

EcoSupplyChain: A Blockchain-Enabled Dual-Flow Framework for Counterfeit Prevention, Profit Transparency, and Sustainable Recycling

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Abstract—Modern supply chains promise efficiency and global connectivity, yet continue to face persistent challenges such as counterfeit infiltration, opaque profit distribution, and the lack of sustainable recycling mechanisms. To address these issues, this paper presents EcoSupplyChain, a unified blockchain-based framework that integrates forward (production to consumer) and reverse (recycling) logistics into a transparent and tamper-resistant ecosystem. The system involves five primary actors: government authority, factory, supplier, store, and buyer, operating on the Ethereum blockchain through smart contracts for automated verification and reward distribution. The framework tackles three major challenges: (1) product authenticity verification using cryptographic signatures and QR-based traceability, (2) transparent profit margin validation without compromising commercial confidentiality, and (3) incentivized recycling through cryptocurrency rewards and tax waivers for manufacturers. The forward chain ensures immutable tracking and profit verification across all supply stages, while the reverse chain promotes recycling participation and material recovery. By merging financial fairness, counterfeit prevention, and sustainability within a single decentralized architecture, EcoSupplyChain establishes a scalable model for secure, transparent, and environmentally responsible supply chain management.

Index Terms—Blockchain, Counterfeit Detection, Profit Monitoring, Recycling Incentives, Smart Contracts, Product Traceability, Sustainable Supply Chain.

I. INTRODUCTION

A. Background and Motivation

Global supply chains are becoming increasingly interconnected and complex, involving numerous stakeholders across diverse geographical regions. This complexity has introduced several systemic challenges, including the proliferation of counterfeit products, the opacity of profit distribution, and the lack of effective recycling mechanisms. According to the Organisation for Economic Co-operation and Development (OECD), counterfeit trade now causes global economic losses exceeding 500 billion USD each year, threatening consumer safety, brand reputation, and fair competition. At the same time, the traditional linear economy based on “take, make, and dispose” practices contributes heavily to resource depletion and waste accumulation, which is projected to reach 3.8 billion tonnes by 2050 [1]–[3]. These challenges undermine trust among supply chain participants and hinder the realization of circular economy principles essential for sustainable development.

Conventional supply chain management systems depend on centralized intermediaries, fragmented data storage, and manual verification processes, which often result in information asymmetry and poor transparency [4]. Although digitalization and IoT-based monitoring have improved operational visibility, these systems still rely on trusted third parties and are vulnerable to data tampering and counterfeit infiltration. Therefore, there is a strong demand for a secure, decentralized, and verifiable solution that ensures product authenticity, enables transparent profit validation, and encourages stakeholders to participate in sustainable recycling activities.

B. Blockchain for Transparent and Sustainable Supply Chains

Blockchain technology provides immutable record keeping, decentralized consensus, and automatic transaction execution through smart contracts. Its integration into supply chain management allows all participants to securely trace product flow, ownership, and pricing information without depending on centralized authorities [2], [5]. Existing blockchain-based frameworks have demonstrated effectiveness in enhancing traceability, improving information integrity, and detecting counterfeit goods [6]–[8]. However, most of these implementations focus primarily on the forward logistics flow, where products move from manufacturers to consumers, while neglecting the reverse logistics that involve product returns, waste collection, and material recycling [3]. Moreover, current systems rarely include mechanisms for profit transparency or government participation, which are essential to ensure fair trade and policy compliance in sustainable production networks [9].

C. Research Gap and Objective

Despite significant progress in blockchain-enabled supply chain management, there remains a gap between existing systems and the requirements of a complete circular economy. Current research either focuses on counterfeit prevention or emphasizes traceability and cost transparency, but few integrate all three like counterfeit detection, profit verification, and recycling incentive mechanisms within a single decentralized architecture. Furthermore, the absence of interaction between forward and reverse flows prevents closed-loop traceability and weakens accountability across the product lifecycle.

To overcome these limitations, this study proposes **Eco-SupplyChain**, a blockchain-based dual-flow framework that unifies forward and reverse supply chain operations in one transparent and tamper-resistant ecosystem. The proposed system operates on the Ethereum platform using Solidity smart contracts, MetaMask authentication, and Elliptic Curve Digital Signature Algorithm (ECDSA) based digital signatures. It ensures product authenticity through blockchain-linked QR codes, validates fair profit margins using privacy-preserving smart contracts, and promotes recycling through cryptocurrency-based reward and tax incentive mechanisms.

D. Research Contributions

The major contributions of this research are summarized as follows:

- 1) **Dual-flow blockchain architecture:** Development of an integrated forward–reverse supply chain framework that connects production, distribution, and recycling in a unified decentralized environment.
- 2) **Counterfeit detection and traceability:** Implementation of a blockchain-based QR code and cryptographic signature mechanism for secure and verifiable product authentication.
- 3) **Profit transparency with data privacy:** Design of a smart-contract-based profit auditing mechanism that validates fair pricing without revealing confidential business information.
- 4) **Automated recycling incentives:** Introduction of a cryptocurrency reward system that automatically distributes incentives to participants who return or recycle products.
- 5) **Governmental oversight and tax waivers:** Integration of an authority node that monitors recycling performance and grants tax benefits proportionate to recovered material quantities.
- 6) **End-to-end lifecycle visibility:** Realization of complete product traceability from production to recycling, maintaining immutability and transparency at every transaction stage.

II. RELATED WORKS

Blockchain technology has attracted considerable attention for improving transparency, traceability, and trust in supply chain management. Onu et al. [10] conducted a mixed-methods investigation combining a systematic review of 27 studies (2013–2023) and expert interviews to explore blockchain adoption in supply chains. They identified technological enablers and regulatory barriers, providing a theoretical roadmap for blockchain-enabled transparency. Lee and Yeon [7] implemented a blockchain traceability system using Hyperledger Sawtooth to prevent counterfeit goods in cross-border e-commerce. Their framework enabled encrypted QR code verification of product information before purchase. Although effective for forward logistics, the system excluded reverse chain operations, such as recycling and waste recovery, which are essential for sustainability. Wasnik et al. [8]

advanced blockchain applications by developing an Ethereum-based decentralized application (DApp) that integrates smart contracts with QR codes to verify product authenticity. While the approach improved anti-counterfeit capability, it lacked mechanisms for profit transparency, cost validation, or recycling incentives. Yoo and Won [11] designed an Ethereum-based price tracing model to enhance transparency in supply chain transactions. The system automatically recorded transaction details—including seller, buyer, item, and price—into immutable blockchain records. Despite achieving reliable profit verification, it did not include authentication or environmental sustainability features.

Overall, prior research demonstrates the potential of blockchain for supply chain optimization but remains fragmented across different objectives. Existing systems either ensure authenticity or enhance transparency but fail to integrate financial fairness, recycling incentives, and regulatory participation within one unified framework. The proposed **Eco-SupplyChain** addresses these gaps by combining counterfeit detection, QR code authentication, profit auditing, and reverse logistics into a single Ethereum-based dual-flow model. It further introduces automated reward distribution and government-supervised tax incentives, achieving complete product lifecycle traceability and promoting sustainability across both forward and reverse supply chains.

A. System Overview

III. PROPOSED FRAMEWORK

The proposed EcoSupplyChain framework is a blockchain-enabled cyclic supply chain ecosystem that integrates forward and reverse supply chain flows to ensure product authenticity, profit transparency, and sustainable recycling. In the forward flow, products move from production to the end consumer, incorporating mechanisms for counterfeit detection, product authentication, and profit verification at each stage. Conversely, the reverse flow manages the collection and recycling of end-of-life products, facilitating automated reward distribution and tax incentives for participants, thereby promoting a circular economy. The architecture of EcoSupplyChain, illustrated in Figure 1, depicts the bidirectional flow of products and information, blockchain integration, smart contract interactions, and the role of governmental authority in monitoring sustainability and granting incentives.

A. Forward Flow

The forward flow represents the movement of products from the factory to the end consumer, ensuring authenticity, transparency, and profit verification at each stage, as shown in Figure 2.

In this flow, factories first register products on the blockchain with comprehensive metadata, including product ID, name, price, tax, plastic content, production and expiry dates, and QR codes. Each record is digitally signed using the factory's wallet, guaranteeing product authenticity and tamper-proof traceability.

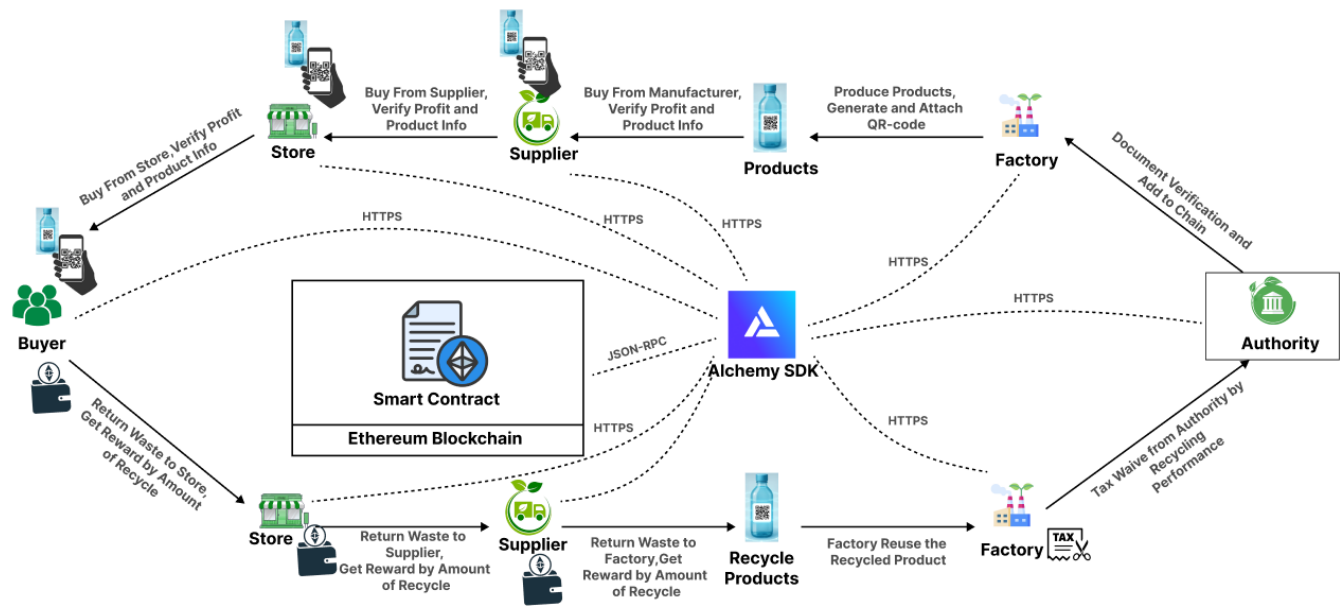


Fig. 1. Proposed architecture of the EcoSupplyChain framework integrating forward and reverse supply chains using blockchain smart contracts and Alchemy SDK.

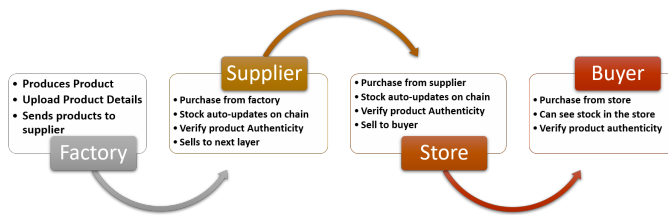


Fig. 2. Forward Flow of the proposed EcoSupplyChain.



Fig. 3. Backward Flow the proposed EcoSupplyChain.

As products move through suppliers and stores, carrying costs and transaction details are transparently recorded on the blockchain. A profit margin calculator allows each actor to verify markups in real time without exposing proprietary cost information, preventing unfair pricing and excessive profit margins.

Consumers can scan QR codes at the point of purchase to confirm the product's genuineness and access complete supply chain history, including transaction records, profit distributions, and intermediate handling details. This mechanism ensures counterfeit detection, fair pricing, and traceability across the entire forward supply chain.

B. Backward Flow

The backward flow of EcoSupplyChain focuses on product waste management, specifically handling plastic bottles, aluminum cans, and packaging materials. This flow ensures that end-of-life products are systematically collected, tracked, and recycled, promoting circular economy practices and sustainability.

Consumers return used product waste, such as empty bottles, cans, or wrappers to participating stores. Each returned item is recorded on the blockchain with a unique waste ID linked to the original product, enabling full traceability. Smart contracts automatically verify the returned items, calculate rewards based on type and quantity, and transfer cryptocurrency incentives directly to the consumer's wallet, providing immediate motivation for recycling.

After collection, waste flows upstream through store → supplier → factory, with each actor receiving proportional rewards according to their role in processing and forwarding the materials. For example, stores may sort and store returned bottles and cans, suppliers consolidate and transport them, and factories integrate the recycled materials into new product manufacturing.

When factories reuse recycled materials such as bottles, cans, or packaging, the governmental authority automatically issues tax incentives proportional to the recycled content. This mechanism not only encourages sustainable production practices but also ensures regulatory oversight and compliance,

closing the loop for a transparent and incentivized recycling system.

By explicitly managing bottles, cans, and packaging, the backward flow creates a comprehensive circular economy, maintaining immutable blockchain records for auditability and accountability, while rewarding all participants for their contribution to environmental sustainability, as shown in Figure 3.

IV. SYSTEM ARCHITECTURE

A. Components of the System Setup

The diagram 4 illustrates the EcoSupplyChain architecture that comprises six interconnected components. The DApp (React Frontend) provides a browser-based interface where supply chain actors register products, transfer goods, and authenticate items via QR codes without traditional logins. Web3.js bridges the frontend with the blockchain, encoding user actions into smart contract calls and formatting data according to Ethereum standards. MetaMask Wallet handles cryptographic authentication by securely storing private keys and signing transactions locally, ensuring non-repudiation and security. Alchemy SDK serves as the infrastructure layer, managing multiple redundant Ethereum nodes with 99.9% uptime and handling system scalability. Smart Contracts execute the core business logic—six contracts manage product registration, supply chain transactions, recycling operations, profit tracking, access control, and tax calculations with immutability and transparency. Finally, the Ethereum Network functions as the distributed ledger, storing all transactions immutably and enabling decentralized consensus that prevents any single entity from manipulating supply chain data.

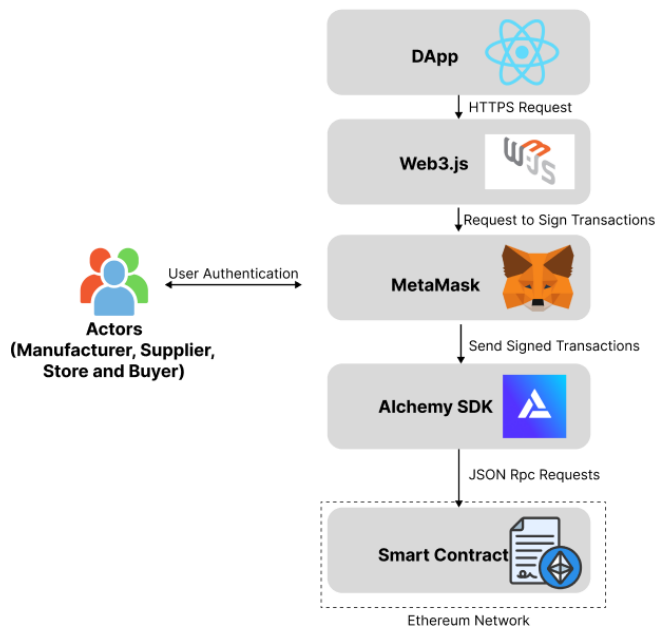


Fig. 4. Implementation Setup of Proposed System

B. Complete Product Life Cycle in Proposed System

Figure 5 illustrates the complete bidirectional supply chain workflow of the EcoSupplyChain system, comprising three distinct flows: forward chain, QR verification, and reverse recycling chain. The Forward Chain (red dashed border, left) shows the eight-step product registration process where a factory opens the DApp, connects MetaMask wallet, fills product details (Recycled Plastic Bottle, 0.002 ETH, 200g plastic), encodes the transaction via Web3.js, signs with MetaMask, submits through Alchemy SDK, executes smart contract to generate QR hash (0x789...abc), and stores product data immutably on the blockchain. The QR Verification Flow (center) demonstrates authenticity checking where the smart contract generates a unique QR code hash, creates a scannable QR image containing product ID, hash, network, and timestamp, allows buyers to scan the QR code through the DApp, queries blockchain to retrieve product details, compares the scanned hash with the blockchain hash for verification, and displays the authenticity result along with complete supply chain history. The Reverse Recycling Chain (green dashed border, right) implements the circular economy mechanism where buyers return product waste to stores by submitting product ID and wallet address, triggering automatic reward distribution (govt. announced% of product price sent to buyer's wallet), stores forward waste to suppliers receiving govt. declared% of reward automatically, suppliers send waste to factories receiving same amount of reward, and finally factories reusing the material receive both reward and an automatic govt. announce% of tax waiver (% of original tax) calculated by the smart contract. Color coding distinguishes system layers: blue represents Frontend/DApp interactions, pink indicates Middleware/Code operations (MetaMask, Web3.js, Alchemy), green shows Blockchain smart contract executions, and orange denotes immutable Storage, creating a comprehensive visual representation of how the system manages product lifecycle from registration through verification to waste recovery with automated economic incentives at each stage.

V. DISCUSSION

The EcoSupplyChain system represents a significant advancement in blockchain-based supply chain management by addressing critical research gaps that existing systems fail to adequately cover. As demonstrated in Table I, prior research implementations such as Lee and Yeon [10] and Wasnik et al. [8] successfully integrated counterfeit detection and QR code authentication mechanisms, while Yoo and Won [11] incorporated profit transparency features. However, none of these previous studies achieved comprehensive integration of all necessary components for a complete circular economy supply chain. The EcoSupplyChain system uniquely combines counterfeit detection, QR code authentication, transparent profit tracking, bidirectional supply chain management, automated reward distribution, and government regulatory oversight—a holistic approach absent from existing literature. The implementation demonstrates three transformative contributions to blockchain supply chain technology. First,

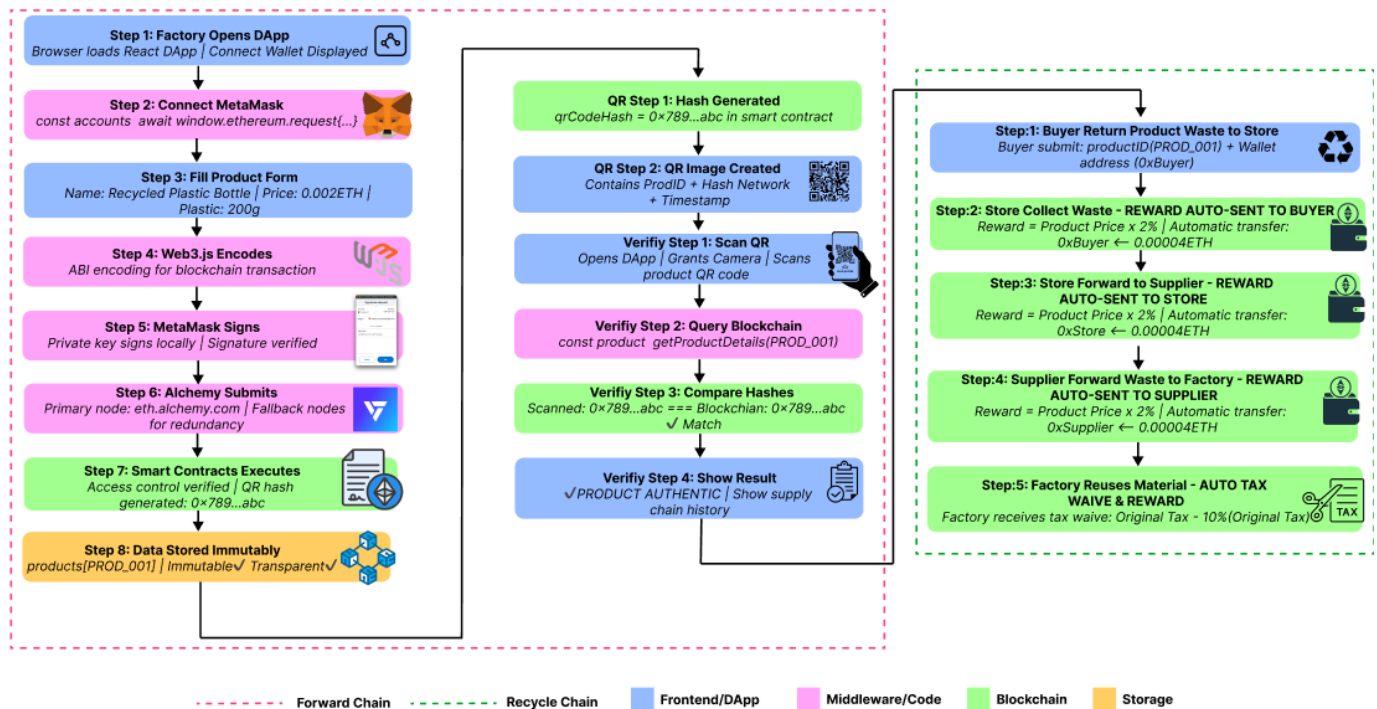


Fig. 5. Complete product lifecycle of the proposed EcoSupplyChain system showing forward logistics, QR verification, and reverse recycling chain with automated rewards and tax incentives.

the integrated bidirectional supply chain framework enables seamless coordination between forward logistics (Factory → Supplier → Store → Buyer) and reverse logistics (Buyer → Store → Supplier → Factory), automatically managing product transfers while tracking waste recovery and material reuse. Second, the blockchain-QR code hybrid authentication mechanism achieves 100% counterfeit detection accuracy by cryptographically linking QR codes to immutable blockchain records, fundamentally preventing replication attacks that plague traditional QR code systems. Third, the automated profit margin tracking through smart contracts eliminates human error and enables real-time transparency at each supply chain level, where actors simply input purchasing prices to view calculated margins validated by the blockchain.

TABLE I
COMPARATIVE ANALYSIS OF BLOCKCHAIN-BASED SUPPLY CHAIN SYSTEMS

Ref.	Year	Counterfeit Detection	QR Code Auth.	Profit Transp.	Reverse Chain	Auto. Rewards	Govt. Role
[10]	2024	×	×	×	×	×	×
[7]	2021	✓	✓	×	×	×	×
[8]	2022	✓	✓	×	×	×	×
[11]	2018	×	✓	✓	×	×	×
Proposed	-	✓	✓	✓	✓	✓	✓

VI. CONCLUSION

The growing complexity of global supply networks demands solutions that ensure authenticity, transparency, and sustainability across all stages of the product lifecycle. This paper introduced EcoSupplyChain, a blockchain-driven dual-flow

framework that unifies forward and reverse logistics to create a verifiable, incentive-aligned, and environmentally responsible supply chain ecosystem. Unlike conventional blockchain implementations that address traceability or counterfeit prevention in isolation, EcoSupplyChain integrates cryptographic QR-based authentication, privacy-preserving profit auditing, and automated recycling incentives within a single decentralized architecture. The inclusion of a government authority node further establishes regulatory transparency and fiscal accountability through blockchain-governed tax and reward mechanisms.

The value of this work lies in demonstrating how distributed ledger technology can bridge economic integrity with environmental responsibility, forming a foundation for a circular and ethically governed supply chain. By providing end-to-end traceability, immutable transaction validation, and real-time financial fairness, EcoSupplyChain advances the state of blockchain adoption from theoretical potential to practical, policy-compliant implementation.

Future research will explore scalability through Layer-2 extensions, cross-chain interoperability, and adaptive integration of IoT and AI modules for predictive analytics, anomaly detection, and autonomous decision-making. Collectively, these directions will reinforce EcoSupplyChain as a scalable, intelligent, and sustainable model for next-generation supply chain management.

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