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A Novel Recycling Framework for Enchanting the Sustainability in Anti-Greenwashing

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Abstract **- Plastic waste upcycling into useful and high-value products is becoming an important part of the circular economy. Many recycling systems today use IoT and blockchain to track waste collection and transportation, but they still cannot prove whether the final product actually contains recycled plastic from the claimed batch. Because of this gap, companies can make false recycling claims, leading to greenwashing and reduced consumer trust. To address this issue, this paper introduces a** Proof-of-Recycling (PoR) **framework. The system works in two ways. First, it uses IoT sensors to monitor and verify the actual operation of recycling machines by capturing unique multi-sensor activity patterns. Second, it embeds a physical watermark into the recycled plastic so that the final product can be traced back to its original batch, allowing verification even at the consumer level. The proposed system is designed for eco-conscious premium brands such as *Behtar*, which convert plastic waste into high-quality products and want to provide clear proof of sustainability. A cybersecurity layer is also included to protect the system through digitally signed machine data, controlled access, and privacy safeguards, ensuring that the recycling records cannot be tampered with. Overall, the PoR framework helps prevent fraud, supports regulatory compliance, and increases transparency in circular manufacturing. Most importantly, it builds stronger trust between brands and consumers by providing reliable proof that products are genuinely made from recycled materials.**

I. INTRODUCTION

A. Background

Plastic waste continues to be a serious environmental problem worldwide. Traditional waste management systems often face issues such as operational inefficiencies, lack of transparency, and minimal consumer involvement. In response, sustainable brands like Behtar are focusing on upcycling plastic waste into premium lifestyle products, encouraging responsible consumption and promoting circular economy practices.

B. Motivation

Many recent waste management solutions use IoT and blockchain technologies to improve traceability. However, most of these systems only track digital events, such as when waste is collected, transported, or recorded in a database. They do not verify whether the final product actually contains the recycled material that was originally claimed.

C. Problem Statement

Existing recycling traceability systems do not provide a reliable connection between waste collection records and the actual recycled plastic used in the final product. This gap allows several forms of misuse, such as submitting false weight data, performing duplicate scans, mixing virgin plastic with recycled material, and making misleading sustainability claims.

D. Objectives

The objective of this work is to develop a Proof-of-Recycling (PoR) architecture that verifies recycling activities through IoT-based machine attestation, embeds physical watermark-based batch identification into recycled plastic, integrates PoR with RFID/NFC and blockchain for end-to-end traceability, and includes a cybersecurity framework to ensure data integrity, security, and privacy compliance.

E. Contributions

This study introduces Proof-of-Recycling (PoR) as a method that ensures both data authenticity and material authenticity. It achieves this by linking recycling machine operational fingerprints with physically watermarked plastic output, allowing the recycled content to be verified throughout the supply chain and even by consumers.

II. LITERATURE REVIEW

A. IoT in Smart Waste Management

The use of IoT in waste management has significantly improved operational efficiency. Smart bins equipped with fill-level sensors help monitor waste in real time, while GPS-enabled tracking and predictive analytics support optimized collection routes and better resource utilization.

B. Blockchain for Traceability in Recycling

Blockchain technology has been widely proposed to enhance transparency and traceability in recycling supply chains. Its immutable ledger helps maintain tamper-resistant records of waste movement and processing. However, these systems still face the challenge of "garbage-in, garbage-out," meaning that if incorrect or fraudulent data is entered, the blockchain will preserve it without verification.

C. Greenwashing Risk in Traceable Supply Chains

While blockchain-based traceability can reduce doubts about sustainability claims, many existing solutions rely only on

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digital records. Without physical validation of recycled materials, such systems may still allow companies to make misleading environmental claims, increasing the risk of greenwashing.

D. Authentication of Recycled Plastic Content

Scientific methods such as laboratory-based material analysis can distinguish between recycled and virgin plastic. Although accurate, these techniques are expensive, time-consuming, and impractical for large-scale deployment or consumer-level verification.

E. Research Gap

Despite advancements in IoT and blockchain-based traceability, very few solutions provide reliable and fraud-resistant proof that recycling has actually taken place and that the final product contains the specific recycled material recorded in the system.

Table I. Comparison with Existing Research

The comparison demonstrates that the proposed Proof-of-Recycling (PoR) framework goes beyond conventional IoT and blockchain recycling approaches by introducing material-level authenticity and enabling consumer-verifiable proof, thereby strengthening protection against greenwashing.

II. METHODOLOGY

This section details the research methodology used to design, validate, and evaluate the proposed Proof-of-Recycling (PoR) framework. The methodology follows a design-science research approach and includes requirement analysis, system architecture design, prototype implementation, and experimental evaluation.

A. Research Approach

The research follows a Design Science Research (DSR) methodology. This approach is well suited for technology-focused studies where the main goal is to create and validate a new solution. In this work, the PoR framework is treated as a novel system artifact, and its effectiveness is examined through conceptual design, prototype planning, and experimental validation.

B. Requirement Analysis and Gap Identification

An extensive review of existing work in IoT-based recycling, smart waste management, and blockchain traceability was conducted to identify limitations in current solutions. Most existing systems improve visibility in waste collection and transportation but do not verify whether the final product actually contains recycled material. Based on this gap, the key requirements for the PoR framework were defined:

(i) verification of recycling events,
(ii) confirmation of material authenticity,
(iii) resistance to fraud and manipulation,
(iv) scalability for real-world deployment, and
(v) the ability for end-users to verify sustainability claims.

C. Framework Design and Modeling

The PoR system was designed as a multi-layer architecture consisting of five main components:

1. IoT-based attestation layer for monitoring recycling operations
2. Batch tokenization and blockchain logging layer
3. Physical watermarking layer for material identification
4. Consumer verification layer using mobile-based validation
5. Cybersecurity and privacy layer for secure data handling

A threat model was also developed to address potential risks such as duplicate scans, false weight reporting, device tampering, and mixing of virgin plastic with recycled material.

D. Prototype-Level Implementation Plan

A proof-of-concept architecture was proposed using the following modules:

- IoT sensing module: Sensors for vibration (accelerometer), temperature (thermistor/RTD), power consumption, machine speed (RPM), and weight measurement using load cells.
- Edge computing module: A microcontroller or single-board computer (such as ESP32 or Raspberry Pi class devices) to collect sensor data, extract features, and generate secure digital signatures.
- Secure telemetry: Sensor data packets are digitally signed and linked using hash chaining to prevent tampering.
- Blockchain module: Only batch hashes and Recycling Fingerprint (RFp) hashes are stored on-chain, while detailed telemetry data is maintained off-chain to reduce storage overhead.
- Watermarking module: Recycled plastic is embedded with UV-reactive or spectral markers, or micro texture patterns, during the extrusion or molding process.
- Verification module: A mobile application allows users to scan QR/NFC tags and detect the embedded watermark to confirm the PoR claim.

E. Data Collection and Feature Extraction

During each recycling cycle, sensor data is continuously recorded to generate a unique Recycling Fingerprint (RFp). Features are extracted from time-series data, including statistical measures (mean and variance), vibration frequency characteristics using FFT, temperature change patterns, power consumption profiles, and the difference between input and output weight. The RFp is then hashed and digitally signed before being recorded in the system.

F. Experimental Validation and Metrics

The framework is evaluated through controlled experimental scenarios, including simulated fraud conditions. Performance is assessed using metrics such as fraud detection

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rate, false acceptance rate, time required to generate and verify proofs, cost per verified batch, and the success rate of consumer-level verification based on watermark detection accuracy.

III. 5. Comparison Table

Table I compares the proposed Proof-of-Recycling (PoR) approach with commonly published IoT and blockchain-based plastic recycling research.

Feature / Criterion	Smart Bins + IoT Routing	RFID/NFC Tracking	Blockchain Traceability	AI Sorting Systems	This Work: PoR (IoT Attestation + Watermark)
Focus	Waste collection efficiency	Item/product tracking	Tamper-evident records	Sorting accuracy	Fraud-resistant proof that recycling happened + product contains recycled content
Proof of Recycling Event	Indirect	No	Only as logged data	No	Yes (machine telemetry fingerprint + signed logs)
Material Authenticity (recycled content verification)	No	No	No (digital only)	Partial (sorting stage only)	Yes (physical watermark embedded in output plastic)
Greenwashing Resistance	Low	Medium	Medium	Medium	High (consumer-verifiable PoR)
Fraud Detection (replay/forged logs)	Low	Low	Medium	Medium	High (attestation + hash chaining + watermark match)
Consumer Verification	No	Limited	Indirect	No	Yes (QR/NFC + watermark scan)
Cybersecurity Layer	Basic	Basic	Medium	Medium	Strong (secure telemetry + signed RFp + privacy controls)
Novelty	Common	Common	Common	Common	High (adds physical proof + attestation)

System Model and Assumption

A. Stakeholders

The proposed Proof-of-Recycling (PoR) framework involves multiple stakeholders across the circular supply chain. These include households and consumers who generate plastic waste, collection partners responsible for aggregation and transportation, recycling and upcycling facilities where waste is processed, and product manufacturers such as *Behtar* that convert recycled material into finished goods. Additional stakeholders include retail customers who purchase the products and independent auditors or regulatory authorities who verify compliance with sustainability and environmental standards.

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B. Threat Model

The system is designed by considering potential security and fraud risks that may arise within the recycling ecosystem. Possible threats include the creation of fake recycling events, manipulation of weight measurements to exaggerate processed quantities, replay attacks using duplicated RFID or NFC scans, unauthorized access or tampering with IoT devices, submission of falsified batch information, and false claims that products contain recycled material when they do not.

C. Design Requirements

To address these risks, the PoR framework is designed with several key requirements. The system must provide reliable and easy-to-verify proof of recycling, ensure strong protection against data tampering or manipulation, and comply with privacy and data protection principles. At the same time, the solution should remain cost-effective for practical deployment and scalable to support large-scale recycling and manufacturing operations.

POR ARCHITECTURE

A. Overview

The Proof-of-Recycling (PoR) system is designed as a multi-layer framework that combines operational monitoring, secure data recording, physical material verification, and user-level validation. The architecture consists of five main components: an IoT Attestation Layer, Batch Creation and Blockchain Logging, a Physical Watermarking Layer, a Consumer Verification Layer, and a Cybersecurity Layer to ensure overall system integrity.

B. IoT Attestation Layer (Machine Fingerprint Evidence)

The IoT attestation layer captures real-time operational data from recycling equipment. Sensors such as vibration (accelerometer), temperature probes, power monitors, RPM or cycle timers, and weight measurement units are attached to the machines. During each recycling cycle, these sensors generate a unique, physics-based operational pattern known as a Recycling Fingerprint (RFp). This fingerprint serves as evidence that the recycling process actually took place under normal operating conditions.

C. Batch Tokenization and Blockchain Logging

For every completed recycling cycle, the system generates a digital batch record containing a unique Batch ID, material type, processing timestamp, facility identification, RFp hash, operator role identifier, and the mapping to the final product category. To maintain transparency and prevent tampering, only cryptographic hashes of the batch information are stored on the blockchain, while detailed operational data is kept off-chain to protect privacy and reduce storage overhead.

D. Physical Watermarking Layer (Material Authenticity)

To ensure that the final product genuinely contains the recycled material, a hidden physical watermark is embedded into the plastic during the extrusion or molding process. This watermark is linked to the batch and may take the form of a microtexture pattern, spectral or UV-reactive pigment, or a micro-pattern stamp. The marker is not visible during normal use but can be detected using low-cost scanning methods, providing proof of material authenticity.

E. Consumer Verification Layer

At the final stage, consumers can verify the product's sustainability claims through a simple two-step process. By scanning a QR code or NFC tag, they can access the digital traceability record of the product. In addition, a watermark scan confirms that the physical material matches the recorded batch. The system then displays a sustainability report, allowing users to verify that the product was genuinely manufactured using recycled plastic.

V. CYBERSECURITY AND PRIVACY FRAMEWORK

A. Secure Telemetry Logging

To ensure the integrity of operational data, all telemetry generated by IoT devices is digitally signed at the device level before transmission. Each data record is linked using cryptographic hash chaining, creating a tamper-evident sequence of events. For efficient and verifiable auditing, telemetry hashes are organized using Merkle tree structures, allowing stakeholders to validate data authenticity without accessing the complete dataset.

B. Privacy Preservation

The system is designed to protect user and operational privacy. Consumer identities are anonymized, and any sensitive personal information is stored securely off-chain. Only cryptographic hashes and essential verification data are recorded on the blockchain. This approach minimizes data exposure while ensuring compliance with applicable data protection and privacy regulations.

IMPLEMENTATION DESIGN

A. Smart Waste Collection

The process begins with IoT-enabled smart bins that monitor waste levels in real time. These bins send fill-level data to a central system, allowing collection teams to plan routes efficiently. GPS-enabled collection vehicles further support route optimization and enable predictive analytics, helping reduce fuel consumption, operational costs, and unnecessary trips.

B. Transparent Production

At the manufacturing stage, transparency is ensured by attaching RFID or NFC tags to product batches. These tags are linked to blockchain-based records that store information about material origin, processing details, and batch history. This allows stakeholders to trace each product and verify its authenticity throughout the supply chain.

C. Smart Inventory and Quality Control

To maintain consistent production standards, the system incorporates smart inventory management and equipment monitoring. Predictive maintenance helps identify potential machine issues before failures occur, while material tracking ensures proper usage and quality control during the manufacturing process.

D. Integration with PoR

The Proof-of-Recycling (PoR) framework enhances the existing system by adding three critical capabilities. It verifies recycling activities through IoT-based machine attestation, embeds batch-linked physical watermarks into recycled materials to confirm material authenticity, and enables consumers to validate sustainability claims using a mobile application that checks both digital records and physical evidence.

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DISCUSSION

A. Practical Benefits

Stops greenwashing, strengthens supply chain integrity, and enables verifiable eco-luxury differentiation.

B. Limitations

Requires watermark standardization, introduces equipment costs, and depends on consumer adoption of verification app.

IV. CONCLUSION

This research proposes a Proof-of-Recycling (PoR) framework designed to reduce greenwashing and improve trust in plastic recycling and upcycling supply chains. Although current IoT- and blockchain-based systems help improve efficiency through smart waste collection, route optimization, and secure digital records, they still face a major limitation. These systems can show that waste was collected and recorded, but they cannot reliably confirm whether real recycling actually took place or whether the final product truly contains the recycled plastic that is claimed.

To address this issue, the PoR framework introduces a two-level verification approach that focuses on both the recycling process and the material itself. The first level verifies the recycling activity using IoT-based machine monitoring. Sensors attached to recycling equipment capture operational data such as vibration patterns, temperature changes, power usage, machine cycles, and weight consistency. This information is used to create a unique Recycling Fingerprint (RFp), which is digitally signed and stored in secure, tamper-resistant records. The second level ensures material authenticity by embedding a hidden, batch-linked physical watermark directly into the recycled plastic during processing. Since this identifier becomes part of the material, it stays with the product and cannot be easily copied or misused like a simple QR code or RFID tag.

By combining secure digital records, physical proof within the material, consumer-level verification, and strong cybersecurity controls, the PoR framework helps build trust across the entire recycling value chain. It supports more reliable sustainability claims, improves readiness for regulatory compliance, and reduces the chances of fraud and misleading environmental practices in circular economy initiatives such as those adopted by eco-focused brands like Behtar.

Future work will focus on developing a complete working prototype and testing the system in real recycling environments. Further improvements will aim to make the embedded watermarks more durable and easier to detect under different operating conditions, compare the system's performance with laboratory-based material testing methods, and explore standard formats and interoperability so the solution can be adopted at scale across different organizations and recycling networks.

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