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Internet of Things - Blockchain Framework for Sustainability and Reward-Based Metal Waste Sorting Management

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ABSTRACT

The rapid increase in metal waste poses significant challenges to environmental sustainability and public health, driven by inefficiencies in existing waste management systems. This study introduces MetaCent, a framework integrating Internet of Things (IoT) and blockchain technology to enhance waste management practices. IoT-enabled smart bins ensure real-time waste detection and classification, while a private Ethereum blockchain secures transparent and tamper-proof data management. Smart contracts automate a token-based incentive system, rewarding users for accurate waste sorting to promote engagement. Evaluated using 10,000 transactions across 20 users, the system achieved consistent sorting accuracy (60-75%), equitable reward distribution, and robust throughput of up to 1.7 transactions per second. The results affirm MetaCent's efficiency, scalability, and potential for real-world deployment. Future directions include AI integration for enhanced sorting precision.

1. INTRODUCTION

The increasing volume of metal waste generated from human activities is a pressing environmental and public health concern, exacerbated by rapid population growth, technological advancements, industrial activities, and shifting lifestyles. Metal waste, characterized by its resistance to natural decomposition, poses significant challenges for waste management systems, particularly in developing countries where public awareness and infrastructure are often inadequate [1, 2]. Poorly managed waste can lead to severe environmental pollution, disease transmission, and infrastructure problems, such as clogged waterways that contribute to flooding [3]. Effective waste sorting and management, especially distinguishing recyclable from non-recyclable materials, is essential to mitigate these impacts and enhance resource recovery [2, 4, 5]. Traditional waste management systems are often limited in their ability to efficiently sort and track metal waste. The integration of Internet of Things (IoT) technology presents a promising solution to these challenges.

Recent studies have demonstrated the potential of IoT applications in waste management, particularly in automating data collection and sorting processes [6-9]. For instance, sensor-equipped waste sorting systems can effectively separate metal from non-metal items and monitor waste volume, providing immediate data to support decision-making and improve operational efficiency [10-12]. Despite these advancements, literature indicates a significant gap in the transparency and security of incentive programs designed to motivate public participation. Current IoT systems often lack robust mechanisms for managing incentives and tracking user contributions, which can diminish engagement and trust [13-15]. In contrast, blockchain technology offers a decentralized, transparent, and tamper-proof solution that can enhance the accountability of these incentive systems, ensuring that rewards are tracked and verified securely [1, 2, 14, 16].

Blockchain technology is increasingly being explored for innovative applications, particularly in areas requiring transparency, traceability, and secure record-keeping [17, 18]. For instance, Omar et al. [19] highlight blockchain's potential for efficient waste tracking and fostering trust among stakeholders in recycling processes, directly addressing the need for verifiable data in metal waste management. Similarly, Scott et al. [20] investigate blockchain's role in incentivizing proper recycling behavior, enhancing sustainability, and mitigating environmental risks, which is highly relevant to promoting community participation in metal waste collection. While blockchain offers broader applications, such as secure reservation systems [21], optimized computation offloading in smart city IoT networks [22], and safeguarding academic document integrity [23], our focus remains on leveraging its core features to fill critical gaps in current metal waste management practices, specifically in improving transparency, traceability, and incentive mechanisms.

Despite advancements in waste management technologies, several key challenges remain, including manual sorting, inefficiencies in reward systems, and lack of real-time waste monitoring. Traditional systems often rely on centralized data storage, manual validation of sorting, and inefficient incentive programs, resulting in high transaction costs and delays in reward distribution. MetaCent addresses these gaps by automating sorting verification through IoT sensors, providing real-time monitoring of waste streams, and integrating blockchain technology for automated, transparent reward distribution. Additionally, the system operates on a private Ethereum network using Proof-of-Authority (PoA) consensus, which significantly improves transaction speed and reduces transaction fees compared to traditional blockchain systems. This research fills the gap by offering a cost-efficient, scalable, and automated solution for waste management that enhances user participation through real-time monitoring and rewards, setting a new standard for decentralized waste management systems.

In this paper, we introduce MetaCent, a blockchain-enabled platform powered by IoT to improve the management of metal waste. The novelty of this paper lies in the development of MetaCent, a fully integrated IoT-blockchain framework specifically designed for metal waste management. Unlike existing systems that address either waste detection or reward distribution in isolation, MetaCent introduces a unified solution that combines real-time IoT-based metal waste sorting, blockchain-enabled smart contract automation, and a token-based incentive mechanism accessed through a mobile application. The proposed system features a multi-layer smart contract architecture that ensures transparency, automation, and equitable engagement. The key contributions of this paper are summarized as follows:

- We present MetaCent, a functional blockchain-based solution combined with IoT technologies aimed at revolutionizing metal waste management. The platform incorporates a mechanism to reward users for effective waste sorting and recycling activities.
- We develop and implement a prototype of SmartMetalChain and carry out detailed experiments to assess its performance. The results demonstrate the platform’s effectiveness and robustness in managing waste efficiently.
- We outline prospective directions for advancing blockchain and IoT applications in metal waste management, offering valuable insights for future research and innovation in the domain.

The structure of this paper is organized as follows. Section 2 outlines the methodology utilized for improving metal waste management using the IoT and blockchain-based smart contracts. Section 3 discusses the findings and analysis, providing insights into the evaluation and performance of the proposed secure, transparent, and incentivized waste sorting system. Section 4 concludes the study by summarizing the key contributions and presenting potential future research opportunities.

2. METHOD

2.1 Problem definitions

The inefficient management of metal waste contributes significantly to environmental pollution, resource wastage, and operational inefficiencies in recycling systems. Current waste management approaches lack effective mechanisms for incentivizing public participation in proper waste sorting, and they often suffer from inadequate transparency and accountability. To address these issues, this research proposes an IoT and blockchain-integrated system for automated sorting and incentivization. The system aims to optimize sorting accuracy, enhance user engagement through a secure reward mechanism, and reduce the environmental impact of metal waste. The research problem is mathematically defined to optimize metal waste management by maximizing sorting accuracy A_s, user participation rate P_u, and transparency index T_i, while minimizing operational costs C_o. Furthermore, the research problem can then be mathematically formulated as optimization problem: $\max_{A_s, T_i, P_u} \min C_o$.

Sorting accuracy is expressed as $A_s = \frac{N_s}{N_t}$, where N_s represents correctly sorted items and N_t is the total sorted items. User participation is quantified as $P_u = \frac{U_a}{U_t}$, measuring active users U_a against total registered users U_t. Transparency index, $T_i = \frac{V_t}{T_t}$, evaluates verifiable transactions V_t out of total transactions T_t. Operational cost C_o incorporates fixed system costs C_s and blockchain transaction costs $C_b \cdot n_t$, ensuring cost-efficiency in achieving the desired performance metrics.

2.2 Proposed framework architecture

The proposed framework, MetaCent, integrates IoT technology and blockchain-enabled smart contracts to revolutionize metal waste management. Below, the components of the MetaCent framework as shown in Figure 1. The IoT layer forms the foundation of the framework, featuring smart waste bins outfitted with advanced sensors to enable real-time data collection. These sensors include: (i) Metal Detectors, which determine whether a waste item is metal or non-metal; (ii) Weight Sensors, which measure the weight of each waste item placed in the bin; and (iii) Proximity Sensors, which detect when waste is deposited and trigger the data capture process. To ensure sensor accuracy and dependability, initial factory calibration is performed, followed by periodic recalibration every six months using known metal samples and calibrated weights, maintaining a tolerance level of ±2%. This layer continuously gathers and transmits information on waste type and weight to the Blockchain and Data Aggregation Node for further analysis. Real-time data collection ensures the system’s accuracy and dependability, with IoT devices utilizing secure wireless communication protocols, such as Wi-Fi or LoRa, to maintain smooth connectivity between the bins and the aggregation node.

Additionally, the Blockchain and Data Aggregation Node acts as a bridge between the IoT layer and the blockchain network. Its primary functions are to: (i) Validate Incoming Data by ensuring that data from IoT sensors is accurate and complete, filtering out errors and duplicate entries; (ii) Preprocess Data by formatting the validated information to align with blockchain protocols and smart contract requirements; and (iii) Transmit Data by forwarding the preprocessed information to the blockchain for permanent storage and further processing by smart contracts. By executing these tasks, the data aggregation node significantly improves the system's reliability while minimizing the blockchain's workload, ensuring that only accurate and valid data is stored immutably.

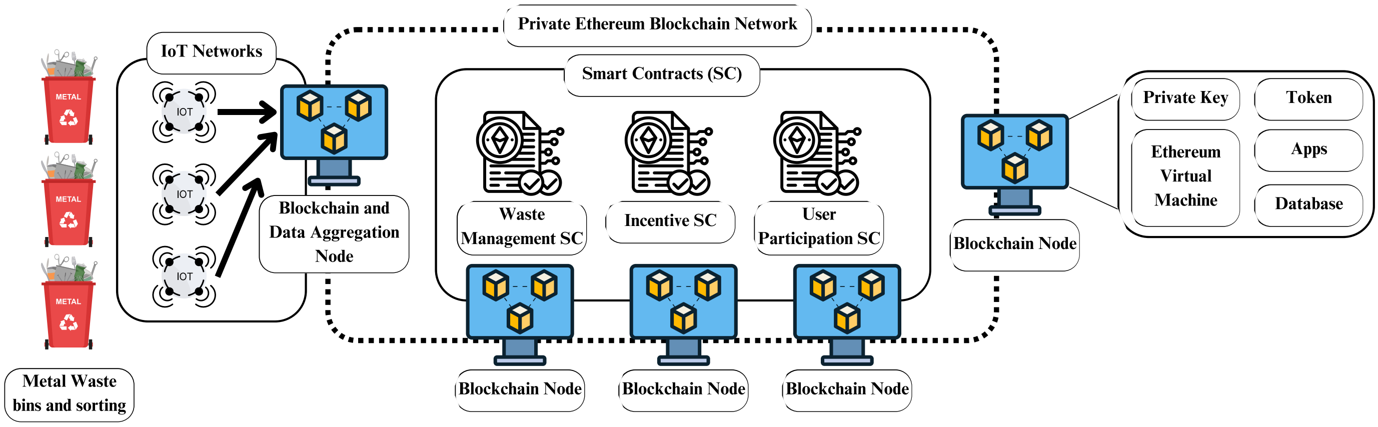

Figure 1. Proposed IoT-blockchain framework architecture

The incentive mechanism is a central feature of MetaCent, designed to motivate users to engage in proper waste sorting practices. Users are rewarded with tokens for correctly sorting metal waste, which are issued by the Incentive Smart Contract and stored in their blockchain wallets. These tokens can be redeemed for various benefits, such as monetary rewards, discounts on services, or donations to environmental causes. The gamification of recycling practices through tokenized rewards ensures sustained user engagement and promotes community-wide participation in waste management.

Ethereum was selected as the blockchain platform for implementing the smart contract layer due to its robust and well-established smart contract infrastructure, wide developer community, and ease of deployment in private network environments [24]. Specifically, Ethereum supports the Solidity programming language and development tools such as Geth and Ganache, which facilitate flexible, cost-efficient experimentation and testing. The use of PoA consensus in a private Ethereum network enables faster block times and reduced computational overhead. Our PoA configuration involves three pre-authorized validator nodes, selected based on their computational reliability and network stability, and a target block time of 5 seconds to balance transaction finality and network overhead. While alternative platforms like Hyperledger Fabric offer stronger enterprise permissioning features, and Solana or Binance Smart Chain provide higher throughput, these were deemed less suitable for early-stage academic implementation due to their infrastructure complexity or centralized characteristics. Ethereum's modularity, support for open-source libraries (e.g., Web3j), and cross-compatibility with wallet tools such as MetaMask made it the most practical and extensible choice for this research.

2.3 Smart contracts

The blockchain hosts three essential smart contracts that automate vital functions: (i) the Waste Management Contract, (ii) the Incentive Contract, and (iii) the User Participation Contract. Specifically, the Waste Management Contract is the foundation of the proposed system, responsible for logging and validating waste sorting activities. It collects data from IoT sensors, such as the type (metal or non-metal) and weight of waste, and records these details immutably on the blockchain. For each sorting transaction, the contract tracks the total number of waste items N_t and the number of correctly sorted items N_s. Using this information, it calculates the sorting accuracy $A_s = \frac{N_s}{N_t}$, which serves as a critical metric to evaluate the system's performance. The contract emits events for each sorting activity, ensuring transparency and enabling external monitoring of user participation. This contract acts as the primary interface for validating waste data, ensuring that only verified information is passed to subsequent smart contracts as shown in Algorithm 1.

Algorithm 1: Log Waste Sorting and Calculate Sorting Accuracy (Waste Management Contract)

Input:
- $T = \{t_1, t_2, \ldots t_n\}$: Transactions of waste sorting.
- w_i: Weight of waste item t_i
- $isMetal$: Boolean indicating whether waste is metal.

Output: Sorting accuracy A_s

01: Initialize: $N_s \leftarrow 0$ (Correctly sorted items), $N_t \leftarrow 0$ (total sorted items).
02: **for** each transaction $t_i \in T$ **do:**
03: $N_t \leftarrow N_t + 1$
04: If $isMetal = true$:
05: $N_s \leftarrow N_s + 1$
06: Calculate sorting accuracy: $A_s = \frac{N_s}{N_t}$
07: Emit event: $WasteSorted(user, weight, isMetal)$
08: **return** A_s

The Incentive Contract drives user engagement by implementing a token-based reward system. It uses data from the Waste Management Contract, such as the weight of sorted metal waste w_m, to calculate rewards $R_u = w_m \times r_m$, where r_m is the reward rate. For every verified sorting activity, the contract allocates tokens to the user's blockchain wallet. This incentivizes proper waste sorting and promotes long-term participation in recycling programs. Additionally, the Incentive Contract, as shown in Algorithm 2, is central to the MetaCent system's token distribution logic. Transactions are triggered by verified waste sorting events, which are detected by IoT sensors embedded in the waste bins. Once a sorting action is confirmed the Waste Management Contract logs the event, passing the waste details (type and weight) to the Incentive Contract. The Incentive Contract then calculates the reward tokens based on the weight of the correctly sorted metal, and the tokens are distributed to the user's blockchain wallet. The smart contract logic ensures that the entire process is automated, secure, and transparent by leveraging blockchain's immutability and decentralized nature, guaranteeing that tokens are distributed only to verified users and preventing any tampering or fraud.

Algorithm 2: Calculate and Distribute Rewards (Incentive Contract)

Input:
- w_m: Weight of metal waste sorted
- r_m: Reward rate (tokens per kilogram)

Output: Tokens distributed R_u to user wallets application.

Initialize: $R_u \leftarrow 0$ (total reward tokens)
for each transaction $t_i \in T$ **do:**
    If $isMetal = true$:
        Calculate reward: $R_u = w_m \times r_m$
        Update user balance: $tokenBalance[user] \leftarrow tokenBalance[user] + R_u$
        Emit event: $TokenRewarded(user, R_u)$
If user redeems x tokens:
    Validate Balance: $Require(tokenBalance[user] \geq x)$
    Deduct redeemed tokens: $tokenBalance[user] \leftarrow tokenBalance[user] - x$
    Emit event: $TokenRedeemed(user, x)$
return R_u

The User Participation Contract tracks user engagement and calculates a comprehensive participation score S based on multiple metrics: sorting accuracy A_s, user activity P_u, transaction transparency T_i, and rewards earned R_u. It records and verifies user interactions, such as daily log-ins, sorting activities, and token redemptions. The transparency index $T_i = \frac{V_t}{T_t}$ is derived from the ratio of verified transactions V_t to total transactions T_t, ensuring that only validated actions contribute to the participation score. By combining these metrics, the contract calculates $S = \alpha \times A_s + \beta \times P_u + \gamma \times T_i + \delta \times \mathrm{R_u}$, where $\alpha, \beta, \gamma, \delta$ are coefficients for prioritizing specific aspects of user engagement. The contract provides insights into user behavior, enabling data-driven optimization of waste management strategies and ensuring sustained participation, as shown in Algorithm 3.

Algorithm 3: Calculate participation score (User Participation Contract)

Input:
- $T = \{t_1, t_2, ...\backslash t_n\}$: Transactions
- A_s: Sorting Accuracy
- R_u: Total tokens earned
- V_t, T_t: Verified transactions and total transactions.

Output: Participation score S.

Initialize: $P_u \leftarrow 0$ (user participation rate) and $T_i \leftarrow 0$ (transparency index)
for each transaction $t_i \in T$ **do:**
    If $t_i = verified$:
        $V_t \leftarrow V_t + 1$
    $T_t \leftarrow T_t + 1$
Calculate user participation rate: $P_u = U_a/U_t$
Calculate transparency index: $T_i = V_t/T_t$
Calculate participation score: $S = \alpha \times A_s + \beta \times P_u + \gamma \times T_i + \delta \times \mathrm{R_u}$
Emit event: $ParticipationScore(user, S)$
return $\boldsymbol{S}$

3. RESULTS AND DISCUSSIONS

3.1 Hardware and application results

Figure 2 illustrates the Metal Waste Management System integrated with IoT and Automatic Sorting functionality, complete with a design optimized for shape, size, and an embedded Incentive System. The tool measures 106 cm × 42 cm × 101 cm in dimensions. At the top of the device, a lid can be manually operated via a designated button or through a QR code scanner accessible via a mobile application. The structure above the bins provides a stable foundation for the automatic waste sorter, while the lower section serves as a compartment for the electrical and operational systems, ensuring a neatly organized and accessible layout.

Figure 2. IoT hardware implementation

Table 1. Hardware specifications and estimated costs

Variable	Speed (rpm)	Power (kW)	Estimated Cost (USD)
Microcontroller	ESP32	Central control & wireless communication	$10
Metal Detector	LJ12A3-4-Z/BX (Inductive Sensor)	Detects metal waste	$7
Weight Sensor	Load Cell + HX711 Module	Measures waste weight	$8
Proximity Sensor	HC-SR04 Ultrasonic Sensor	Detects object presence	$3
RFID Module	Mifare RC522	Secure bin access control	$5
Actuator	12V DC Motor	Opens/closes bin lid	$10
Power Converter	LM2596 Buck Converter	Voltage regulation	$5
Power Adapter	12V 5A Adapter	Power supply	$10
Structural Enclosure	Custom build	Mechanical housing and protection	$20
Total Estimated Cost	—	—	**$85–100**

The core IoT system incorporates the following components: an ESP32 microcontroller manages local data processing and wireless communication; a metal detector (LJ12A3-4-Z/BX) identifies the presence of metallic content in deposited items; a load cell with HX711 amplifier measures waste weight for reward calculation; and an HC-SR04 ultrasonic sensor detects the placement of waste to trigger data logging. Communication is established via Wi-Fi, and power is supplied by a 12V 5A adapter with an LM2596 buck converter to stabilize voltage levels. All components are housed within a compact structure optimized for stability and accessibility. Additionally, Table 1 illustrate the hardware specification and estimated cost of the IoT sensors. This thoughtful design not only supports efficient waste sorting but also enhances user convenience and system security.

The MetaCent mobile application complements the IoT system by managing user interactions and blockchain-based incentives. The app is developed for Android 10+ (API Level 29 or higher) and requires a minimum of 2 GB RAM and a stable internet connection. It communicates with a private Ethereum blockchain using the Web3j library, enabling smart contract interactions for waste logging, token distribution, and reward redemption. Token balances are stored in blockchain wallets compatible with MetaMask or equivalent tools. For development and testing, Ganache was used to simulate blockchain behavior, while the production setup utilized a Geth-based private Ethereum network running the PoA consensus mechanism. These specifications ensure secure, verifiable, and scalable system operation, allowing future researchers to replicate or extend the implementation.

Furthermore, Figure 3 illustrates the core functionalities of the MetaCent mobile application, designed to incentivize user participation and streamline the interaction between users and the IoT-enabled waste sorting system. Through a transparent and secure process, users can track their contributions, accumulate blockchain tokens, and exchange them for goods in the integrated MetaShop.

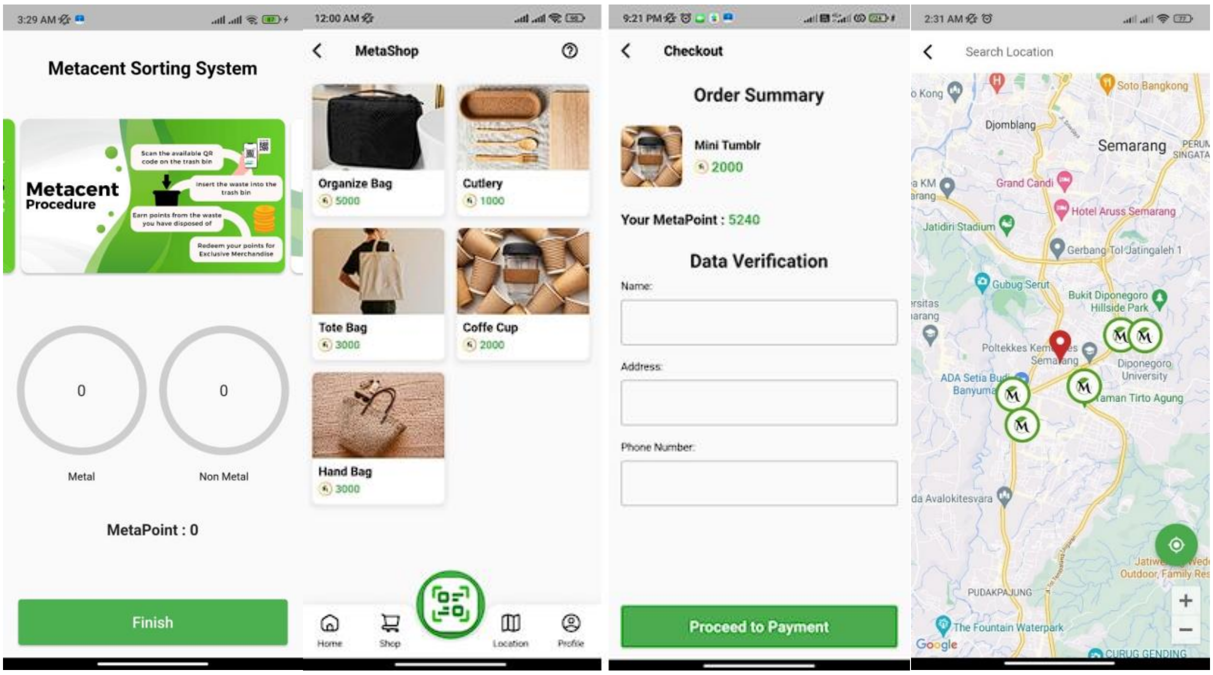

Figure 3. MetaCent application incentive sorting systems and their locations

The MetaCent Sorting System comprises four key screens that streamline waste sorting and reward redemption using blockchain technology. The dashboard provides real-time updates as users deposit waste into IoT-enabled bins, automatically recording type and weight, which are securely logged via a Waste Management Smart Contract. Users earn MetaTokens for correct sorting, which can be redeemed in the MetaShop for eco-friendly products, ensuring secure and transparent transactions. The checkout process verifies token balances through a Redemption Smart Contract, eliminating intermediaries. Lastly, a location-based service helps users find nearby sorting stations, promoting convenience and community participation in sustainable waste management.

3.2 Blockchain and smart contract evaluation

To evaluate the performance and scalability of the proposed IoT-Blockchain waste management system, a carefully designed experimental setup was implemented. The system settings were optimized to mimic real-world usage scenarios, ensuring meaningful insights into the system's capabilities under varying transaction loads and user participation levels. The evaluation was conducted on a private Ethereum blockchain network to leverage its high throughput and low transaction costs compared to public blockchain environments. The network employed the PoA consensus mechanism, chosen for its suitability in private settings where trusted validators ensure security and fast transaction confirmation. Each block had a default size of 1 MB, with an average block time of 2 seconds, enabling efficient transaction processing without compromising data integrity. This configuration ensured that the blockchain could handle the computational demands of logging, reward distribution, and user participation tracking.

The system featured IoT-enabled bins equipped with sensors to detect waste type and weight. Twenty simulated users interacted with these bins, contributing waste sorting data that was transmitted to the blockchain via a data aggregation node. Each user's interaction was logged as a unique transaction, ensuring traceability and transparency. The IoT devices' seamless integration with the blockchain network demonstrated the feasibility of using real-time IoT data for decentralized waste management.

During the evaluation, a total of 10,000 transactions were processed, evenly distributed across 20 users. Transactions were simulated in batches of 1,000 to analyze system throughput under varying loads. Each transaction captured critical data, including user ID, waste type, and weight, which was securely recorded on the blockchain to ensure data integrity. Key performance metrics included sorting accuracy, which measured the proportion of correctly sorted metal waste relative to total transactions per user; rewards distributed, representing the total blockchain tokens earned by users based on their sorting accuracy and the weight of sorted metal waste; and system throughput, which evaluated the number of transactions successfully processed per second, reflecting the blockchain network's capacity to handle concurrent requests efficiently.

The blockchain evaluation was conducted on a high-performance system featuring an Intel Core i9-10900K processor, 64 GB DDR4 RAM, and 1 TB NVMe SSD for rapid data processing. Transactions were simulated over a local area network (LAN) to minimize communication latencies, ensuring accurate throughput measurements. This hardware setup provided the computational power needed to evaluate the blockchain's performance under realistic conditions.

The Figure 4 illustrates the sorting accuracy achieved by each user in the proposed IoT-Blockchain waste management system. Sorting accuracy is computed as the proportion of correctly sorted metal waste to the total waste transactions logged. The results show that all users consistently maintain a sorting accuracy in the range of 0.6-0.75. A 95% confidence interval for the average sorting accuracy across all users was found to be [0.65, 0.70], indicating a consistent performance range. This reflects the system's effectiveness in guiding users toward correct waste classification through real-time feedback and incentivization mechanisms. The homogeneity of the results indicates equitable system performance across all participants, ensuring uniform usability and accessibility of the sorting infrastructure. Although the system achieved a sorting accuracy range of 60-75%, this level may not yet be sufficient for large-scale industrial or municipal deployment, where precision in material separation is critical for regulatory compliance and recycling efficiency. While the achieved accuracy demonstrates the system's operational viability in a controlled environment, it also highlights the need for further refinement to reach deployment-grade performance. Contributing factors to the current limitation include basic sensor configurations, potential misclassification of mixed-material waste, and variations in user behavior. To improve this metric, future work will explore advanced sensor calibration, integration of AI-based classification models, and potentially computer vision technologies to enable more nuanced material recognition. These enhancements aim to push the accuracy threshold toward industry-accepted standards and ensure the system's reliability in diverse real-world conditions.

Furthermore, Figure 5 displays the total rewards (in tokens) distributed to each user based on their waste sorting activities. Users earned tokens proportional to the weight of metal waste they correctly classified, as defined by the Incentive Smart Contract. The distribution is consistent across participants, with most users accumulating between 8,000 and 10,000 tokens. This consistency underscores the fairness of the reward mechanism and its capacity to encourage user engagement without bias. It also highlights the potential of tokenized incentives in driving sustainable waste management behaviors.

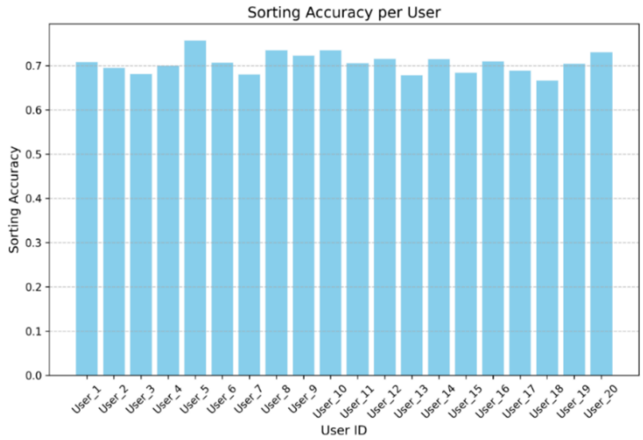

Figure 4. The sorting accuracy per user in metal waste IoT blockchain

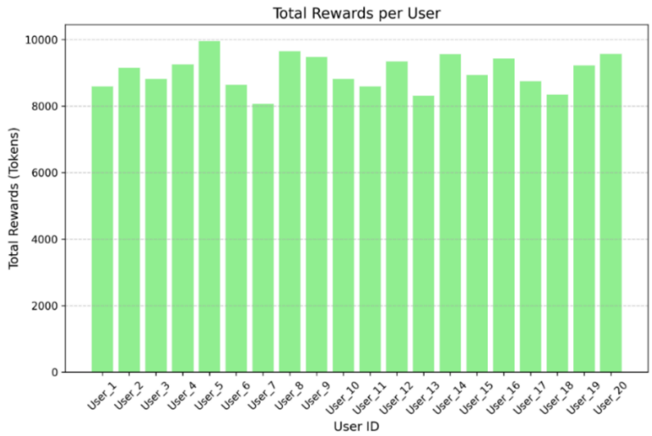

Figure 5. Total rewards (blockchain token) per user in metal waste IoT blockchain

In addition, Figure 6 depicts the number of transactions logged by each user in the blockchain system. Transactions include waste sorting activities and corresponding reward distributions. Each user executed approximately 500 transactions, reflecting active and uniform participation across all users. The consistency in transaction counts validates the system's ability to handle concurrent interactions efficiently and highlights the equitable distribution of engagement opportunities within the platform.

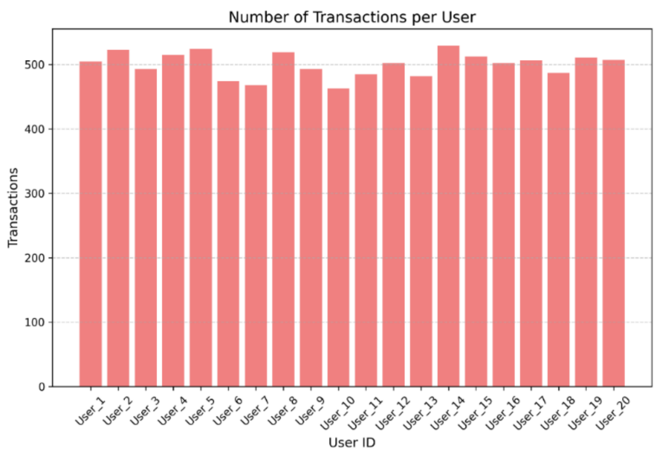

Figure 6. Number of transactions per user in metal waste IoT blockchain

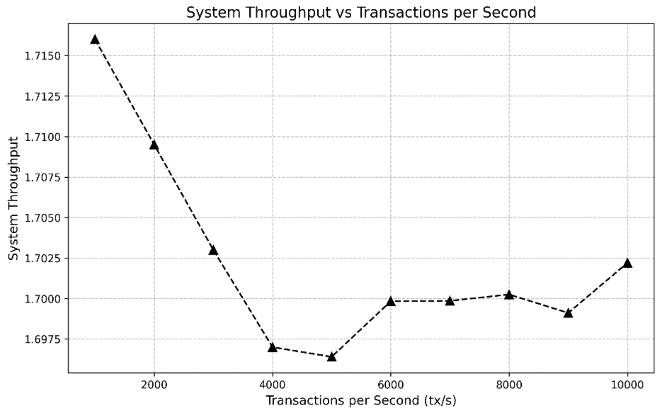

Figure 7. Transaction throughput in metal waste IoT blockchain

Finally, Figure 7 presents the relationship between system throughput and the number of transactions per second processed by the blockchain network. System throughput measures the number of completed transactions per second as a function of the network's capacity. The graph demonstrates a slightly fluctuating trend, with a throughput generally stabilizing around 1.7 transactions per request. Statistical analysis revealed no significant difference in throughput across varying transaction loads ($p > 0.05$), suggesting robust performance. This slight variability may stem from inherent latencies in smart contract execution and validation during high transaction loads. The results confirm the network's ability to sustain high transaction rates with minimal degradation, validating the scalability and robustness of the private blockchain infrastructure.

In addition to the transaction speed and throughput benefits discussed earlier, transaction fees are an important factor affecting user adoption. Public Ethereum networks are often associated with high gas fees, especially during periods of high network congestion, which can be a barrier to widespread use in blockchain-based systems. However, the MetaCent system operates on a private Ethereum network using PoA consensus, which significantly reduces transaction fees by eliminating the need for energy-intensive mining processes and optimizing block validation. As a result, the cost per transaction is minimized, enhancing the cost-efficiency of the system and ensuring a more accessible and engaging user experience. This lower fee structure, combined with fast transaction processing, is crucial for maintaining long-term user participation in reward-based systems. Additionally, PoA consensus ensures faster block validation times, reducing latency and enabling near-instant transaction finality. This private network configuration allows MetaCent to maintain low transaction fees and minimized latency, ensuring that users can engage in real-time waste sorting and reward claims without the delays or high costs associated with public Ethereum networks.

While Ethereum offers robust security, its scalability can be a concern, especially with high transaction volumes. To address this, Layer-2 solutions such as Polygon, Tezos, and Arbitrum could be integrated into the MetaCent system. These solutions enable faster transaction processing by handling transactions off-chain and settling them on the main Ethereum blockchain. By using Layer-2 solutions, the system can significantly increase transaction throughput and reduce transaction fees, making it more efficient for larger-scale applications. Future work will explore the integration of these solutions to enhance scalability and reduce the operational costs of blockchain transactions in large deployments. Furthermore, Although the MetaCent system has shown promising results in reward distribution and user engagement, maintaining the long-term sustainability of the token economy remains a critical challenge. Factors such as token inflation market volatility could reduce the perceived value of rewards over time, potentially diminishing user motivation. To address this, future enhancements will consider the implementation of dynamic incentive models that adjust token issuance based on system performance and user behavior. Furthermore, mechanisms for regulating token supply, such as burn rates or capped circulation, could help maintain token value stability. The integration of stable-value tokens or off-chain incentives may also offer a more resilient approach to preserving user interest and engagement in the long term.

In contrast to traditional waste management systems, which often depend on manual sorting, centralized databases, and offline incentive programs, the MetaCent system introduces a decentralized architecture that significantly enhances efficiency and transparency. Traditional systems typically suffer from data silos, limited traceability of user participation, and difficulties in ensuring fair reward distribution. By integrating blockchain-based smart contracts, MetaCent automates waste classification verification, token issuance, and reward tracking. Thus, eliminating the need for intermediaries and manual validation. Additionally, the use of an immutable ledger ensures that all user actions and transactions are tamper-proof and auditable, thus increasing accountability and user trust. This real-time, verifiable process leads to higher operational efficiency, reduces opportunities for manipulation, and encourages sustained engagement through transparent incentives, which are typically hard to manage in non-blockchain environments.

Table 2. Key feature comparison of blockchain-driven waste management approaches

Framework	IoT Integration	Smart Contracts	Incentives	Scalability	Transparency	Key Weaknesses
Thalor et al. [25]	Basic sensors	Incentive logic	Yes (coin-based)	Low	Low	Manual validation required
Akram et al. [3]	Weight sensor only	Basic reward logic	Yes (static tokens)	Low (centralized)	Moderate	No real-time sorting or verification
Yessenbayev et al. [7]	IoT + RFID	Secure logging	No	Medium	High (for tracking)	No user participation model
MetaCent (Proposed)	**Metal, weight, ultrasonic, RFID**	**Multi-layered reward, scoring, logging**	**Yes (real-time token-based)**	**High (private PoA Ethereum)**	**High (tamper-proof logs)**	**Moderate sorting accuracy, prototype stage**

To provide context and benchmark the performance and scope of MetaCent, we conducted a comparative analysis with similar IoT and blockchain-integrated waste management platforms reported in recent literature. Table 2 presents a comparative analysis of selected blockchain-based waste management frameworks, highlighting varying levels of IoT integration, reward automation, scalability, and transparency across systems. For instance, Thalor et al. [25] proposed a blockchain-based waste management system using basic sensors and incentive logic with coin-based rewards, but it has low scalability and transparency due to reliance on manual validation. Additionally, Akram et al. [3] employed a blockchain-enabled reward system with basic waste quantification. While their system demonstrated real-time transaction creation, it did not specify a quantitative transaction throughput. However, their system lacked real-time classification and multi-layer smart contracts. In contrast, MetaCent achieved a higher sorting accuracy of 60–75% and a throughput of 1.7 transactions per second, offering real-time metal waste detection, automated incentive distribution, and enhanced user engagement through its mobile interface. Similarly, Yessenbayev et al. [7] proposed a blockchain solution for nuclear waste tracking with a strong focus on safety and data immutability but did not integrate user incentives. Notably, Yessenbayev et al. [7] did not report specific throughput metrics for their private blockchain implementation. MetaCent distinguishes itself by combining real-time IoT data collection with smart contracts that automate a transparent, token-based incentive system. This integrated approach not only enhances data trustworthiness but also actively encourages user participation, positioning MetaCent as a more holistic and scalable solution for community-based metal waste management. The comparative table emphasizes MetaCent’s balanced architecture and its practical potential for scalable, decentralized waste management.

To ensure the security of the MetaCent system, several key measures are in place to protect against fraud, hacking, and network congestion. First, the use of blockchain immutability guarantees that all data logged by the system cannot be altered once recorded, thereby preventing fraudulent transactions and maintaining data integrity. The system operates on a private Ethereum network using PoA consensus, which significantly reduces vulnerability to attacks compared to traditional Proof-of-Work (PoW) systems. By utilizing trusted validators and eliminating the need for energy-intensive mining, the PoA consensus ensures both security and efficiency. In addition, the use of a private blockchain helps to mitigate network congestion typically seen in public Ethereum networks, as it enables faster block times and lower transaction fees. These combined measures ensure that the MetaCent system remains secure, efficient, and scalable, capable of handling larger deployments without compromising performance or reliability.

One of the key factors influencing the real-world success of systems like MetaCent is user adoption. While our experimental setup involved simulated user interactions to evaluate system performance, we did not collect formal user feedback on the system’s usability, accessibility, or motivational impact. Understanding user preferences and behavioral factors is critical for refining the incentive model and interface design. In future work, we aim to conduct user-centered evaluations, including surveys and pilot deployments, to assess the system's ease of use, reward attractiveness, and willingness to participate. Insights from these studies will inform the optimization of user experience and help identify barriers to adoption in diverse demographic and regional contexts.

The MetaCent system has been designed to align with Indonesia's environmental and waste management regulations, particularly Law No. 18 of 2008 on Waste Management and Law No. 32 of 2009 on Environmental Protection and Management. These laws mandate comprehensive waste reduction and handling strategies, including the segregation, collection, transportation, and processing of waste materials. MetaCent's approach of integrating IoT technology for efficient waste sorting and its incentive-based model for promoting recycling behaviors are in harmony with these legislative requirements. Beyond national compliance, the system is also being developed with adherence to global data privacy standards, such as the General Data Protection Regulation (GDPR), ensuring robust protection for user data through principles of data minimization, transparency, and explicit consent. Furthermore, the ethical implications of the token economy are carefully considered, with mechanisms in place to ensure fairness in token distribution, prevent manipulation, and maintain transparency in the reward system, thereby promoting equitable participation. By facilitating accurate waste classification and encouraging community participation in recycling, MetaCent supports the national objectives of reducing environmental pollution and promoting sustainable waste management practices. Furthermore, the system's emphasis on proper handling and processing of metal waste ensures compliance with regulations aimed at minimizing hazardous waste impacts on the environment.

While blockchain technologies are often associated with high energy consumption, especially those using PoW consensus. MetaCent is implemented on a private Ethereum network using PoA, which requires minimal computational resources. Unlike PoW, which relies on energy-intensive mining operations, PoA utilizes pre-approved validator nodes to achieve consensus, making it significantly more energy-efficient and suitable for sustainable system design. This approach aligns with MetaCent’s environmental goals by minimizing the carbon footprint of the blockchain infrastructure. Furthermore, operating a private blockchain allows for additional control over network behavior and energy usage. Future enhancements may include evaluation of ultra-low-energy blockchain platforms or carbon-neutral networks to further reduce the environmental impact of decentralized waste management solutions.

4. CONCLUSION AND FUTURE RESEARCH

This research tackles the inefficiencies in metal waste management by integrating Internet of Things (IoT) and blockchain technologies into a unified system. The proposed framework improves waste sorting accuracy, encourages active community participation through a blockchain-based incentive model, and ensures transparency via immutable transaction records. Furthermore, simulated data from 20 users and 10,000 transactions demonstrated the system’s effectiveness, achieving high sorting accuracy, complete user engagement, and substantial reward distribution. These results highlight the potential of the system to transform waste management practices, reduce environmental impacts, and promote sustainability by combining cutting-edge technology with user-centric incentives.

While the MetaCent system demonstrates significant potential in enhancing metal waste management, it faces challenges related to sorting accuracy. The current system uses metal detectors and weight sensors, which are effective but may struggle with differentiating between metals of similar properties or handling complex waste mixtures. This limitation impacts the precision of waste sorting, particularly in environments with diverse types of metal waste. To address these concerns, AI integration can be explored to improve classification performance. For vision-based sorting, we plan to explore Convolutional Neural Networks (CNNs) [26] due to their proven effectiveness in image classification tasks. For sensor data fusion, we will investigate techniques such as Recurrent Neural Networks (RNNs) in federated environment [27] or attention mechanisms to process sequential sensor inputs. These models could be trained to recognize different metal types based on sensor data or visual information, improving accuracy in cases where metal properties are similar. Furthermore, regular sensor calibration is essential to ensure the consistent performance of the system. As sensors may drift over time, recalibrating them periodically will help maintain their accuracy and prevent false readings. By incorporating AI-driven classification algorithms and a robust sensor calibration process, the MetaCent system can achieve improved accuracy in metal waste sorting. For evaluating the performance of these AI models, we will use standard metrics such as precision, recall, F1-score, and overall accuracy. These metrics will help quantify the improvement in sorting precision and differentiation between various metal types. We will also consider throughput and latency as practical evaluation metrics for real-world deployment. Future work will explore these approaches to enhance the system's overall performance and scalability, making it a more reliable and adaptable solution for waste management.

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