



Artificial Intelligence and Blockchain Traceability for Circular Value Chain Optimization

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Abstract. The global transition from linear to circular economy necessitates transformative solutions for managing complex value chains. However, persistent challenges such as information asymmetry and lack of transparency hinder their full potential. This study proposes an integrated framework that synergistically combines artificial intelligence (AI) and blockchain technology to address these barriers. Using scenario-based simulations in electronics, reverse logistics, and agri-food supply chains, we empirically validate this approach. The results demonstrate that this integration creates a robust decision support system, achieving a 60% reduction in administrative processing time and a 40% decrease in food spoilage. Consequently, the study argues that this technological fusion offers a powerful mechanism to accelerate the transition towards a more resilient circular economy, fostering the trust and transparency fundamental to large-scale adoption.

Keywords: circular economy, circular value chains, artificial intelligence, blockchain, resource traceability, reverse logistics

JEL Classification: Q57, L15, O33, D47, M11

1. Introduction

The prevailing linear economic model, characterized by a one-way flow from resource extraction to production, consumption, and disposal, has placed unprecedented strain on global ecosystems and resource reserves. This model is responsible for extensive environmental degradation, resource depletion, and a growing waste crisis, posing significant threats to long-term sustainability. In response, the concept of a circular economy (CE) has emerged as a compelling

alternative paradigm. Central to this paradigm is the development of circular value chains (CVCs), which redesign traditional supply chains to facilitate the continuous flow of materials through processes of maintenance, reuse, remanufacturing, and recycling. However, the operationalization of CVCs presents profound complexities, including the coordination of reverse logistics, assessment of returned product quality, management of fragmented information across multiple stakeholders, and the verification of circularity claims (Despotovic and Glatschke, 2024).

Overcoming these challenges requires a technological leap beyond traditional supply chain management systems. The digital transformation, powered by advancements in Industry 4.0 technologies, offers a promising pathway to enable the intricate processes inherent in a circular model. Among these technologies, artificial intelligence (AI) and blockchain have emerged as particularly potent enablers of supply chain innovation. AI, with its capacity for machine learning, predictive analytics, and optimization, can significantly enhance decision-making in complex systems. It can be leveraged to forecast product returns, optimize collection and sorting processes, assess the condition of used products, and identify markets for secondary materials, thereby driving efficiency and value recovery in CVCs (Bashynska and Prokopenko, 2024).

Simultaneously, blockchain technology offers a foundational layer of trust and transparency, which is often lacking in conventional multi-stakeholder supply chains. As a distributed, immutable ledger, blockchain can create a verifiable and tamper-proof record of a product's entire lifecycle, from raw material sourcing to its end-of-life treatment. This enhanced traceability is crucial for a functioning circular economy, as it allows stakeholders to verify the origin, composition, and history of materials, ensuring their suitability for reuse or recycling (Hamed and Madancian, 2025). The integration of smart contracts – self-executing contracts with the terms of the agreement directly written into code – can further automate and secure transactions within the CVC, such as buy-back schemes, warranty claims, or the trading of recycled materials (Hong and Xiao, 2024). By fostering transparency and accountability, blockchain can build the trust necessary for collaborative circular ecosystems to thrive (Awashreh et al., 2025).

While the individual applications of AI in supply chain optimization and blockchain in enhancing traceability are well documented, the specific application of these technologies to the unique demands of the circular economy is an emerging field of research (Hamed and Madancian, 2025). Moreover, the potential synergies arising from their integration remain largely unexplored. AI algorithms are fundamentally dependent on the quality and integrity of the data they process; “garbage in, garbage out” remains a critical limitation. Blockchain can address this by providing a secure and trustworthy data source, ensuring that AI-driven optimizations are based on reliable, auditable information. Conversely, blockchain systems can be enhanced with AI-driven intelligence. For instance, AI can analyse

on-chain and off-chain data to trigger smart contracts under optimal conditions, moving beyond simple, pre-defined rules to dynamic, intelligent automation that adapts to real-world complexities.

Contrary to the existing literature, which mainly studies mature economies, this study particularly highlights the frictions of emerging markets. We present a hybrid architecture validated through a discrete-event simulation calibrated on real-world data from the Algerian ecosystem. This approach allows for a rigorous assessment of feasibility and scalability prior to physical deployment. This paper aims to bridge this research gap by developing a comprehensive conceptual framework for an integrated AI-blockchain system designed specifically for the optimization of circular value chains.

The remainder of this paper is structured as follows. Section 2 reviews the literature on circular value chains and the respective contributions of AI and blockchain. Section 3 presents the integrated conceptual framework and its architecture. Section 4 describes the scenario-based simulation methodology and defines the KPIs. Section 5 presents the electronics and agri-food simulation scenarios and reports the results. Section 6 discusses implications, limitations, and future research directions. Section 7 concludes.

2. Literature Review

The transition from a linear “take–make–dispose” economic model to a circular one represents a fundamental paradigm shift in how value is created and sustained. This transition necessitates the redesign of value chains to prioritize resource longevity, material recovery, and waste elimination. The complexity inherent in circular systems managing reverse logistics, assessing the quality of returned products, and coordinating a diverse network of stakeholders presents significant operational challenges. In response, emerging digital technologies, particularly artificial intelligence (AI) and blockchain, are being explored as powerful enablers of this transformation. This review of the literature examines the foundational concepts of circular value chains and delves into the distinct contributions of AI and blockchain to supply chain management. It further synthesises existing research to identify the synergistic potential of integrating these two technologies and highlights the current gaps in knowledge that this paper aims to address.

2.1. The Imperative of Circular Value Chains

The concept of the circular economy (CE) has gained significant traction as a strategic response to mounting global pressures, including resource scarcity, environmental degradation, and climate change. Unlike the traditional linear

economy, which relies on the continuous extraction of virgin resources and generates vast amounts of waste, the circular economy is fundamentally regenerative. It aims to decouple economic growth from resource consumption by designing products and systems that facilitate reuse, repair, remanufacturing, and recycling. A core operational component of the CE is the circular value chain (CVC), or circular supply chain (CSC), which redefines material and information flows to close loops and retain value within the system for as long as possible (Meena et al., 2025).

The imperative for CVCs is driven by a confluence of economic, environmental, and social factors, often framed within the “triple bottom line” perspective of people, planet, and profit (Meena et al., 2025). Environmentally, CVCs are critical for mitigating the negative externalities of industrial production. By emphasizing the use of sustainable materials and optimizing resource use, they reduce the demand for raw material extraction, lower energy consumption, and minimize pollution and waste generation. This approach is central to achieving sustainable development goals and fostering more resilient industrial ecosystems.

Economically, CVCs unlock new avenues for value creation and competitive advantage. By extending the lifecycle of products and recovering materials, companies can reduce input costs, mitigate supply chain risks associated with volatile commodity markets, and develop new revenue streams from services like refurbishment, remanufacturing, and material brokerage. The transition to circular models also fosters innovation in product design, business models (e.g. product as a service), and logistics. Blockchain technology, for example, is increasingly recognized for its potential to support this transition by creating transparent and traceable ecosystems for products and materials (Elgez et al., 2025).

Socially, the development of CVCs can lead to the creation of new jobs in areas such as collection, sorting, repair, and recycling. Furthermore, by promoting responsible sourcing and providing greater transparency into product lifecycles, CVCs can enhance corporate social responsibility and build consumer trust. However, operationalizing CVCs is inherently complex. It requires managing intricate reverse logistics networks, developing methods for assessing and sorting returned products of varying quality, and fostering collaboration among a wide array of stakeholders, including manufacturers, consumers, collectors, and recyclers. This complexity necessitates advanced technological solutions to manage data, optimize processes, and ensure trust and transparency among participants.

2.2. Artificial Intelligence in Supply Chain Optimization

Artificial Intelligence, particularly its subfield of machine learning (ML), has emerged as a transformative force in supply chain management, offering powerful tools to enhance efficiency, predictability, and decision-making. AI's capacity to

analyse vast and complex datasets enables a level of process optimization and intelligent management that is essential for navigating the complexities of modern supply chains, especially those designed for circularity (Liu et al., 2024; Farshadfar et al., 2024). AI-driven approaches are increasingly being leveraged to optimize resource use, streamline logistics, and embed sustainability into core operational practices (Bashynska and Prokopenko, 2024).

One of the primary applications of AI in supply chain optimization is in forecasting and demand planning. Machine learning algorithms can analyse historical sales data, market trends, seasonality, and external factors (e.g. weather, economic indicators) to generate highly accurate demand predictions. This capability is crucial for CVCs, as it allows for better planning of reverse logistics and anticipates the volume and type of returned products, thereby optimizing collection and remanufacturing schedules. AI can also predict trends in waste generation and material availability, facilitating more effective resource management and planning within sustainable smart cities (Jogarao et al., 2024).

AI-driven optimization models also play a critical role in logistics and network design. Algorithms can determine the most efficient transportation routes, optimize vehicle loads, and manage inventory across complex networks, significantly reducing fuel consumption, emissions, and operational costs. In the context of CVCs, this extends to optimizing reverse logistics, i.e. the process of moving goods from their final destination for the purpose of capturing value or proper disposal. AI can identify the optimal locations for collection centres, design efficient collection routes, and automate sorting processes by using computer vision to identify and classify returned materials. These AI innovations, including machine learning calculations and predictive analytics, enable more dynamic and responsive decision-making, helping to transform sustainable goals into operational realities (Mankar et al., 2024).

Furthermore, AI contributes significantly to supplier management and material sourcing, which are vital for circularity. Machine learning techniques can be used to evaluate and select suppliers based on a wide range of criteria, including sustainability performance and their capacity to provide recycled or remanufactured components. AI can help identify “green suppliers” that optimize circular economy metrics like recyclability and resource efficiency (Ibrahim, 2024). By analysing material composition and performance data, AI can also assist in the design of products that are easier to disassemble, repair, and recycle, thereby embedding circularity at the earliest stage of the value chain. As a whole, the application of AI in supply chains is pivotal for enhancing sustainability by improving resource management and optimizing processes across the entire product lifecycle (Farshadfar et al., 2024).

2.3. Blockchain for Enhanced Supply Chain Traceability and Transparency

While AI provides the intelligence to optimize supply chain operations, blockchain technology offers the foundational architecture for trust, transparency, and traceability. Blockchain is a decentralized and distributed ledger technology (DLT) that records transactions in a secure, immutable, and verifiable manner (Oriekhoe et al., 2024). Each transaction, or “block”, is cryptographically linked to the one before it, creating a chain of records that is resistant to tampering. This architecture provides a single, shared source of truth for all participants in a supply chain network, from raw material suppliers to end consumers and recyclers (Fattahi Bafghi, 2024).

The primary value of blockchain in supply chain management lies in its ability to enhance traceability. By recording every movement and transaction of a product or material on an immutable ledger, blockchain creates a verifiable digital history of its journey through the value chain (Dissanayake et al., 2025). This capability is indispensable for CVCs, where tracking the origin, composition, and condition of products and components is essential for effective reuse, remanufacturing, and recycling. For instance, a manufacturer can verify the quality and authenticity of recycled materials, and a consumer can access the complete lifecycle history of a product, fostering trust and enabling more informed purchasing decisions. Governments and regulatory bodies can also leverage this transparency to promote and verify compliance with sustainability standards (Hong and Xiao, 2024).

Another key feature of blockchain is the smart contract, which is a self-executing contract with the terms of the agreement directly written into code (Saber et al., 2018). Smart contracts automate processes and enforce predefined rules without the need for intermediaries, thereby increasing efficiency and reducing transaction costs. In a CVC, smart contracts can automate a wide range of activities such as triggering payments to suppliers upon delivery of certified recycled materials, executing buy-back programmes when a product reaches its end-of-life, or facilitating transactions on a marketplace for secondary materials (Tsolakis et al., 2023). By automating these processes, smart contracts streamline operations, ensure that circular economy principles are adhered to, and foster seamless collaboration among network participants (Elgez et al., 2025; Isiaku and Dawud, 2025).

The decentralized nature of blockchain also helps to break down information silos and create a more collaborative and equitable supply chain ecosystem. In traditional supply chains, data is often held in centralized, private databases, leading to a lack of transparency and information asymmetry. Blockchain's distributed ledger mechanism allows authorized stakeholders to access the same information in real time, fostering a more transparent and efficient environment

for monitoring and documenting material flows (Kshetri, 2018). This enhanced transparency not only helps in optimizing the supply chain but also builds a robust foundation for a truly integrated and sustainable digital economy (Hong and Xiao, 2024). By providing a secure and transparent platform for data exchange, blockchain technology is a critical enabler for building the trust and accountability required to make circular value chains viable at scale.

2.4. Synergies and Gaps in Integrating AI and Blockchain for Circularity

While AI and blockchain offer distinct and powerful capabilities for supply chain management, their true transformative potential for CVCs lies in their synergistic integration. Blockchain can provide the secure, transparent, and trustworthy data that AI algorithms need in order to function effectively, while AI can bring advanced analytics and intelligent automation to blockchain-based networks. This combination creates a dynamic feedback loop where trusted data enables smarter decisions, and intelligent actions are recorded on an immutable ledger, enhancing accountability and continuous improvement.

The synergy begins with data quality. AI models, particularly machine learning algorithms, are highly dependent on the quality, integrity, and availability of data. In complex CVCs, data is often fragmented, inconsistent, and prone to manipulation. Blockchain addresses this fundamental challenge by creating a single, tamper-proof source of truth for product lifecycle data (Tsolakis et al., 2023). When IoT devices capture real-time data on a product's location, condition, or usage, this data can be recorded on a blockchain, ensuring its immutability. AI algorithms can then analyse this high-integrity data to generate more accurate predictions, optimize logistics, and assess product quality for remanufacturing with a much higher degree of confidence (Dissanayake et al., 2025). This integration of blockchain-enabled transparency with AI could effectively automate sustainability practices across the value chain (Ibrahim, 2024).

This integration also enables more intelligent and autonomous CVC operations through “smart” smart contracts. A standard smart contract executes based on simple, predefined rules (e.g. “if delivery is confirmed, then release payment”). However, by integrating AI, smart contracts can become dynamic and context aware. For example, an AI model could analyse market data to determine the optimal price for secondary materials and then trigger a smart contract to execute the sale. Similarly, AI could predict a product's end of life based on usage data and automatically initiate a smart contract for buy-back or collection programme. This combination facilitates the optimization of network activities, where AI provides the intelligence for decision-making, and blockchain and smart contracts provide the secure and automated execution framework (Isiaku and Dawud, 2025).

Despite this promising potential, significant gaps remain in both the academic literature and practical implementation of integrated AI-blockchain systems for CVCs. First, much of the existing research tends to examine AI and blockchain in isolation. Studies often focus on the role of AI in process optimization or that of blockchain in traceability, without deeply exploring the mechanics of their integration. While some recent work has begun to highlight the potential combination of these technologies (Ibrahim, 2024; Isiaku and Dawud, 2025; Tsolakis et al., 2023), there is a lack of comprehensive conceptual frameworks that detail the architecture, data flows, and governance models for a fully integrated system specifically designed for CVC optimization.

Second, there is a scarcity of empirical evidence and real-world case studies demonstrating the tangible benefits of such an integrated approach. Most discussions remain at a conceptual or theoretical level. Without robust performance metrics and comparative analyses, it is difficult for businesses and policymakers to assess the return on investment and justify the significant upfront costs and organizational changes required for implementation. Key questions remain unanswered regarding scalability, interoperability between different blockchain platforms and AI systems, and data privacy concerns in a transparent yet intelligent network.

Finally, the governance and operational challenges of managing a decentralized, AI-driven ecosystem are not yet fully understood. Reconciling the centralized nature of many AI optimization algorithms with the decentralized ethos of blockchain presents a significant technical and organizational hurdle. Issues such as data ownership, algorithmic transparency (explainable AI), and the rules governing the network need to be addressed to ensure fairness, security, and long-term viability. These are the challenges that highlight for us the importance of integrated frameworks that also take both the technical design and governance, implementation pathways. Leveraging on these gaps, this paper develops an integrated AI-blockchain framework for optimizing the circular value chain and tests it through simulation-based case studies in the Algerian electronics and agri-food sectors, offering context-specific implications beyond developed countries.

3. Conceptual Framework: An Integrated AI-Blockchain Model

The transition from a linear to a circular value chain necessitates a fundamental shift in how information is managed, decisions are made, and trust is established among disparate stakeholders. While the preceding literature review establishes the individual potential of artificial intelligence (AI) and blockchain technology, their true transformative power lies in their synergistic integration. This section

proposes a conceptual framework that combines AI's analytical and predictive capabilities with the capacity of blockchain for providing immutable, transparent, and auditable data trails. The framework is designed to create a resilient, intelligent, and trustworthy ecosystem for circular value chain optimization, addressing the core challenges of information asymmetry, process inefficiency, and lack of stakeholder trust that currently hinder the widespread adoption of circular economy principles.

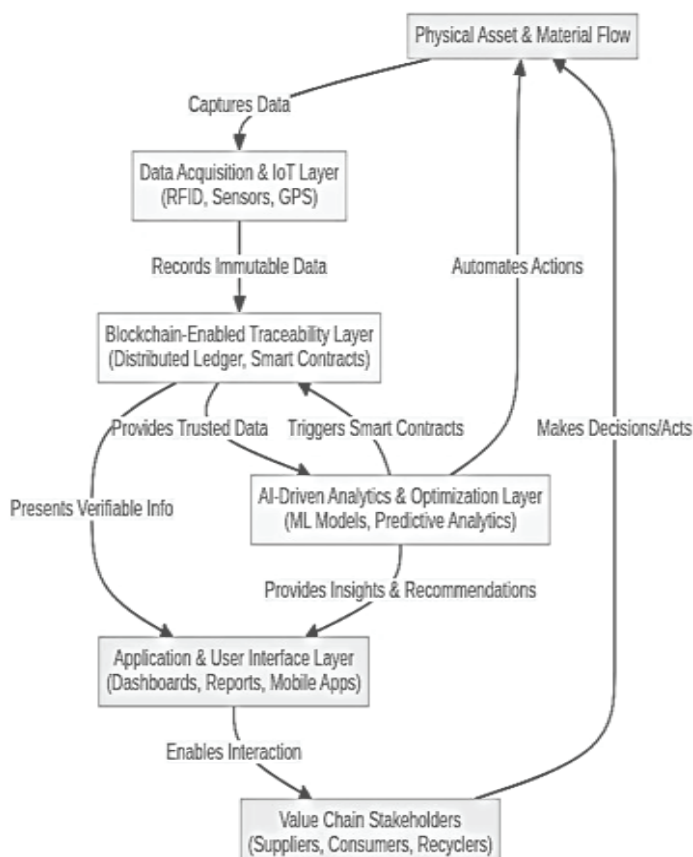
This integrated model is not merely a sequential application of two technologies but a symbiotic system where each component enhances the functionality of the other. Blockchain provides the high-quality, tamper-proof data that AI algorithms require for accurate forecasting, dynamic optimization, and intelligent automation. Conversely, AI infuses the blockchain layer with the intelligence needed to execute complex, context-aware decisions through smart contracts, moving beyond simple transactional logic to proactive and adaptive governance. The following sections will detail the architecture of this integrated system, delve into the specific functions of the AI-driven optimization engine and the blockchain-enabled traceability layer, and elucidate the pivotal role of smart contracts in automating and governing circular processes.

3.1. Architecture of the Integrated System

The proposed architecture for an integrated AI-blockchain system is a multi-layered construct designed for modularity, scalability, and interoperability. It comprises a foundational data layer, which is the system's sensory organ, responsible for capturing real-time data from various points across the circular value chain. It includes Internet of Things (IoT) devices such as RFID tags, GPS trackers, environmental sensors (e.g. temperature, humidity), and optical scanners embedded in products, packaging, and logistics assets. This layer collects raw data on product location, condition, usage patterns, material composition, and environmental factors, forming the initial data points that will be recorded and analysed.

Then there is a blockchain-enabled traceability layer, which is the system's "single source of truth". Data from the IoT layer is cryptographically hashed and recorded as transactions on a distributed ledger. This layer creates an immutable and chronological record of a product's entire lifecycle, from raw material extraction and processing to manufacturing, distribution, use, repair, collection, and recycling (Hamed and Madancian, 2025). The use of a permissioned or consortium blockchain is often most appropriate for supply chain contexts, allowing stakeholders (e.g. suppliers, manufacturers, logistics providers, recyclers) to participate as nodes in the network while maintaining necessary levels of privacy and control over sensitive data. This distributed ledger mechanism for documenting and monitoring product flows is fundamental to building trust and transparency (Kshetri, 2018).

Further, the AI-driven analytics and optimization layer acts as the system's "brain". It interfaces with the blockchain layer, pulling trusted, time-stamped data for analysis. This layer houses a suite of AI and machine learning (ML) models tailored for specific circular economy functions. These models perform predictive analytics (e.g. forecasting return volumes, predicting products' end of life), prescriptive analytics (e.g. recommending optimal reverse logistics routes, suggesting disassembly strategies), and classification tasks (e.g. automated sorting of waste materials based on sensor data). The combination of AI and blockchain provides a robust framework for data-driven decision-making and optimization activities across the value chain (Isiaku and Dawud, 2025). The integrated structure of these technological layers is illustrated in *Figure 1*.



Source: inspired by Pal et al. (2024), Wang et al. (2020), Thakker et al. (2024)

Figure 1. Optimized circular value chain architecture using artificial intelligence, IoT, and blockchain

As a user-facing application layer, this top layer provides stakeholders with access to the system's data and insights through intuitive dashboards, reporting tools, and mobile applications. It allows managers to monitor key performance indicators (KPIs) for circularity, consumers to verify product provenance and sustainability claims, and regulators to audit compliance with environmental standards. This layer also facilitates the execution of transactions and the triggering of smart contracts based on decisions made by the AI layer or by human operators.

This design ensures a clear separation of concerns while facilitating a continuous and dynamic feedback loop between the core technological components. The synergy within this architecture is critical. The blockchain layer guarantees the integrity of the data fed into the AI models, preventing a “garbage in, garbage out” scenario. In turn, the AI layer provides the advanced intelligence necessary to make sense of the vast datasets recorded on the blockchain, transforming passive data records into actionable, forward-looking insights that drive efficiency and circularity.

3.2. AI-Driven Optimization Engine

The AI-Driven Optimization Engine is the core component responsible for transforming the transparent, trusted data from the blockchain into strategic and operational advantages. It leverages a portfolio of AI techniques to address key optimization challenges inherent in circular value chains. The maturation of AI technologies, such as deep learning, has made these sophisticated applications increasingly feasible and effective in the circular economy context (Filho et al., 2025). The engine's functions can be categorized into three primary areas: predictive analytics – one of the greatest challenges in circular systems is the uncertainty surrounding the timing, quantity, and quality of returned products. AI models, particularly machine learning algorithms like regression analysis and neural networks, can analyse historical data on sales, product usage (from IoT sensors), and consumer behaviour to forecast the volume and geographic distribution of end-of-use products. This allows organizations to plan collection and reverse logistics infrastructure proactively, reducing costs and improving collection rates. AI-driven predictive models permit more informed and forward-looking decisions, transforming reactive recovery processes into strategic asset management (Mankar et al., 2024).

Regarding the prescriptive optimization of circular value chains, the engine moves beyond mere prediction to provide specific recommendations for optimizing resource allocation. This implies firstly the implementation of dynamic routing, where using algorithms such as ant colony optimization or genetic algorithms, the engine can calculate the most efficient collection routes for returned products in

real time, considering factors like fuel costs, vehicle capacity, traffic conditions, and the value of the collected items. Next, regarding remanufacturing and recycling decisions, by analysing data on a returned product's condition, repair history, and the current market demand for spare parts versus recycled materials, AI can recommend the most economic and environmentally friendly recovery strategy, be it repair, remanufacturing, harvesting components, or recycling. Finally, the system ensures inventory management, as the engine optimizes stock levels for both recovered components and remanufactured finished goods, balancing supply and demand to minimize holding costs and waste.

Finally, automated classification and quality assessment: in recycling and remanufacturing facilities, the AI engine can automate critical sorting and assessment tasks. By integrating with machine vision systems and various sensors, deep learning models can be trained to identify different material types (e.g. plastics, metals) with high accuracy, assess the quality and condition of returned components, and detect contaminants in waste streams. This automation increases processing speed, improves the purity and value of secondary raw materials, and reduces manual labour costs and human error.

The effectiveness of this entire engine is contingent upon the quality and reliability of the underlying data. By drawing its inputs directly from the blockchain-enabled traceability layer, the AI engine operates on a foundation of verifiable, tamper-proof information, significantly enhancing the accuracy of its predictions and the reliability of its recommendations.

3.3. Blockchain-Enabled Traceability Layer

The blockchain-based traceability layer constitutes the immutable backbone of the integrated framework, providing the transparency and trust necessary for a functional circular economy. Unlike traditional supply chains, which are often opaque, this technology creates a shared and decentralized database where every transaction and state change is recorded as a permanent block (Elgez et al., 2025), thereby enhancing traceability essential for resource optimization (Tathavadekar and Mahankale, 2025). This mechanism enables end-to-end lifecycle tracking through the creation, right from procurement, of a unique “digital twin”; each step, from manufacturing to distribution, is then recorded in a verifiable history crucial for authenticating recycled content and ethical standards. In parallel, this architecture strengthens collaboration and trust among the numerous independent entities of the value chain by providing a neutral platform without a central intermediary, which fosters the growth of secondary material markets (Awashreh et al., 2025). Finally, by ensuring the integrity and accessibility of critical data such as material composition and repair history, the blockchain guarantees that recyclers have the unalterable information needed to treat products efficiently at

their end of life, thus avoiding value loss and supporting a smart circular economy (Isiaku and Dawud, 2025).

3.4. The Role of Smart Contracts in Automation and Governance

Smart contracts are self-executing contracts with the terms of the agreement directly written into code. They reside on the blockchain and automatically execute when predefined conditions are met. Within the integrated AI-blockchain framework, smart contracts are the key mechanism for translating the insights generated by the AI engine and the data verified on the blockchain into automated, enforceable actions, functioning as the connective tissue that automates processes and governs interactions among stakeholders, significantly reducing administrative overhead and the potential for disputes (Fattahi Bafghi, 2024). Smart contracts can automate a wide range of circular economy processes, such as releasing payment or rebate to a consumer once returned products are received and verified at a collection centre, enabling pay-per-use models in product as a service (PaaS) by calculating and processing payments based on IoT-measured usage and facilitating automated trading of recycled materials by transferring ownership and payment once quality and quantity conditions recorded on the blockchain are met. Smart contracts also serve as powerful tools for creating and managing incentive systems, automatically issuing rewards (e.g. discounts, loyalty points, or tokens) to consumers for returning products, to logistics partners for meeting collection targets, or to designers for creating products that are easily repairable or recyclable, with the logic of these incentive structures encoded directly into the blockchain, ensuring transparent and fair execution (Takkar et al., 2025). Furthermore, integration with the AI engine elevates smart contracts from the simple “if-then” logic to intelligent, adaptive governance: the AI can, for example, analyse market data and predict a future shortage of a specific recycled polymer and trigger a smart contract to increase financial incentive, returning products containing that polymer, thereby creating a dynamic, self-regulating system that adapts to changing market conditions to optimize material flows and resource utilization, reflecting a truly integrated approach to circular value chain management (Elgez et al., 2025; Farshadfar et al., 2024).

4. Methodology

In order to conduct a systematic evaluation of the proposed framework, this study adopts a scenario-based simulation approach combining discrete-event modelling and domain-specific physicochemical modelling (Banks et al., 2010).

4.1. Simulation Environment and Mathematical Formulation

The simulation environment was implemented in Python 3.9. A discrete-event simulation (DES) of supply chain flows was developed using the SimPy library to describe stochastic processes, arrival times, and processing delays (SimPy Development Team, 2018). Predictive decision-making modules were built using Scikit-learn and TensorFlow frameworks (Abadi et al., 2016).

We used a rigorous experimental protocol to ensure the statistical robustness of our results. In order to capture the inherent stochastic variability in arrival rates and processing delays, we specifically carried out 30 independent replications for each scenario using different random seeds. To ensure the system had reached a stable state before data collection started, we also included a 30-day simulated warm-up period. We employed unit tests that validated mass balance conservation and logical flow to ensure the integrity of the code. Lastly, as shown in *Table 1*, we calibrated the baseline parameters against local historical data to guarantee the model accurately represented observed reality within a 10% margin of error.

Table 1. *Key simulation parameters and calibration settings*

Parameter Category	Variable	Value/Setting	Description
General Setup	Simulated time horizon (per scenario)	(Electronics: 12 mo. / Agri-food: 6 mo.)	Simulated operational period
	Replication Count	N = 30	Independent runs per scenario
	Warm-up Period	30 Days	Initialization phase to stabilize queues
Electronics (BBA)	Throughput Volume	3,200 Units	Laptops, tablets, smartphones
	Manual Entry Error	15%	Simulates human error in legacy systems
	Refurbishment Yield (base)	Mean (65%) Stochastic	Base probability of repairability; sampled per unit/condition state
Agri-Food (Biskra)	Total Volume	45 Metric Tons	Organic Deglet Nour Dates
	Spoilage Model	Arrhenius-based kinetics	Temp-dependent degradation rate using simulated/calibrated IoT temperature stream
	Transport Latency	Gamma Dist.	Simulates road/logistics delays (stochastic travel times)

Source: authors' elaboration

The core logic of the framework is driven by two objective functions optimized under constraints specific to the Algerian operating context:

A. Electronics Case: Maximizing Net Circular Value – in the electronics reverse logistics scenario (Bordj Bou Arreridj model), the AI engine maximizes the Net Circular Value (NCV) following the principles of value recovery optimization (Guide and van Wassenhove, 2009):

$$MaxNCV = \sum[(P_r \cdot \delta_{refurb}) + (P_M \cdot \delta_{recycle})] - (C_{log} + C_{proc} + C_{trans}), \quad (1)$$

where P_r and P_M are the current market prices of refurbished units and recycled raw materials in the local market; δ_{refurb} and $\delta_{recycle}$ are binary decision variables chosen by the AI agent (1 if selected, 0 otherwise); the cost terms C_{log} , C_{proc} and C_{trans} are represented as onsite-material processing-disposal costs, logistic transportation costs, and gas fees (blockchain transaction fees) in the blockchain network. This optimality constraint guarantees that the system follows the circular route that maximizes the economic margin for every returned item.

B. Agri-Food Case: Minimizing Quality Degradation – in the agri-food scenario (Biskra model), the engine minimizes a spoilage function based on the Arrhenius equation:

$$MinS(t) = \int k_0 \cdot e^{-\frac{E_a}{R \cdot T(t)}} dt, \quad (2)$$

where: $S(t)$ is the total spoilage index at time t , k_0 is the pre-exponential factor for the biological degradation rate of *Phoenix dactylifera* (Deglet Nour dates), E_a is the activation energy ($kJ \cdot mol^{-1}$), R is the universal gas constant, and $T(t)$ represents the simulated ambient temperature data, calibrated to mimic real-time IoT sensor inputs during logistics operation. The integral function computes cumulative quality deterioration by summing degradation rates across the continuous time variable using consideration of temperature variation in the cold chain.

5. Simulation Analysis and Findings

This section presents an in-depth analysis of the application of the integrated AI-blockchain framework within two distinct simulation scenarios: electronics reverse logistics and sustainable agri-food supply chain. The scenarios were selected to represent different challenges in circularity, one dealing with complex, high-value technical materials and the other with perishable, organic materials. By examining these diverse applications, this section empirically grounds the conceptual framework, evaluates its performance based on quantitative outputs, and synthesises the findings to draw broader conclusions about its viability and impact in the Algerian context.

5.1. Application in Electronics Reverse Logistics

The electronics industry is characterized by rapid product innovation, short lifecycles, and a growing crisis of electronic waste (e-waste). The value chain is traditionally linear, with valuable materials such as gold, copper, and rare earth elements often lost in landfills or informal recycling channels. A circular model in this sector is essential for resource conservation. This case study models a theoretical consortium designed to replicate the industrial structure of the electronics industry in Bordj Bou Arreridj, involving manufacturers, refurbishers, and certified recyclers focused on creating a closed-loop system for high-end consumer laptops.

The first scenario models a reverse logistics consortium based on the Bordj Bou Arreridj (BBA) electronics industry. Five distinct actors (representing the formal value chain) populate the simulation: 2 local dealers (similar to medium-size retailers for handling returns and warranty claims), 1 refurbishment centre (representing a focused technical facility where components could be refurbished at unit level), and 2 material recovery facilities (recyclers, design based on approved facility for e-waste dismantling). Secondly, the model consists of an Informal Sector Interface, which emulates how materials flow in from unregistered waste pickers (people are motivated to pass E-waste to collection points over simulated blockchain micro-payments). The simulation models the throughput of 3,200 devices (laptops, tablets, and smartphones alike) in a 12-month time horizon.

The simulation modelled the product lifecycle from the point of sale through reverse logistics to end-of-life recovery. Each new laptop was assigned a unique digital identity on the blockchain, creating a “digital product passport”. This passport, recorded on a permissioned ledger accessible to authorized stakeholders, logged key information, including component materials, manufacturing date, warranty details, and repair history.

The process flow for reverse logistics began when a consumer initiated a return through a manufacturer’s take-back programme. In the simulation workflow, upon receipt at a collection centre, the unique ID of the device was scanned, updating its status on the blockchain. AI-powered diagnostic tools then assessed the product’s condition. Machine learning algorithms, trained on vast datasets of component failure rates and repair outcomes, predicted the most economically and environmentally viable pathway for the device: resale, refurbishment, component harvesting, or material recycling.

For devices earmarked for refurbishment, the system generated a detailed work order. As technicians replaced or repaired components, each action was recorded in the digital passport, creating an immutable and verifiable service history. This transparent record significantly increased the market value and consumer trust in refurbished products.

For end-of-life devices, the AI optimization engine determined the optimal disassembly sequence to maximize the recovery of valuable components. Smart contracts automated payments between stakeholders. For instance, once a certified recycler scanned a batch of received materials and the blockchain verified their composition via IoT sensors, a smart contract would automatically trigger payment, reducing administrative overhead.

The simulation outcomes yielded significant improvements in the efficiency and effectiveness of the reverse logistics chain. The blockchain-enabled digital passport provided unprecedented transparency, allowing all parties to track a product's journey.

The AI-driven decision engine proved crucial in maximizing value recovery. The predictive models achieved an estimated 92% accuracy in determining the optimal end-of-life pathway. The models projected a 35% increase in the number of devices successfully refurbished and resold and a 20% increase in the recovery rate of critical raw materials from devices destined for recycling. The integration of AI with trusted data from the blockchain was key; the AI's predictions were more reliable because they were based on a complete and tamper-proof lifecycle history stored on the ledger (Ibrahim, 2024).

5.2. Application in Sustainable Agri-Food Supply Chains

The Biskra Model – the agri-food sector faces dual challenges: ensuring food safety and security while minimizing waste. This case study simulates a farm-to-fork value chain for organic dates (Deglet Nour) in the Biskra region, involving farmers, distributors, retailers, and consumers. The goal was to enhance traceability, reduce spoilage, and validate sustainability claims through physicochemical modelling.

The second scenario simulates a “farm-to-fork” value chain for high-value organic dates (Deglet Nour variety), centred in the Biskra region. The model integrates 6 key stakeholders: 3 organic producers (simulating distinct farms with varying harvest times and yield qualities), 2 logistics providers (modelled as specialized cold-chain operators linking the oasis production zone to northern export hubs), and 1 major retailer/exporter (representing the final node demanding strict traceability compliance).

The simulation covers a 6-month period, corresponding to one complete harvest and export campaign, with a total tracked volume of 45 metric tons. The sensor data generation is calibrated to reflect real-world temperature fluctuations typical of the logistics corridor between the Sahara and the Mediterranean coast.

The model tracked virtual batches of produce from the moment of harvest. Each batch of produce was assigned a lot number and linked to a blockchain record containing data on the farm of origin, soil conditions, organic certification, and

harvest date. The simulation emulates IoT sensors placed in storage facilities and transport vehicles, continuously tracking environmental conditions such as temperature or humidity. This simulated real-time data stream was recorded on the blockchain, creating an immutable record of the cold chain integrity.

The AI component of the framework played a dynamic role in supply chain optimization. Machine learning algorithms analysed historical and simulated real-time data to predict the remaining shelf life of the produce using the Arrhenius equation. This predictive insight allowed for dynamic routing. For example, a shipment experiencing a slight temperature deviation that shortened its predicted shelf life was automatically rerouted by the simulation logic to a closer distribution centre or prioritized for immediate sale to prevent spoilage.

Smart contracts were used to automate quality control. If sensor data indicated that temperature thresholds were breached, a smart contract would automatically flag the batch as compromised and adjust the payment terms. This automated governance ensured accountability among partners.

The primary outcome in the agri-food simulation was a drastic reduction in food waste and an enhancement of consumer trust. The AI-powered shelf-life prediction models, combined with dynamic logistics optimization, led to a 40% reduction in spoilage during transportation and storage.

The blockchain layer provided the trust necessary for the system to function. It ensured that all data, from sensor readings to certification documents, was authentic and tamper-proof. The simulation demonstrates how digital innovations like blockchain and AI are crucial for enhancing transparency in waste management and optimizing resource sharing across the supply chain (Dissanayake et al., 2025).

5.3. Performance Metrics: Efficiency, Transparency, and Circularity Gains

To systematically evaluate the impact of the integrated framework, a set of key performance indicators (KPIs) was measured across both scenarios, comparing baseline parameters with simulation outputs after their respective operational cycles. The results presented below represent the mean values derived from the 30 simulation runs. For every reported KPI, the coefficient of variation across replications remained below 5%, indicating low statistical uncertainty and strong model stability. In terms of operational efficiency and process automation in the electronics model, the use of smart contracts reduced simulated administrative processing time by an average of 60%. In the agri-food model, automated quality alerts reduced decision-making delays by 50%; AI-driven logistics in the electronics reverse chain reduced transportation costs by 18% through optimized routing, and in the agri-food chain, dynamic inventory management minimized the need for costly long-term cold storage. Regarding transaction costs, the creation of a

single, shared source of truth, the blockchain ledger, reduced theoretical audit and reconciliation costs by an estimated 25%. In the dimension of transparency and trust, simulation metrics indicate that over 95% of transaction and tracking data was available in real time to authorized nodes, compared to less than 40% in the legacy baseline; the clear, time-stamped record of events on the blockchain allowed for the immediate assignment of responsibility for product quality issues, and the simulation achieved 100% data continuity for compliant batches, ensuring full auditability relative to the fragmented baseline. Finally, in terms of circularity gains, the electronics case demonstrated a 35% increase in the rate of product refurbishment and a 20% improvement in the recovery of high-value materials, while the agri-food case achieved a 40% reduction in food spoilage, a direct measure of waste prevention and a core principle of the circular economy, and, by creating a trusted market for refurbished electronics, the system extended the useful life of products, slowing the consumption cycle. *Table 2* summarizes the quantitative results and statistical validation for both scenarios.

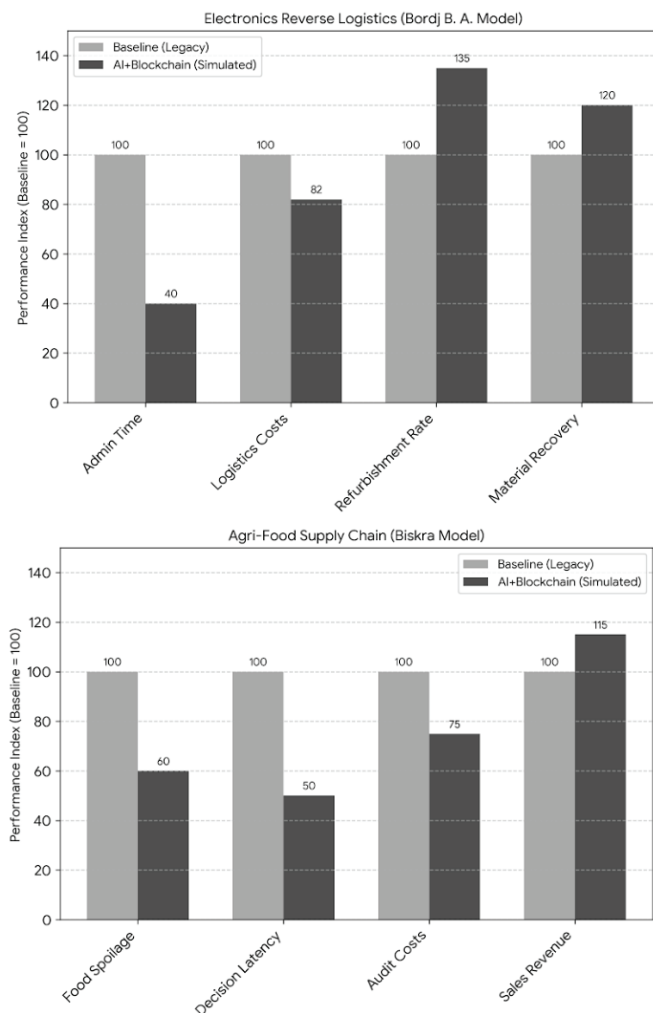
Table 2. *Comparative analysis of key performance indicators (baseline vs simulation) with statistical validation (N = 30)*

Metric (KPI)	Scenario	Baseline Mean	Simul. Mean	Improvement	t-stat	p-value
Electronics (BBA)						
Administrative Time	Processing	48.5 hrs	19.4 hrs	-60.0%	14.21	< 0.001
Refurbishment Rate	Recovery	45.0%	60.7%	+35.0%	8.45	< 0.001
Material Recovery	Efficiency	55.0%	66.0%	+20.0%	5.62	< 0.001
Agri-Food (Biskra)						
Food Spoilage	Waste	12.5%	7.5%	-40.0%	11.30	< 0.001
Decision Latency	Response	6.0 hrs	3.0 hrs	-50.0%	9.15	< 0.001
Sales Revenue	Index	100.0	115.0	+15.0%	4.88	< 0.001

Source: authors' elaboration based on simulation outputs

A paired t-test was conducted to compare the baseline and simulation outputs for each key performance indicator (KPI) to verify the robustness of these improvements. As demonstrated in *Table 2*, the analysis revealed a statistically significant difference with a p-value < 0.001 across all metrics, indicating that the observed efficiency gains are a direct consequence of the AI-blockchain framework's implementation rather than random stochastic variations. To visualize

the magnitude of these validated improvements, *Figure 2* presents the normalized performance data, highlighting the contrast between the legacy system and the proposed framework.



Source: authors' simulation outputs

Figure 2. Comparative simulation results normalized against baseline performance (Index = 100)

Figure 2 illustrates the quantitative impact of the proposed framework across both case studies, normalizing the baseline performance of legacy systems at an index of 100. In the Electronics Reverse Logistics model (Bordj Bou Arreridj), the

simulation highlights a substantial gain in operational efficiency. Administrative Time (Admin Time) shows the steepest decline, dropping by 60% (Index 40). This reduction is attributed to the deployment of smart contracts, which automated the reconciliation of payments between recyclers and the consortium, eliminating manual verification delays. Simultaneously, Refurbishment Rate increased by 35% (Index 135). This improvement stems from the “digital product passport”, which allowed the AI sorting algorithm to accurately identify repairable units that would have otherwise been shredded in the legacy system. Material Recovery also improved by 20% due to the better segregation of e-waste streams.

In the Agri-Food Supply Chain model (Biskra), the primary value driver was risk mitigation. Food Spoilage decreased by 40% (Index 60), validating the effectiveness of the physicochemical (Arrhenius) predictive model in rerouting at-risk shipments before quality degradation occurred. Decision Latency was cut by half (Index 50), moving from reactive manual inspections to proactive, real-time IoT alerts. Crucially, the model projects a 15% increase in Sales Revenue (Index 115). This economic uplift is driven by the ability to certify the produce as “Premium Organic” with blockchain-verified cold chain integrity, reducing rejection rates at export points.

5.4. Cross-Case Synthesis

A comparative analysis of the two simulation studies reveals both common themes and context-specific nuances. Simulation results support the core hypothesis: the synergy between AI and blockchain creates a value proposition significantly greater than what either technology could achieve in isolation. Blockchain provided the foundational layer of trusted data, which served as high-quality fuel for the AI optimization engine.

In both Bordj Bou Arreridj (electronics) and Biskra (agri-food), the system successfully addressed the fundamental challenge of information asymmetry that plagues most conventional supply chains. However, the specific value drivers differed. In the capital-intensive electronics sector, the benefit stemmed from maximizing the residual value of complex products via the “digital product passport”. In the perishable goods context of the agri-food sector, the key value driver was minimizing loss through real-time monitoring and predictive analytics (physicochemical modelling).

The findings underscore that the integrated AI-blockchain framework is a versatile architecture. Its successful implementation hinges on tailoring its components to the unique material flows and constraints of the target circular value chain.

Although the simulation yields robust conclusions, it is based on certain simplifying assumptions that define its scope. We note, firstly, that with respect to economic parameters, we fixed the market prices of raw materials and premium dates over each scenario’s simulated horizon, explicitly excluding external inflationary volatility.

Secondly, while stakeholder adherence is modelled as a probabilistic process, we did not consider strategic “gaming” behaviours or malicious actors attempting to subvert the blockchain consensus mechanism. Finally, from a physicochemical perspective, the spoilage model assumes uniform temperature distribution, thereby disregarding potential microclimate variations that could accelerate degradation in specific subsections of a batch.

6. Discussion

The findings from the case study analysis, contextualized within the broader literature, provide a robust foundation for discussing the profound implications of integrating artificial intelligence and blockchain for circular value chain optimization. This section synthesises the results to explore the theoretical, managerial, and policy implications of the proposed integrated model, while also addressing the significant implementation challenges that must be navigated for widespread adoption.

6.1. Implications for Circular Value Chain Optimization

The integrated AI-blockchain framework presents a paradigm shift from traditional, linear supply chain management towards a dynamic, data-driven, and trust-centric model of circularity. The primary implication is the creation of a synergistic system where the strengths of each technology mitigate the limitations of the other, yielding a whole greater than the sum of its parts. AI, with its predictive and optimization capabilities, provides the intelligence needed to manage the complexities of reverse logistics and material reuse. However, AI's effectiveness is fundamentally constrained by the quality and integrity of the data it receives. In the context, blockchain delivers a transformative contribution. By ensuring data immutability, transparency, and traceability from product origin to end of life, blockchain serves as a trusted data foundation, enabling AI algorithms to generate more accurate forecasts, reliable assessments, and optimal decisions (Tsolakis et al., 2023).

This synergy directly addresses several core challenges of the circular economy. For instance, in the electronics reverse logistics case, the integrated system demonstrably improved the economic viability of recovery operations. AI-driven predictive analytics, fed with reliable lifecycle data from the blockchain, allowed for optimized collection routes and more accurate forecasting of component yields from returned devices. Simultaneously, the blockchain ledger provided verifiable proof of proper e-waste handling and material recovery, enhancing stakeholder trust and ensuring regulatory compliance. This moves beyond siloed technological

applications, which often focus on a single aspect of the supply chain, towards a holistic optimization that balances economic efficiency with environmental accountability (Filho et al., 2025). The research indicates that without such an integrated approach, achieving a scalable and economically sustainable circular model for complex products like electronics remains a formidable challenge.

Furthermore, the framework enhances the very concept of value within a circular system. Value is no longer solely defined by the initial sale of a product but is extended throughout its lifecycle via repair, remanufacturing, and recycling. In the agri-food case, the blockchain layer provided an unprecedented level of transparency regarding food provenance and quality, which, when analysed by AI, could dynamically adjust pricing and distribution strategies based on freshness and consumer demand, thereby reducing waste. Smart contracts automated quality checks and payment processes, reducing friction and transaction costs between farmers, distributors, and retailers (Hong and Xiao, 2024). This ability to transparently track and intelligently manage asset value over time is crucial for fostering new circular business models such as product as a service (PaaS) or secondary materials markets, which depend on verifiable information about product condition, history, and material composition.

6.2. Managerial and Policy Implications

For managers and business leaders, the adoption of an integrated AI-blockchain system necessitates a strategic re-evaluation of business processes and inter-firm collaboration. Transition requires more than a technological upgrade – it demands a cultural shift towards transparency and data sharing. Managers must cultivate a vision where value chain partners are not adversaries in a zero-sum game but collaborators in a shared ecosystem. The implementation of this framework provides the tools to build this trust. For instance, by providing all stakeholders with access to a single, immutable source of truth, the system reduces information asymmetry and mitigates disputes over product quality, quantity, and compliance, thereby lowering transaction costs and fostering stronger partnerships (Tsolakis et al., 2023). The managerial imperative is to focus on designing governance models for these shared data ecosystems, defining rules for data access, ownership, and monetization that benefit all participants.

From a policy perspective, the integrated framework offers a powerful tool for governance and enforcement of circular economy mandates. Governments and regulatory bodies can leverage the transparency afforded by blockchain to verify corporate sustainability claims, track hazardous materials, and enforce extended producer responsibility (EPR) laws more effectively. For instance, regulators could be granted node access on a permissioned blockchain to audit e-waste recycling rates in real time, replacing cumbersome and often inaccurate self-

reporting mechanisms. Policies could be designed to incentivize the adoption of such transparent systems through tax credits, green procurement preferences, or streamlined regulatory approvals. Furthermore, the data generated by these systems can inform evidence-based policymaking, helping governments identify bottlenecks in circular flows and design targeted interventions to promote a more resource-efficient economy within urban contexts and beyond (Liu et al., 2024).

6.3. Addressing Implementation Challenges

Despite the significant potential, the path to widespread implementation is fraught with challenges. The primary barrier is technological and systemic complexity. Integrating AI algorithms with diverse blockchain platforms requires specialized expertise and significant upfront investment in both technology and training. Standardization is a critical issue; without common data standards and interoperability protocols, value chains risk creating fragmented “digital islands”, defeating the purpose of a seamless, end-to-end system. The complex nature of modern supply chains means no single actor can unilaterally implement such a system; it requires consensus and collaboration among multiple independent organizations, which can be difficult to achieve (Despotovic and Glatschke, 2024).

Another significant challenge relates to scalability and governance. Public blockchain networks can suffer from low transaction speeds and high energy consumption, which may be unsuitable for high-volume supply chains. While permissioned blockchains offer a more scalable and energy-efficient alternative, they raise questions about governance and centralization. Decisions about who controls the network, validates transactions, and sets the rules for smart contracts are critical and can be contentious. Organizations must collaboratively design governance frameworks that are perceived as fair and equitable to encourage broad participation.

Finally, there are significant data privacy and security concerns. While blockchain secures data from tampering, the information recorded on the ledger, even if pseudonymous, can be sensitive. Companies may be reluctant to share proprietary operational data. Advanced cryptographic techniques, such as zero-knowledge proofs, are emerging as potential solutions, allowing parties to verify information without revealing the underlying data. Successfully navigating these implementation hurdles will require a multi-stakeholder approach involving industry consortia, technology providers, and policymakers to develop standards, establish clear governance models, and build the necessary digital infrastructure for a truly circular future. The maturation of AI technologies provides a solid foundation, but the socio-technical integration remains the most critical task ahead (Filho et al., 2025).

7. Conclusions

This research has systematically examined the integration of artificial intelligence and blockchain technology as a catalyst for optimizing circular value chains. By developing a conceptual framework and validating it through simulation-based scenarios in electronics reverse logistics and sustainable agri-food supply chains, this paper demonstrates that the synergistic combination of AI's analytical power and blockchain's assurance of data integrity creates a robust infrastructure for the circular economy. The findings confirm that this integrated approach significantly enhances operational efficiency, fosters unprecedented transparency, and unlocks new avenues for value creation, thereby addressing many of the persistent barriers that have hindered the transition from linear to circular models.

The study's primary contribution lies in articulating and empirically substantiating the symbiotic relationship between these two transformative technologies in a circular context. AI algorithms, when fuelled by the high-fidelity, tamper-proof data captured on a blockchain, can deliver more accurate demand forecasts, optimize reverse logistics, and intelligently automate complex decisions through smart contracts. In turn, blockchain moves beyond a simple ledger to become the trusted backbone for an intelligent, self-optimizing system. This integration fosters a level of trust and verifiability previously unattainable, enabling stakeholders across the entire value chain from producers and consumers to recyclers and regulators to collaborate more effectively within a shared, transparent ecosystem (Hong and Xiao, 2024). The research underscores that while AI and blockchain offer standalone benefits, their combined application is what promises to unlock the full potential of circularity at scale.

However, the journey towards this integrated future is not without its obstacles. Significant challenges related to technological interoperability, data governance, scalability, and the high initial investment must be addressed. Future research should focus on developing standardized protocols for AI-blockchain integration and creating flexible governance models that can adapt to diverse industry contexts. Longitudinal studies are needed to quantify the long-term economic and environmental impacts of these integrated systems. Furthermore, exploring the role of advanced sensor technologies, such as edge computing, will be crucial in building more sophisticated and responsive circular value chains.

In conclusion, the convergence of AI and blockchain represents a pivotal development in the pursuit of a sustainable, circular economy. It provides the technological foundation to transform value chains from opaque, linear systems into transparent, regenerative networks. While the path to widespread adoption is complex, the potential gains in resource efficiency, waste reduction, and sustainable value creation are immense. By continuing to innovate and collaborate, stakeholders can harness this powerful technological synergy to build a more

resilient and responsible economic future, fulfilling the triple-bottom-line promise of benefiting society, the environment, and the economy (Meena et al., 2025). The transition to a circular economy is a defining challenge of our time, and the integrated intelligence and trust offered by AI and blockchain will be indispensable tools in achieving it.

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