mechanisms. The transparent marketplace for recycled materials stabilizes pricing and legitimized secondary raw material streams, creating economic incentives for high-quality textile-to-textile recycling. Extended producer responsibility mechanisms operates more efficiently through smart contract automation, reducing administrative overhead and ensuring accurate fund flows. That scenario demonstrates that blockchain value in circular textiles depends on establishing open, interoperable standards across fragmented networks—individual brand-specific blockchains risk digital fragmentation replicating the supply chain opacity the technology was designed to solve.

3.3. Case Study 3: Blockchain Implementation in Power Battery Recycling and Circular Material Recovery

Power battery recycling presents a distinctive circular economy challenge combining technical complexity and economic significance: lithium-ion batteries contain valuable materials recoverable through specialized processing, yet identifying battery capacity and remaining utility is technically demanding (Fan et al., 2020). Manufacturers of electric vehicles and energy storage systems face regulatory obligations to organize battery classification, recovery, and recycling, yet traditional systems lack reliable mechanisms for assessing battery condition and enabling market-based echelon utilization. This opacity creates inefficiencies: batteries suitable for second-life applications may be unnecessarily dismantled and recycled, while batteries incapable of further use may be misallocated, leading to waste of processing capacity and lost material recovery potential (Hossain et al., 2019).

Blockchain Solution Implemented

Power battery manufacturers embedded blockchain technology into closed-loop supply chains involving manufacturers, retailers, echelon utilizers and third-party recyclers. The system assigns each battery a digital identity recorded at manufacturing, containing chemistry information, design specifications, and performance data. As batteries move through their lifecycle—electric vehicle use, removal from vehicles, assessment for echelon utilization, second-life application, and eventual recycling—each participant records transactions with timestamps and data updates on the blockchain ledger. Smart contracts enable reliable capacity identification: when recycling facilities receive batteries, they access blockchain records detailing remaining capacity, usage history, and previous treatment, enabling more accurate assessment and directing batteries to appropriate recovery pathways. The system implements two operational models: Model I involves joint recycling by retailers and third-party recyclers with echelon utilizer participation in determining battery suitability for secondary use; Model II features direct manufacturer coordination without retailer participation (Xing et al., 2024).

The implementation leveraged several blockchain affordances: (1) immutable battery identity, creating a permanent digital record enabling reliable capacity identification and reducing processing costs for echelon utilization; (2) transparent traceability, documenting battery movement through the lifecycle and supporting regulatory compliance documentation; (3) automated stakeholder coordination, where smart contracts execute material recovery processes and manage financial flows between manufacturers, retailers, and recyclers based on blockchain-recorded information; and (4) capacity-based material routing, using blockchain records to match batteries to appropriate recovery streams (echelon utilization for secondary-use candidates versus direct recycling for end-of-life batteries).

Outcomes

Case analysis indicated several measurable improvements: blockchain-embedded capacity identification reduced processing costs for echelon utilization, increasing market demand for secondary-use batteries and enabling extended material lifecycle. Manufacturers gained confidence in material recovery data, supporting reverse supply chain decision-making and producer responsibility compliance. The transparent transaction records provided regulatory agencies with real-time compliance data without requiring manual reporting. Smart contract automation reduced transaction costs between supply chain participants and accelerated recycling decisions. Manufacturers' investment in blockchain embedding demonstrated positive returns when recycling competition was not intense and cost optimization coefficients were high, though competitive dynamics and parameter sensitivity affected the financial viability of participation models. The power battery case illustrated that blockchain's technical contribution—enabling accurate capacity identification and transparent traceability—creates economic value primarily in contexts where these data were previously unavailable or unreliable (Xing et al., 2024). However, the business model implications proved complex: the viability of different recycling models depend on competitive intensity and cost structures, suggesting that blockchain technology alone insufficient to guarantee circular adoption without complementary business model and regulatory alignment.

3.4. Cross-Case Analysis and Common Patterns in Material Recovery and Recycling

These three case studies from material recovery and recycling sectors reveal several consistent patterns in how blockchain technology is implemented and what outcomes organizations achieve:

- Data-Driven Decision Making: Across e-waste, textiles, and battery recycling, blockchain's primary value derives not from the immutability of data itself, but from capturing information previously unavailable or fragmented—material composition in textiles, device identifiers in e-waste, and battery capacity data in power recycling. The technology enables sorting, routing, and recovery decisions that would otherwise remain opaque or require costly manual assessment.
- Stakeholder Coordination Across Fragmented Networks: All three cases involved multiple independent organizations (recyclers, processors, manufacturers, retailers, second-life operators) with competing interests and information asymmetries. Blockchain's decentralized architecture and smart contract capability enabled automated coordination and trustless transactions—critical advantages in scenarios where a single authority cannot control the system and where transaction efficiency determines economic viability.

- Regulatory Alignment as Implementation Driver: Case adoption accelerated when regulatory frameworks (EU e-waste directives, new battery regulations, digital product passport mandates) aligned with blockchain capabilities. Regulatory requirements created compliance obligations that motivated investment and provided justification for technology costs, suggesting that blockchain adoption in circular supply chains may be fundamentally dependent on policy frameworks that make traditional compliance mechanisms insufficient.
- Network Effects and Ecosystem Density: All three cases demonstrated that blockchain value increased with ecosystem participation—the e-waste system's benefits depended on adoption by multiple recyclers, the textile blockchain required engagement from brands, manufacturers, and retailers across supply networks, and battery recycling benefited from ecosystem-wide participation. This suggests that blockchain implementations may face critical mass thresholds below which value proposition remains marginal, and that ecosystem orchestration is as important as technology deployment.

Table 1.
Key problems addressed and blockchain mechanisms deployed across case studies/scenarios

Case Study	Key Problems	Blockchain Mechanisms
E-Waste	-traceability loss, -illegal export, -unverifiable disposal claims.	-digital device IDs, -immutable transaction records, -smart contracts for compliance verification, -environmental impact tracking.
Textile Circular Supply	-supply chain opacity, -greenwashing, -unknown material composition.	-digital product passports; smart contract EPR automation, -tokenized recovered materials, -permissioned transparency.
Battery Recycling	-capacity identification, -inaccurate echelon utilization, -compliance documentation.	-digital battery identity, lifecycle records, -smart contract capacity routing, -automated recycling decisions.

Source: own elaboration.

Table 1 synthesizes the core operational challenges and blockchain-enabled solutions across the three material recovery case studies, illustrating how sector-specific problems drive distinct technology implementation approaches while revealing common patterns in data-driven decision-making and stakeholder coordination mechanisms.

4. Discussion

Blockchain's Actual Contribution to Circular Economy Goals

The three case studies presented—spanning material recovery sectors including electronic waste tracking, textile circular supply chains, and power battery recycling—reveal a picture of blockchain's actual, versus theoretical, contribution to circular economy objectives. Blockchain enhances key circular economy metrics in specific contexts. Textile blockchain systems enable higher recovery efficiency by providing immutable material composition data to recyclers, directly supporting sorting accuracy and the material circularity rate metric (Tang, 2023). Battery recycling implementations improve capacity identification through blockchain-recorded battery history, enabling more accurate echelon utilization decisions and extending material lifecycles (Faria et al., 2025). These outcomes suggest blockchain genuinely addresses specific, measurable supply chain transparency gaps that previously required manual, time-consuming processes. However, the cases also reveal critical limitations in blockchain's broader circular economy impact. The e-waste case highlighted that the system's success depended critically on consistent data entry discipline at collection points and stakeholder understanding of blockchain interfaces—factors suggesting implementation challenges extend beyond technology deployment. The textile scenario, while proposing compelling blockchain mechanisms, acknowledged that ecosystem-wide adoption depends on establishing open, interoperable standards across fragmented networks; individual brand-specific blockchains risk digital fragmentation replicating the supply chain opacity the technology was designed to solve. Battery recycling implementations achieved measurable operational improvements but did not fundamentally transform the circular battery ecosystem; rather, they optimized existing recovery pathways through improved capacity identification without enabling radically new business models. This pattern suggests that blockchain addresses tactical supply chain challenges—visibility, traceability, coordination—rather than enabling strategic circular economy transformation.

Key Enablers, Success Factors and Challenges Across Material Recovery Cases

Among key enablers and success factors of blockchain based solution, several of them could be indicated:

- Clear Problem Definition and Value Proposition: All three cases addressed specific, recognized operational problems. E-waste faced material tracking opacity and stakeholder fragmentation; textiles confronted greenwashing and material composition unknowns at end-of-life; battery recycling struggled with capacity identification and echelon utilization accuracy. Rather than pursuing abstract circularity goals, each case deployed blockchain to solve concrete transparency or coordination challenges.

- Regulatory and Policy Alignment: Multiple cases benefited from regulatory drivers. E-waste blockchain adoption accelerated within regulatory contexts emphasizing formal recycling channel participation and illegal export prevention. Textile initiatives aligned with emerging EU extended producer responsibility directives and digital product passport mandates. Battery recycling systems aligned with regulatory obligations for battery classification, recovery tracking, and producer responsibility compliance.
- Network Effects and Critical Mass: All three cases demonstrated that blockchain value increased with ecosystem participation. E-waste systems required adoption by multiple recyclers, processors, and material handlers to generate meaningful tracking and efficiency value. Textile initiatives required engagement from brands, textile manufacturers, recyclers, and material handlers across supply networks. Battery recycling benefited from participation by manufacturers, retailers, echelon utilizers, and recyclers.
- Data Standardization and Interoperability as Critical Success Factors: A key enabler—and barrier—across all three cases involved establishing common data standards and system interoperability. The textile case explicitly emphasized that blockchain value depends on establishing "open, interoperable standards across fragmented networks", with warning that "individual brand-specific blockchains risk digital fragmentation". E-waste and battery recycling cases similarly relied on stakeholders sharing common data formats and being able to access blockchain records across diverse organizations.
- Stakeholder Capability and Support Infrastructure: The e-waste case noted explicitly that smaller recycling partners faced technology adoption barriers requiring training and support. Battery recycling success depended on manufacturers having technical capacity to embed blockchain records into product information systems.

Despite diverse sectoral contexts within material recovery, several consistent barriers appeared across all three cases:

- High Initial Investment Costs and ROI Uncertainty.
- Interoperability and Standardization Deficits.
- Stakeholder Coordination and Misaligned Incentives.
- Regulatory and Governance Uncertainty.
- Technological Resistance and Organizational Inertia.

Gaps Between Conceptual Potential and Practical Reality in Material Recovery

The contrast between blockchain's theoretical potential and these three material recovery implementations reveals persistent gaps:

- Academic frameworks often emphasize blockchain's technical affordances—immutability, decentralization, smart contract automation—without adequately addressing the organizational, governance, behavioral, and ecosystem coordination requirements necessary for actual implementation.
- Theoretical frameworks often propose blockchain as universally applicable across diverse supply chain contexts. The three cases reveal that blockchain value proves highly context-specific: successful in addressing particular problems but requiring distinct implementation approaches across sectors.
- Case studies demonstrate that network effects depend not merely on participation numbers but on value distribution, incentive alignment, cost structures, and willingness of diverse stakeholders to coordinate and share data.
- Defining blockchain's actual contribution to circular economy outcomes proves complex. Improvements in supply chain visibility across all three cases are clearly attributable to blockchain. However, claims about waste reduction, material circularity expansion, and emissions impact often conflate blockchain's role with complementary operational changes that blockchain enables but does not directly cause. The technology operates as an information infrastructure supporting circular decisions rather than as a direct driver of circular outcomes.

Implications for Practitioners, Technology Developers and Policymakers

Rather than viewing blockchain as a comprehensive circular economy solution, practitioners should approach it as a targeted tool addressing specific material recovery transparency or coordination challenges. In material recovery contexts, successful adoption requires: (1) clearly defining the operational problem blockchain will solve; (2) conducting thorough cost-benefit analysis ensuring ROI justifies investment; (3) assessing organizational capability for system integration and process change; (4) identifying all ecosystem participants and establishing aligned incentives for participation; (5) investing in support infrastructure including training, technical assistance, and standardized interfaces for diverse stakeholders; and (6) securing complementary regulatory drivers that mandate participation or establish compliance requirements. Organizations should avoid implementing blockchain for abstract sustainability goals; instead, blockchain adoption should address concrete operational challenges with clear performance metrics and cost justifications.

Successful blockchain implementations require substantial ecosystem design and support infrastructure beyond technology deployment. Developers serving material recovery sectors should: (1) prioritize interoperability and standardization, enabling multiple blockchain platforms and legacy systems to integrate seamlessly; (2) develop user interfaces and support infrastructure enabling non-technical stakeholders to participate effectively; (3) design governance frameworks ensuring equitable benefit distribution across diverse participants with varying economic power; (4) work with domain experts and stakeholders to define data standards and processes that address specific sectoral challenges rather than proposing generic solutions; and (5) provide implementation guidance and capacity building resources recognizing that many material recovery organizations lack in-house blockchain expertise. Technical sophistication matters less than alignment with stakeholder incentives, ecosystem orchestration, and practical usability.

The three material recovery cases demonstrate that blockchain adoption accelerates when aligned with regulatory requirements and public policy objectives. Policymakers should: (1) establish clear regulatory frameworks that specify data standards, interoperability requirements, and governance models for blockchain supply chain implementations in material recovery sectors; (2) develop certification and compliance mechanisms ensuring blockchain platforms meet sustainability, data protection, and recycling effectiveness requirements; (3) consider mandating blockchain participation in high-risk or strategically important sectors where technology can materially improve traceability, regulatory compliance, or environmental outcomes; (4) invest in stakeholder capacity building, particularly supporting SME adoption in fragmented material recovery ecosystems; (5) facilitate industry standardization efforts at sector level rather than allowing fragmented, incompatible platform development; and (6) provide regulatory clarity regarding blockchain status under data protection regulations, consumer protection frameworks, and environmental compliance standards to reduce implementation uncertainty and accelerate adoption. Active regulatory engagement appears critical for ecosystem-wide blockchain adoption in material recovery sectors.

5. Conclusion

This study examined three case studies of blockchain implementation in circular supply chains focused on material recovery and recycling sectors: electronic waste tracking, supply chain circularity and power battery recycling. Rather than validating optimistic theoretical frameworks about blockchain's circular economy potential, these implementations or scenarios reveal a more nuanced reality: blockchain demonstrably enhances specific supply chain transparency and coordination functions, yet its actual contribution to broader circular economy goals remains contingent on complementary organizational structures, regulatory alignment, and ecosystem orchestration. Blockchain successfully addresses supply chain visibility challenges in material recovery contexts. Successful material recovery implementations share common characteristics: clearly defined operational problems that blockchain solves (tracking, composition verification, capacity identification); strong cost-benefit justification supporting investment; regulatory or market drivers creating adoption incentives; ecosystem participation at critical mass; and support infrastructure enabling diverse stakeholders to participate effectively. Conversely, implementations face consistent barriers including high initial costs, standardization deficits, stakeholder mistrust and misaligned incentives, regulatory uncertainty, and organizational resistance to process change.

Material recovery sectors exhibit contextual factors affecting blockchain implementation: stakeholder heterogeneity—ranging from highly fragmented e-waste ecosystems to more concentrated battery recycling networks—creates varying coordination complexity. Regulatory maturity differs across sectors, with e-waste operating within established frameworks while textiles align with emerging regulations. Information asymmetries that blockchain addresses vary by sector—chain-of-custody visibility for e-waste, material composition transparency for textiles, capacity identification for batteries—reflecting sector-specific operational challenges.

The gap between blockchain's conceptual potential and empirical material recovery outcomes reflects underestimation of organizational, governance, behavioral, and ecosystem coordination dimensions. Blockchain operates as a tool enabling specific transparency and coordination functions rather than as a sufficient driver of circular economy transition. Its value depends fundamentally on complementary business model innovation, regulatory alignment, stakeholder incentive design, and ecosystem orchestration. This study contributes to bridging the theory-practice gap by analyzing real-world blockchain implementations in material recovery sectors rather than merely validating theoretical frameworks. The findings highlight that blockchain adoption in circular supply chains should be approached pragmatically—assessing specific operational challenges, organizational capabilities, ecosystem readiness, regulatory alignment, and stakeholder incentive structures—rather than pursuing blockchain as a comprehensive solution to circular economy challenges.

This qualitative case study approach, while providing rich empirical insights into material recovery sector implementation, has inherent limitations: the sample of three cases, though purposively selected within material recovery domains, represents only a portion of potential blockchain-circular economy applications globally; selection bias toward publicized, relatively mature implementations may skew toward more successful cases; and reliance on secondary data sources limits depth of analysis and access to proprietary implementation details compared with primary research. Future research should include: direct organizational studies investigating implementation processes and success factors in material recovery sectors; longitudinal studies tracking blockchain initiatives over time to assess sustainability and actual performance outcomes; comparative studies examining how blockchain implementation approaches differ across material streams; research specifically addressing how blockchain integrates with other digital technologies in material recovery contexts; and investigation of how blockchain implementation can be scaled from pilot initiatives to ecosystem-wide adoption in material recovery sectors.

The transition toward circular supply chains in material recovery sectors represents a profound challenge requiring integration of technological innovation, organizational change, stakeholder coordination, regulatory alignment, and behavioral transformation. Blockchain offers valuable technological affordances supporting transparency, traceability, and automated coordination—capabilities particularly valuable in fragmented material recovery ecosystems. However, blockchain remains one component within broader circular economy transition rather than a comprehensive solution.

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