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How can a plastic credit system improve traceability and verifiability in plastic waste management?

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ABSTRACT

Plastic credit schemes are increasingly adopted to mitigate plastic pollution, yet existing systems remain centralized, opaque, and prone to double counting and fraud. This study proposes and validates a plastic credit system that leverages blockchain technology aimed at enhancing transparency, traceability, and accountability in plastic recovery efforts. A modular three-layer architecture was implemented, comprising a user interaction layer, a blockchain execution layer, and a utility layer for metadata and analytics integration. The system employs two smart contracts on the Polygon Proof-of-Stake (PoS) mainnet using Ethereum standards: ERC-20 for fungible tokenization of plastic credits and ERC-721 for non-fungible certificate issuance. Functional testing confirmed successful execution of token lifecycle operations. Stress testing across 5000 sequential transactions yielded stable performance, with average confirmation times of 5.29 s for fungible token operations and 5.59 s for non-fungible processes. A decentralized application (DApp) was developed to support role-based interaction, credit traceability, and certificate validation. User evaluation returned a high usability score (86.4%), while benchmarking against existing platforms demonstrated improved auditability, automation, and stakeholder control. These findings indicate that blockchain infrastructure can enable decentralized, tamper-resistant plastic credit systems. The proposed model provides a scalable foundation for Extended Producer Responsibility (EPR) compliance and plastic waste traceability, which could potentially support the credibility of Environmental, Social, and Governance (ESG) reporting and supporting circular economy transitions across diverse policy and economic contexts.

Introduction

Plastic pollution represents one of the most critical environmental challenges of the 21st century. Global plastic production has increased from 2 million tonnes in 1950 to over 430 million tonnes annually today, with projections reaching 1.2 billion tonnes by 2050 if current trends continue (Yu et al., 2023). Despite its versatility, durability, and affordability, plastic is predominantly used for single-use products, with more than 60 % of them being discarded improperly, thereby leaking into natural ecosystems (Goh et al., 2025). Alarmingly, less than 10 % of global plastic waste is recycled, while the rest accumulates in landfills or enters waterways, posing substantial risks to marine biodiversity and human health (Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024). In 2024, global plastic waste generation reached 220 million tonnes, with 69.5 million tonnes mismanaged (Earth Action, 2024; Gritsch et al., 2025). As a result, it is estimated that over 170 trillion plastic particles are currently afloat in the oceans, forming a "plastic smog" that threatens marine ecosystems and contaminates the food chain (Eriksen et al., 2023).

The problem is particularly severe in Southeast Asia due to high population density and inadequate waste management infrastructure. The widespread reliance on informal recycling sectors further contributes to the escalating plastic leakage. (Maskun et al., 2023). Indonesia is one of the world's most significant contributors to marine plastic pollution. It generates approximately 7.8 million tonnes of plastic waste annually, with an estimated 620,000 tonnes of mismanaged waste entering the marine environment each year (Yu et al., 2023). Most of this plastic originates from poorly collected or unrecycled post-consumer packaging, which accumulates in rivers, coastal zones, and urban drainage systems (Sorino et al., 2025; Veiga et al., 2023). The inefficiency of collection systems and limited coverage of municipal services have constrained waste management efforts.

Additionally, the lack of incentives for proper sorting and recycling allows plastic waste to routinely escape into the environment (Arumdani

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et al., 2021; Dey et al., 2024). Moreover, the lack of sufficient infrastructure for waste segregation and recovery remains a significant barrier. Combined with low public awareness and minimal corporate accountability, these factors hinder Indonesia's transition toward sustainable plastic waste management. (Pramiati et al., 2021).

To address these issues, global and regional institutions have introduced regulatory measures to promote plastic reduction, circularity, and accountability. The United Nations Environment Assembly (UNEA) has emphasized the need for coordinated global action. This includes frameworks such as the Global Plastics Treaty and national extended producer responsibility (EPR) policies (Alamsyah et al., 2022a). However, successful implementation requires transparent and verifiable systems that go beyond paper-based monitoring (Pathak et al., 2023; Yu et al., 2023). Tokenizing plastic recovery data into blockchain-based digital assets offers a promising solution to address monitoring, traceability, and accountability gaps in the plastic credit market (Liu and Zhang, 2021). In this study, a plastic credit is defined as a tradable certificate that represents a verified quantity of plastic waste that has been recycled or co-processed. By linking plastic recovery to blockchain-based tokens and verifiable certificates, companies can pursue credible offsetting pathways toward plastic neutrality (Alamsyah et al., 2023). In addition to addressing practical challenges, this approach opens new academic avenues in environmental informatics, decentralized governance, and digital sustainability infrastructure.

The proposed research aligns closely with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water) (Chiucchi et al., 2025). SDG 12 encourages sustainable waste management, waste reduction, and reuse through technological innovation (Alam et al., 2022). Meanwhile, SDG 14 targets the urgent need to reduce marine pollution, especially from land-based sources like plastics, by 2025 (Gacutan et al., 2023). As plastics degrade into microplastics and enter marine food webs, protecting the ocean requires interventions that begin on land. Robust and transparent systems for waste management and recycling are crucial (Chaudhary and Garg, 2024; Yu et al., 2023).

Traditionally, plastic waste management in Indonesia relies heavily on manual sorting, informal collectors, and low-technology recycling centers. This centralized structure is economically crucial for many livelihoods. However, it lacks systemic traceability due to fragmented data flows, limited interoperability among stakeholders, and over-reliance on manual reporting processes. These weaknesses expose the system to fraud, greenwashing, and double counting while undermining real-time verification and adaptive policy responses. In practice, double counting may occur when the same recycled batch is reported by multiple actors or across different reporting systems, while fraud can involve overstating recycling volumes or issuing credits for non-existent recovery activities. Existing platforms, such as Verra and Plasticpay, have introduced crediting systems; however, their dependence on centralized audits and disconnection from physical recovery workflows perpetuates these systemic bottlenecks. Moreover, companies pursuing offsetting are unable to validate whether recovered waste truly aligns with their claimed sustainability goals.

This systemic bottleneck underscores the need for technological innovation that ensures transparency and verifiability across all stakeholders. Blockchain provides an incorruptible ledger and enables decentralized data validation, addressing traceability gaps in waste governance. Recent studies suggest its potential to reduce fraud and enhance transparency in waste management systems, particularly in developing regions such as Indonesia (Gong et al., 2022; Yu et al., 2023). This highlights a critical research gap: the absence of a decentralized infrastructure that links verified plastic recovery to token issuance in a traceable, automated, and tamper-proof manner (Sulaiman et al., 2022). From an academic perspective, this also limits empirical research on the performance and scalability of blockchain systems in environmental contexts, particularly in countries facing infrastructure and transparency challenges.

Blockchain technology offers a transformative alternative (Alamsyah et al., 2022b; Asmawi et al., 2024). With its immutable ledger and smart contract functionalities, blockchain can facilitate transparent data recording and automatic token issuance and burning (Alamsyah and Muhammad, 2024). Smart contracts enable trustless execution of offset agreements, minimizing administrative overhead and ensuring data consistency (de Sousa, 2021). Coupled with fungible ERC-20 tokens for quantifying plastic credits called Plastic Credit Token (PLST) and non-fungible ERC-721 tokens for unique certificate issuance. This study models the entire offset lifecycle as a digital ecosystem where real-world plastic recovery is cryptographically recorded and verified.

Several projects globally have explored blockchain applications in carbon markets and circular economies (Liu et al., 2025a; Tan and Yeoh, 2025). However, in Indonesia, such initiatives are still in their early stages of development. Previous research has demonstrated the potential of blockchain for plastic traceability (Priyana et al., 2023). Still, there is a limited implementation of an integrated, functional prototype that combines token economy, smart contracts, and user interaction through a decentralized application (DApp). This gap is significant, given Indonesia's ambition to reduce plastic leakage by 70 % by 2025 (Arumdani et al., 2021). By addressing both implementation and design challenges, this research provides practical solutions to plastic waste management while simultaneously advancing academic understanding of scalable, blockchain-enabled systems in environmental contexts. This study builds on our previous research on the plastic credit model by transitioning from conceptual modeling toward functional prototyping and system evaluation. In this study, we define a plastic credit system as a blockchain-enabled offsetting system that ensures traceability, verifiability, and automation. The system is developed following the principles of Design Science Research (DSR) to ensure methodological rigor and real-world relevance (Huseynli et al., 2022).

Therefore, this study aims to design and implement a plastic credit system that leverages blockchain technology, tailored to the Indonesian context. Specifically, this research seeks to: (1) develop a three-layer architectural model comprising user, blockchain, and utility layers, (2) create smart contracts for minting and burning PLST and issuing non-fungible tokens (NFT) certificates, (3) build a DApp dashboard to facilitate traceable and user-friendly interactions, and (4) evaluate the system through functional testing, stakeholder feedback, and benchmarking with existing traceability models. This approach explicitly addresses the research question of how a plastic credit system can improve traceability and validity by embedding immutable, auditable, and decentralized verification mechanisms into plastic waste governance workflows. Beyond its practical implications, the study also contributes to the broader academic discourse on digital accountability systems. It further expands knowledge on blockchain-based environmental governance applicable across diverse international contexts.

Literature review

This section reviews existing literature relevant to the development of a plastic credit system within the framework of a circular economy. The review encompasses four key areas: (1) the limitations of linear plastic waste management systems and the potential of circular economy frameworks, (2) the structure and challenges of plastic credit mechanisms, particularly regarding traceability, (3) the application of blockchain technology in waste management, and (4) the role of smart contracts and tokenization in enhancing the efficiency and transparency of plastic credit systems.

Plastic waste management within circular economy frameworks

Linear waste management systems remain inadequate for addressing the scale and complexity of plastic pollution. Circular economy principles, such as reduce, reuse, and recycle are globally endorsed. However, implementation in low- and middle-income countries is inconsistent due to infrastructure gaps, material diversity, and lack of packaging standards (Callewaert et al., 2023; Cristóbal et al., 2023). In Southeast Asia, informal collection networks further undermine traceability, regulatory enforcement, and system integration (Goh et al., 2025). This study reframes these barriers through a sociotechnical systems lens, recognizing that effective plastic recovery requires alignment between technological design and social-institutional contexts (Risku et al., 2025). Blockchain, beyond being a data recording tool, offers a digital infrastructure for verifiable plastic recovery, decentralized accountability, and inclusive circular economy practices (Gong et al., 2022). These structural barriers underline the need for systems that embed traceability and transparency directly into waste management workflows, enabling scalable and verifiable circular economy solutions.

Plastic credit mechanisms and traceability issues

Plastic credit systems, such as Verra and the Plastic Credit Exchange, enable organizations to offset their plastic footprints by funding certified recovery or recycling efforts (Jylhä et al., 2025; Verra, 2021). However, these platforms are heavily centralized and rely on manual audits. This reliance raises concerns about limited traceability, gaps in real-time verification, and the exclusion of informal waste collectors who play a crucial role in global plastic recovery systems (Klingenberg et al., 2024; Ranjbar et al., 2025). These limitations create risks of greenwashing, double counting, and restricted transparency and inclusivity, as illustrated in Appendix A (Fig. A1) (Lee, 2021). The figure provides a conceptual overview of existing plastic credit systems. It highlights centralized flows of data, materials, and financial transactions, as well as the exclusion of informal actors. This study aims to address these gaps through a decentralized, blockchain-based system.

Recent initiatives in blockchain-enabled environmental credit markets further provide methodological parallels for plastic credit mechanisms. For example, Toucan Protocol and KlimaDAO automate carbon credit issuance and retirement via smart contracts, enabling decentralized oversight and near real-time Environmental, Social, and Governance (ESG) reporting (KlimaDAO, 2022; Toucan Protocol, 2022). WaterLedger, piloted in water credit markets, and BASF's ReciChain, applied in enterprise supply chains, similarly demonstrate how blockchain infrastructures can improve traceability, accountability, and incentivize circularity (BASF, 2021; WaterLedger, 2023). These cases highlight how blockchain can embed MRV processes, role-based access control, and immutable records into crediting mechanisms. By reducing reliance on intermediaries, blockchain enables broader participation, including informal actors (Fatimah et al., 2020; Marchetti et al., 2024; Tajabadi et al., 2024). This highlights the need for a decentralized and tamper-resistant plastic credit system that can ensure real-time verification, inclusivity, and accountability across diverse waste management contexts.

In this regard, international standards such as ISO 22095:2019 on chain of custody and ISO 14064–1:2018 on MRV requirements provide critical benchmarks. ISO 22095 establishes consistent tracking of material flows and data claims across supply chains, while ISO 14064–1 specifies transparent reporting and third-party assurance for crediting schemes. Aligning blockchain-based plastic credit systems with these standards strengthens both their technological reliability and institutional credibility (ISO, 2018, 2019).

Blockchain technology for waste management applications

Blockchain technology has been widely explored as a means to enhance data integrity, transparency, and traceability in environmental systems (Daudén-Esmel et al., 2025). In waste management, initiatives such as Plastic Bank, SAP's GreenToken, and Empower.eco demonstrate the feasibility of using blockchain to track plastic flows, validate recovery claims, and issue digital incentives (Priyana et al., 2023; Zhang et al., 2023). While these projects show the potential of distributed ledgers for trust and accountability, most remain proprietary and centralized, limiting interoperability and integration with policy frameworks. Moreover, most fail to involve the informal sector, which remains critical in plastic recovery efforts across much of the Global South.

From an environmental informatics perspective, blockchain functions not only as a data infrastructure but also as a governance mechanism for coordinating diverse stakeholders (Ante et al., 2025). Its use of smart contracts and immutable records provides an alternative to manual audits and fragmented reporting (Bhatt and Emdad, 2025; R. Liu, 2024). This study positions blockchain not as a passive data layer but as an active foundation for digital accountability. The proposed system is designed to include informal actors, enable public verification, and link recovery outcomes to auditable certification processes aligned with environmental policy goals.

Smart contracts and tokenization for plastic credit systems

Smart contracts automate predefined rules on blockchain networks, providing a secure and transparent mechanism for managing digital transactions (Emami et al., 2025; Mnasri et al., 2025). In plastic credit systems, they enable the conditional issuance, transfer, and retirement of tokens based on validated recycling activities, reducing dependence on manual audits and minimizing risks of manipulation (Du et al., 2025; Liu et al., 2025b). This study adopts a dual-token design using Ethereum-compatible standards (ERC-20 for PLST and ERC-721 for NFT certificates), ensuring that each certificate corresponds to a specific token burn event (Koustas et al., 2023; Songsom et al., 2025).

Governance logic embedded in these contracts incorporates role-based access, automated verification, and transparent transaction records, shifting trust from external institutions to the system infrastructure. By aligning with ESG reporting and EPR frameworks, this tokenization approach strengthens accountability and provides a foundation for scalable, fraud-resistant credit systems (Mankata et al., 2025; Zhu and Liu, 2024). This highlights the necessity for plastic credit systems that integrate smart contract automation and dual-token mechanisms to ensure transparency, verifiability, and robust governance across diverse waste management contexts.

Nevertheless, smart contracts are not immune to vulnerabilities. Documented risks such as reentrancy attacks, integer overflow, and gas limit constraints can undermine trust if not mitigated (Mishra and Phansalkar, 2025). The proposed system addresses these threats by adopting audited ERC standards, enforcing strict role-based controls, and implementing transaction logging. While these measures reduce exposure to common attack vectors, future iterations should undergo independent security audits. Applying formal verification methods would further strengthen robustness in production environments (Sivakumar et al., 2025).

Method

This study adopts a design-oriented and exploratory approach, grounded in the principles of Design Science Research (DSR), to develop the proposed plastic credit system using blockchain technology for implementation. As shown in Fig. 1, the research process is divided into four main phases: business process understanding and data collection, model design and construction, DApp prototyping, and system evaluation. Each phase reflects the iterative nature of DSR, integrating conceptual reasoning with practical validation. This ensures that the developed artefact addresses real-world stakeholder needs while maintaining methodological rigour and technical feasibility.

Business process understanding and data collection

The research began with an examination of existing workflows in plastic waste management, focusing on the roles of collectors,

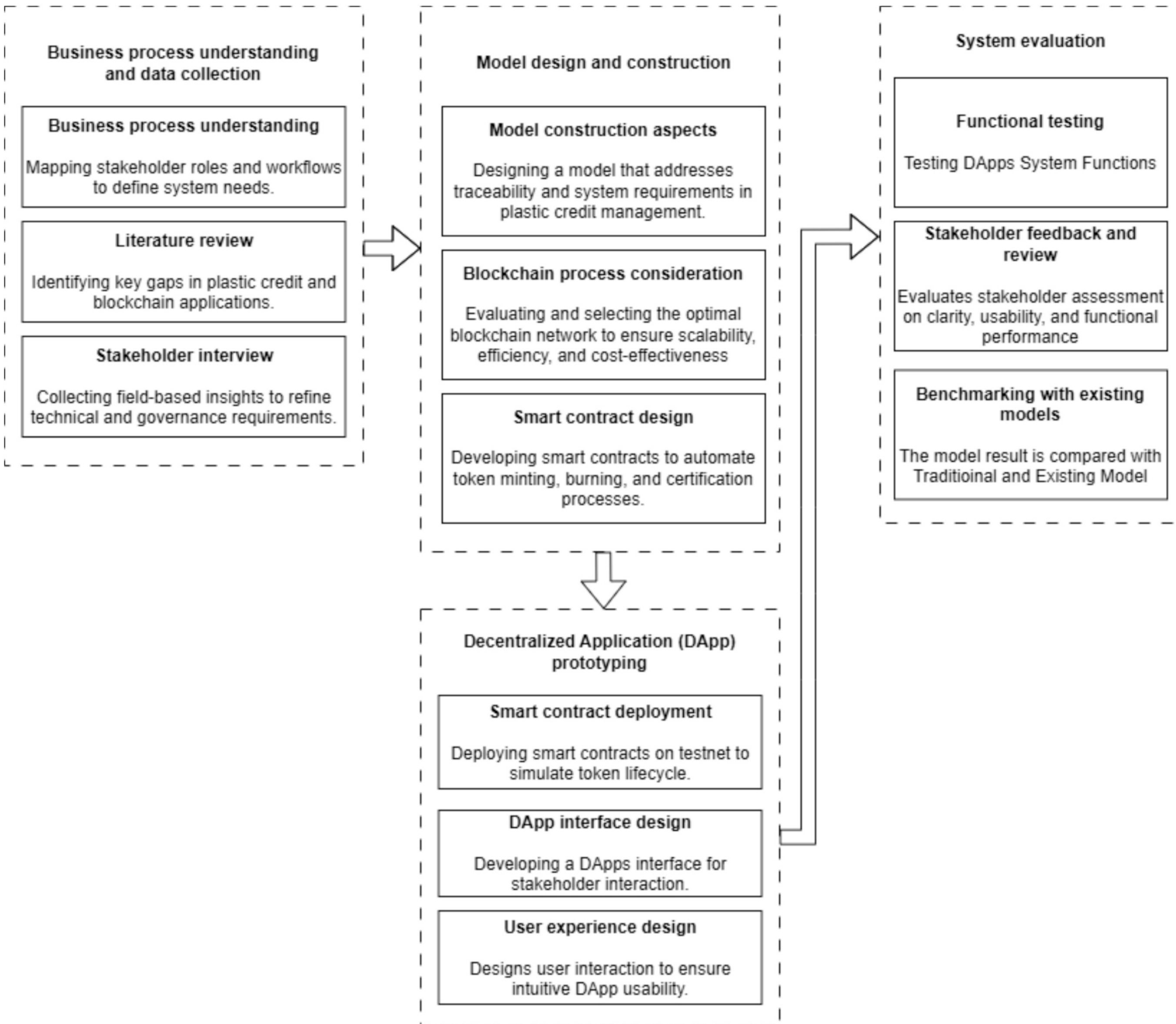


Fig. 1. Research flow diagram.

validators, and credit issuers. Stakeholder mapping was conducted to identify key operational bottlenecks and assess the potential for blockchain-based intervention. A review of relevant literature was undertaken to explore prior applications of blockchain in traceability, circular economy initiatives, and environmental credit systems. This helped establish both conceptual and technical foundations for the proposed model. To supplement these findings, semi-structured interviews were conducted with four stakeholders. They represented blockchain developers (token makers), ecological practitioners (plastic waste managers), plastic credit consumers, and a government representative. Participants were purposively selected based on their direct involvement in plastic recovery, validation, token issuance, or utilization. Each interview lasted approximately 30–45 min, and responses were thematically analysed to extract insights that informed the system's governance logic and process design.

System design and conceptual development

Based on the collected inputs, a modular system model was designed to capture the interactions between user roles, smart contracts, and data outputs. The proposed architecture adopts a three-layer approach: a User Layer to facilitate interaction, a Blockchain Layer to manage autonomous execution, and a Utility Layer for data storage and visualisation. This configuration was intended to support scalability, traceability, and decentralization. In parallel, a comparative analysis was conducted to identify the most suitable platform based on criteria such as transaction cost, energy efficiency, and smart contract support. Transaction costs were categorized as Very Low (<$0.05/transaction), Low ($0.05–$0.30), Moderate ($0.30–$0.50), and High (>$0.50), while energy efficiency was classified by Wh/transaction as Very High (<0.1), High (0.1–1), Moderate (1–10), and Low (>10). Table 1 presents a comparison of several blockchain platforms that were considered as candidates for implementation. Based on this analysis, Polygon was selected as the preferred platform due to its low transaction fees, high scalability, EVM compatibility, and robust developer ecosystem. The chosen platform enabled the deployment of two smart contracts: one based on the ERC-20 standard for PLST, and another using ERC-721 for certificate issuance via NFTs. These contracts were designed in Solidity to encode core system functions, including minting, burning, and metadata validation.

Table 1
Blockchain platform comparison.

	Ethereum	Polygon	Algorand	Binance Smart Chain (BSC)	Solana
Consensus Mechanism	Proof of Stake (PoS)	Proof of Stake (PoS)	Pure Proof of Stake	Proof of Staked Authority	Proof of History + PoS
Transactions Per Second (TPS)	~30	~7,000	~1,000	~100	~65,000
Energy Efficiency	Moderate (4 Wh/ transaction)	High (0.7 Wh/ transaction)	Very High (0.0002 Wh/ transaction)	High (0.3 Wh/ transaction)	High (0.5 Wh/ transaction)
Transaction Cost	High (~$0.51)	Very Low (~$0.01-$0.05)	Very Low (~$0.001)	Low (~$0.10-$0.30)	Very Low (~$0.00025)
Finality Time	~6 min	~2 s	~5 s	~3 s	~0.4 s
EVM Compatibility	Yes	Yes	No	Yes	No

DApp prototyping

Following the completion of system modeling and smart contract design, the next phase involved the development and prototyping of a DApp to operationalize the proposed architecture. The DApp served as a User Interface (UI) connecting stakeholders with the underlying smart contracts, enabling role-specific action, covering data submission, tracking, and certification. The user interface was built with attention to clarity, ease of navigation, and accessibility, ensuring usability for both technical and non-technical users. User experience (UX) design was integrated through scenario-based interaction flows, focused on clarity and task efficiency. These flows were structured to align with expected user behaviour and were used to guide the system's usability testing during the evaluation phase.

System evaluation and comparison

The final phase involved evaluating the system's performance and relevance through three key dimensions: technical testing, user feedback, and comparative benchmarking. We conducted functional testing in a blockchain Polygon PoS mainnet environment to assess the system's ability to execute token lifecycle operations autonomously and reliably. The evaluation criteria are summarised in Appendix A (Table A1), covering aspects such as functionality, transparency, user access control, cost-effectiveness, performance, user adoption, immutable records, and scalability. Following this, we distributed a structured questionnaire to stakeholders who interacted with the DApp through predefined scenarios. The questionnaire used a 1 to 5 point Likert scale, ranging from 1 = strongly disagree to 5 = strongly agree. The feedback was used to assess system usability, clarity, and stakeholder satisfaction. To ensure a diverse range of perspectives, the survey was administered to a group of respondents representing key stakeholder roles in the plastic credit ecosystem. The evaluation involved 52 respondents purposively selected to represent key roles in the plastic credit ecosystem. The participants comprised plastic waste managers ($n = 12$), government representatives ($n = 8$), validators ($n = 4$), plastic credit consumers ($n = 18$), and blockchain/technical experts ($n = 10$). This distribution ensured variation across technical ($n = 24$) and non-technical ($n = 28$) groups, enabling subgroup comparisons of system usability and acceptance. Technical participants included developers, validators, and digitally literate consumers, while non-technical participants comprised waste managers, government representatives, and consumers with limited prior experience of DApps. Lastly, the system was benchmarked against existing traceability platforms such as Verra and Plasticpay. The comparison focused on auditability, decentralization, and automation. This holistic evaluation provided insight into the system's strengths and areas for further refinement, while demonstrating its potential to enhance long-term traceability in support of sustainable plastic waste management goals.

Result

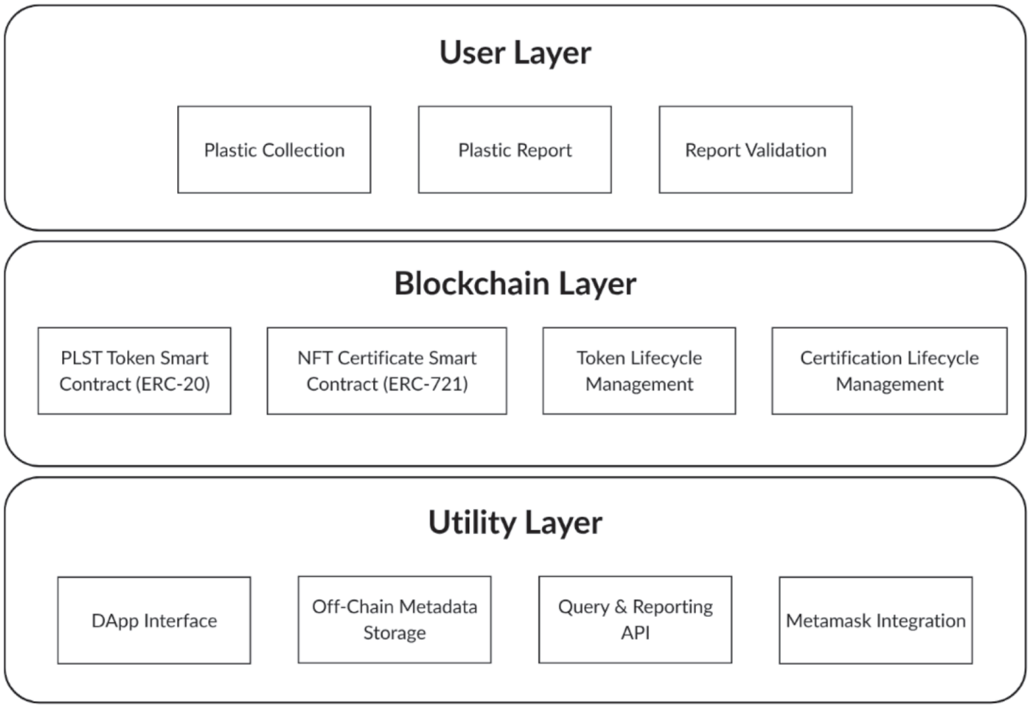
Model design and construction

The system adopts a modular architecture that enables traceable issuance and transparent management of plastic credits via blockchain. It is structured into three distinct layers: a User Layer, a Blockchain Layer, and a Utility Layer. Each layer is designed to fulfill specific roles in supporting traceability, auditability, and overall system interoperability. To visualize this layered configuration and its role in decentralized plastic credit management, Fig. 2A provides an overview of the system architecture. The User Layer contains modules such as Plastic Collection (data submission by collectors), Plastic Report (report preparation), and Report Validation (verification by validators and government authorities). The Blockchain Layer comprises smart contracts for issuing PLST Smart Contract (ERC-20) and NFT Certificate Smart Contract (ERC-721), along with lifecycle management modules. The Utility Layer supports the system with components like the DApp Interface, Off-Chain Metadata Storage via the InterPlanetary File System (IPFS), Query & Reporting Application Programming Interfaces (APIs), and MetaMask Integration for secure user authentication. Fig. 2B illustrates the operational workflow, showing how key actors interact with these modules in sequence, from waste submission and validation to token issuance and NFT certification. The workflow highlights the logical relationships between system components and stakeholders across the platform.

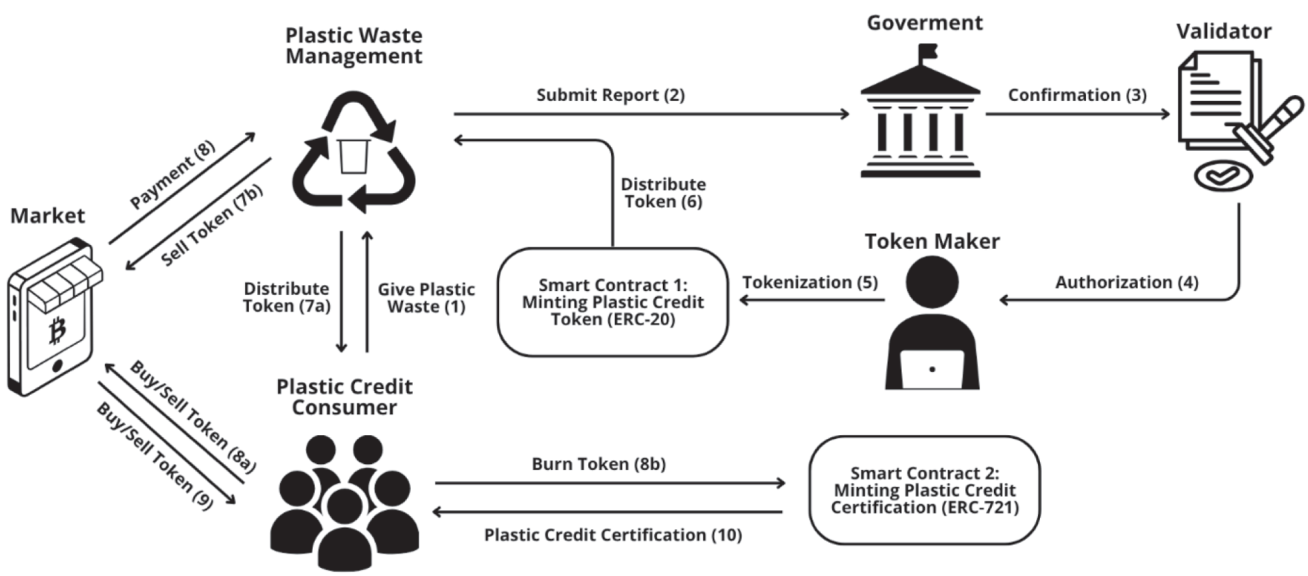
The User Layer facilitates physical interactions among real-world actors, including plastic waste collectors, credit validators, token issuers, consumers, and government authorities. Key processes at this level include plastic collection, report submission, and validation, which is performed within the DApp by both third-party validators and government authorities. These steps initiate the credit lifecycle and ensure that all activities are captured digitally. The interactions are visualized in Fig. 3, which highlights the roles of real-world actors while excluding technical components to emphasize user engagement. Detailed stakeholder roles and responsibilities are summarised in Appendix A (Table A2), outlining how each actor contributes to the system's operation. These mappings guide the implementation of role-based access control, governance mechanisms, and accountability protocols embedded in smart contracts.

Blockchain process consideration

The blockchain execution process was implemented using the Polygon PoS mainnet, chosen for its low transaction costs, high throughput, and full Ethereum Virtual Machine (EVM) compatibility. This strategic choice ensured a realistic simulation of system operations under varying loads, demonstrating its scalability and cost efficiency for large-scale deployment. The mainnet provided a realistic environment for executing smart contract interactions, ensuring consistency and reliability during the testing process. At the core of the system's architecture lies token lifecycle management and certification, implemented through



(A)



(B)

Fig. 2. System architecture and operational workflow of the plastic credit system. (A) Three-layer architecture comprising the User Layer (plastic collection, reporting, validation), the Blockchain Layer (ERC-20 Plastic Credit Token, ERC-721 NFT Certificate, lifecycle management on Polygon PoS mainnet), and the Utility Layer (DApp interface, IPFS metadata storage, reporting API, MetaMask authentication). (B) Workflow showing stakeholder interactions from waste submission and validation to PLST minting, distribution, burning, and NFT issuance, linking physical recovery with on-chain tokenization.

two smart contracts developed in the Solidity programming language. This dual-contract design establishes a functional separation between PLST operations and unique certification processes, thereby strengthening supply chain visibility and reducing operational bottlenecks. Further details on the smart contracts' functionalities and their role in managing plastic credits are discussed in Section 4.3.

Smart contract execution follows event-driven logic, activating only after multi-tiered verification processes such as plastic collection validation, role authorization, and consistency checks. This conditional execution paradigm reduces vulnerability to fraudulent or erroneous data inputs, ensuring that only verified transactions progress through the system. Safeguards within the contracts reject duplicate reports and

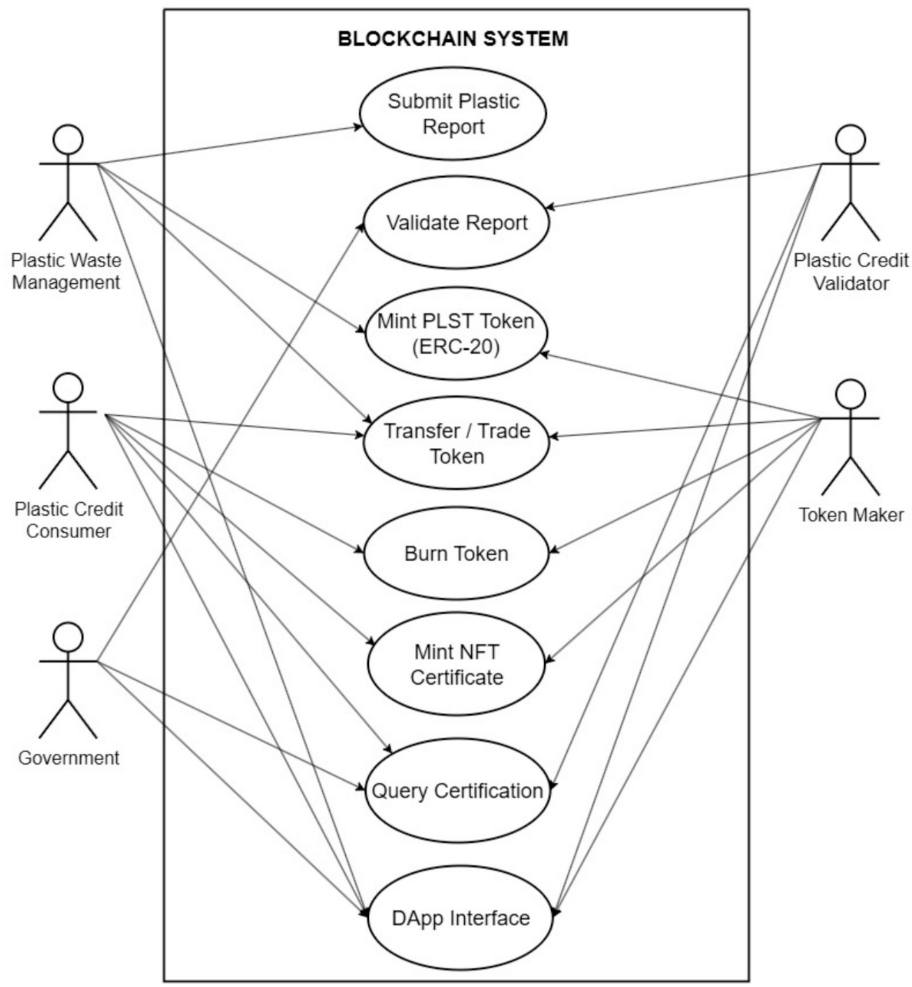


Fig. 3. Use case diagram of the plastic credit system. Stakeholders include Plastic Waste Managers (submit reports), Government and Validators (verify data), Token Makers (mint ERC-20 PLST and ERC-721 certificates), and Consumers (redeem, transfer, burn). Core functions cover report submission, validation, token lifecycle management, certificate issuance and queries, and DApp interface access, ensuring transparency and traceability.

unauthorized access, enabling trustless execution across user roles. On-chain records captured all token-related events, allowing independent audits and real-time tracking of plastic credits. In addition to strengthening data integrity, this immutable ledger provides a tamper-resistant framework critical for aligning with EPR and ESG reporting requirements. Such capabilities directly address longstanding challenges in plastic waste management systems, particularly in ensuring accountability across complex multi-stakeholder environments.

Smart contract implementation

We deployed two smart contracts to manage the end-to-end lifecycle of plastic credits. The ERC-20 smart contract was designed to ensure that each minted PLST directly corresponds to a verified recovery activity. This minimizes overissuance risks and strengthens supply chain governance. Its logic encompasses token supply management, transfer permissions, and burn rules, which collectively enforce automatic compliance with predefined recovery thresholds, eliminating the need for manual intervention. We supported dynamic adjustments to the token supply through mint and burn events, which further enhanced real-time auditability and discouraged token hoarding, thereby improving overall system integrity.

The ERC-721 smart contract manages the issuance of NFTs as digital certificates of plastic offset. By embedding metadata (e.g., recycling date, quantity, issuing organization, token ID) on IPFS and referencing it on-chain, the system ensures the immutability and verifiability of certificates. This design facilitates independent verification by regulators and third parties, which is critical for ESG reporting credibility and compliance with EPR frameworks. As verifiable environmental assets, these NFTs provide a transparent mechanism for organizations to substantiate their sustainability claims and reinforce public trust.

We rigorously tested both smart contracts on the Polygon PoS mainnet. The results confirmed functional accuracy, secure state transitions, and role-based access enforcement, demonstrating system resilience and scalability for real-world deployment. The incorporation of role-based function modifiers, event emission logging, and metadata hashing enhances institutional trust and mitigates the risks of unauthorized actions, thereby supporting decentralized governance models. The complete pseudocode for these contracts is presented in Appendix A (Algorithm 1 for ERC-20 token minting and Algorithm 2 for ERC-721 NFT certification). The complete smart contract implementation is available at: https://github.com/Saekkkk/plastic-credit-smart-contracts.

DApp prototyping results

The DApp prototype serves as the primary user interface connecting stakeholders to the plastic credit system. By supporting multiple user roles such as plastic collectors, validators, credit issuers, and plastic consumers, the DApp enables multi-stakeholder participation. It also ensures that each role operates within defined permissions and tailored dashboards. The interface integrates wallet authentication (via MetaMask), form-based data submission, transaction tracking, and real-time interaction with deployed smart contracts. This design enables the seamless orchestration of verification workflows and plastic credit issuance, while maintaining security and operational efficiency. All DApp modules functioned as expected during testing, validating its operational reliability and usability across diverse user groups.

The plastic collection submission module allows users to provide recovery details such as location, volume, plastic type, and photographic evidence. Once validated, users proceed to the certificate issuance interface to burn PLST, select an NFT template, and input metadata for offset certification. The DApp also includes a certificate verification interface for validating NFT authenticity using token IDs or contract addresses, and a consumer-facing marketplace that displays verified PLST along with token prices and recovery data. These components support end-to-end traceability, from plastic recovery to on-chain certification and credit redemption. Their designs and functionalities are detailed in Appendix A (Figs. A2-A5).

The DApp modular design supports coordinated and verifiable execution from data submission to marketplace integration. Aligning user interactions with automated smart contract functions minimizes administrative overhead, reduces reliance on intermediaries, and ensures reliable tracking of plastic recovery outcomes. This architecture indicates how a DApp can bridge real-world environmental action with blockchain infrastructure. It is also designed to support scalable, inclusive, and user-friendly plastic credit systems that foster trust among stakeholders. Furthermore, during testing the prototype, off-chain data verification was also simulated through a dual-authorization workflow. Plastic recovery data submitted by collectors via the DApp required approval from both a third-party validator and a government representative before plastic credits could be issued. This process mirrors how documentary evidence (e.g., recovery receipts or certificates) would be validated in practice prior to being recorded on-chain. By incorporating this step, the prototype demonstrates how governance rules can be enforced to prevent unverified claims from being tokenized, thereby strengthening the reliability of the overall system.

System evaluation

The system was evaluated across eight key criteria: functionality, transparency, user access control, cost-effectiveness, performance, user adoption, immutable records, and scalability. These criteria were previously defined in the evaluation matrix presented in Table 2 (Section 3.4), which integrates technical, operational, and user-centered dimensions relevant to blockchain-based waste management systems. The following subsections assess each dimension based on prototype performance, user feedback, and system-level observations. Functional testing confirmed reliable execution of token lifecycle operations across all user roles, demonstrating robust logic and role-based access control. Transparency and traceability were operationalized through blockchain records, publicly accessible transaction explorers, and metadata-linked NFT issuance. As illustrated in Appendix A (Fig. A6), on-chain validation via the Polygon PoS mainnet enables verifiable tracking of plastic credit transfers and reinforces auditability within a decentralized infrastructure.

To assess user satisfaction and adoption, a structured 14-item questionnaire was distributed following user interaction sessions with the DApp. Each item was rated using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) and covered aspects such as ease of use, task flow, access clarity, performance, and trust in on-chain data. The results showed an average satisfaction score of 4.32, equivalent to 86.4 %, indicating a high level of acceptance and usability. The highest-scoring item (4.38) highlighted users' confidence in performing plastic credit transactions without technical disruptions. The lowest score (4.21) was recorded for role-based access clarity, indicating difficulties in distinguishing accessible functions across different user roles. An illustration of this usability issue is provided in Appendix A (Fig. A7). This suggests the need to enhance interface indicators or implement feature filtering based on login status. These findings indicate strong usability and functional alignment, while highlighting opportunities to improve user guidance and reduce learning curves for diverse stakeholder groups. Exploratory statistical comparisons between technical ($n = 24$) and non-technical ($n = 28$) groups showed no significant differences in overall satisfaction (Mann–Whitney $U = 344.0$, $p = 0.889$). However, non-technical participants more frequently noted challenges with role-based access clarity.

Scalability and performance were assessed through a stress test using the Polygon PoS mainnet, as detailed in Appendix A (Fig. A8). The platform achieved a 98.6 % successful execution rate over 5000 transactions. Average confirmation times were 5.29 s for PLST and 5.59 s for NFT, indicating stable throughput under sustained loads. This level of performance validates operational stability and supports feasibility for high-volume deployments. These results confirm that the platform can maintain consistent responsiveness and reliability, enabling real-world application scenarios in plastic credit systems. The total failure rate was 1.4 % (70 failed transactions). Of these, 60 % (42 transactions) were caused by insufficient gas price configurations, while 40 % (28 transactions) were due to nonce mismatches. To address these issues, the future design includes recommendations for dynamic gas adjustment, nonce management mechanisms, and clearer user interface prompts, in addition to more robust error handling and user training. If we compared to academic research, Liu and Zhang (2021) reported simulated throughputs of 16–58 tx/s using a consortium–public hybrid architecture. Meanwhile, Zhang et al. (2023) achieved millisecond-scale execution (7.8–20.5 ms) on Ethereum test networks. However, these results were obtained in controlled environments and do not reflect the

Table 2
Comparative feature analysis of existing plastic credit systems and the proposed system.

	Verra (Verra, n.d.)	Plasticpay (PlasticPay, n.d.)	Plastic Bank (Plastic Bank, n.d.)	Empower.eco (Empower.eco, n.d.)	Our Proposed System
Smart Contract Execution	No (Registry and crediting are manual)	No (Digital credits but not on smart contracts)	No (Operates on internal database)	No (Mentions blockchain but no public smart contracts)	Yes
Digital Credit Issuance	No (Credits issued manually)	Partial (Digital eco-credits but still centralized)	No (Credits managed internally, not tokenized)	Yes (Issues blockchain-verified plastic credits)	Yes
Certification Mechanism	Manual (Auditor-based certification)	Manual (Operator-based certification)	Internal system without transparency	Partial (Blockchain verification but not standardized)	NFT-based
Traceability and Auditability	Limited (Registry only, not real-time)	Partial (App tracking but not fully auditable)	Partial (Claims blockchain traceability but proprietary)	Partial (Provides traceable credits but limited transparency)	Full
Role-based System Access	Partial (Defines roles but not on-chain)	Yes (Roles for collectors, partners, and clients)	Partial (Roles exist but not programmable)	No (Roles not clearly defined)	Yes
Platform Interactivity	No (Static registry, minimal interaction)	Yes (App allows users to collect and redeem credits)	Partial (App for members but limited openness)	No (Mainly for credit purchase)	Yes
Plastic Credit Trading	No (Credits only issued or retired)	Partial (Earn and redeem credits, no open marketplace)	No (Provides rewards but not tradable credits)	No (Credits can be bought or generated, but no open market)	Yes

dynamics of public blockchains (Liu and Zhang, 2021; Zhang et al., 2023). By contrast, our Polygon PoS mainnet deployment processed 5,000 transactions with confirmation times of 5.29–5.59 s at a cost of only US$0.0055, demonstrating stronger external validity and production-grade feasibility.

To benchmark the system against existing solutions, we conducted a comparative analysis across major plastic credit systems, including Verra, Plasticpay, Plastic Bank, and Empower.eco. As summarized in Table 2, this comparison highlights several advantages of the proposed plastic credit system. These include smart contract enforcement, digital credit issuance, transparency, and role-based access to features. Unlike centralized counterparts, the proposed system offers real-time auditability, integrated marketplace functions, and NFT-based certification, positioning it as a scalable and decentralized alternative for plastic offset management.

This comparison underscores the system's ability to address limitations observed in existing platforms. Unlike broader carbon or water credit frameworks discussed in the literature, the proposed plastic credit system directly operationalizes traceability in plastic recovery workflows, bridging the gap between environmental governance requirements and on-the-ground waste management practices. Cost-effectiveness emerged as a key advantage of the system's architectural and infrastructural design. By deploying the platform on the Polygon PoS mainnet, transaction costs per operation remained consistently low, with gas fees averaging around 0.0195 POL per transaction (approximately $0.0055 USD at current rates). This value was calculated based on actual mainnet conditions and is even lower than the Very Low category defined in Table 1 (Section 3.2), which ranges from ~$0.01 to $0.05. This reduction in operational expenses compared to traditional systems, which may reach several dollars in administrative costs per certificate, highlights the financial efficiency of the blockchain-based approach. The use of smart contracts for verification and issuance also reduces manual oversight requirements. This lowers barriers to adoption and supports wider scalability across diverse international contexts. This efficiency highlights the system's scalability potential in low-governance or high-volume contexts, making it adaptable to various environmental and regulatory conditions.

To synthesize the technical and operational performance, the consolidated evaluation results are presented in Table 3. These findings reinforce the system's potential for scalable deployment and long-term reliability. The results highlight how plastic credit systems can address key limitations in traceability, cost-efficiency, and governance found in conventional frameworks, advancing Indonesia's circular economy agenda and supporting broader ESG alignment.

Table 3
Summary of system evaluation results based on eight criteria.

Evaluation Criteria	Indicators / Measures	Result Summary
Functionality	Successful execution of token lifecycle operations	All token lifecycle operations performed as expected under defined user roles
Transparency	On-chain data visibility, NFT metadata linkage, public explorer access	Achieved via blockchain logs and metadata verification (Appendix A, Fig. A6)
User Access Control	Role-based permissions and interface clarity	Fully functional; minor improvements suggested (score: 4.21/5) for UI-based access clarity
Cost-effectiveness	Average transaction fee per operation (Table 1)	Average around 0.0195 POL per transaction (approximately $0.0055 USD), significantly lower than traditional certificate processing costs
Performance	Transaction response time and success rate over 5000 operations	Avg. confirmation: PLST = 5.29 s, NFT = 5.59 s; 98.6 % successful execution rate under stress test
User Adoption	User satisfaction from a 14-item Likert-scale survey	Overall satisfaction score of 4.32/5 (86.4 %); high usability and positive user experience
Immutable Records	Blockchain event logging	All operations are immutably recorded on-chain, ensuring data integrity and auditability
Scalability	Stress test across high-volume transactions	Maintained low confirmation times and stable throughput across 5000 transactions (Appendix A, Fig. A8)

Discussion

The results presented in Section 4 demonstrate the technical feasibility, scalability, and cost-effectiveness of the proposed plastic credit system. Smart contract automation for token issuance and NFT certification achieved consistent performance and low transaction costs under stress testing. Comparative analysis also highlighted its advantages over existing plastic credit platforms. These findings provide a foundation for exploring practical, institutional, and policy implications, as discussed in the following sections.

Practical and technological implications

This section discusses how the proposed platform improves traceability and verifiability in plastic waste management by analyzing its practical and technological implications. The system developed in this study offers transformative potential for improving the credibility of plastic waste recovery initiatives by ensuring verifiable and tamper-proof transactions. Preliminary projections suggest that applying this system to 10 % of Indonesia's plastic waste could divert 780,000 tonnes annually from mismanagement. This represents a significant contribution to the country's target of reducing plastic leakage by 70 % by 2025. Scaling the system to 25 % or 50 % of national plastic waste streams could potentially divert 1.95–3.9 million tonnes of plastic waste annually, accelerating progress toward SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water).

Unlike conventional credit mechanisms that rely on centralized oversight, this solution employs smart contracts to enable programmable and tamper-evident governance, as demonstrated in the Results section. By separating credit quantification from certification, the architecture improves supply chain visibility and enables robust on-chain validation. This functional separation empowers regulators and consumers to independently verify plastic credits, strengthening institutional trust. It also highlights blockchain's potential as a foundational infrastructure for environmental accountability, bridging data gaps that hinder EPR and ESG reporting systems.

The modular DApp developed in this research facilitates multi-stakeholder engagement and decentralized verification workflows. For producers, it strengthens compliance tracking under EPR schemes. Auditors and stakeholders benefit from a transparent platform for certifying plastic offset transactions and monitoring progress. This functionality is particularly critical in Indonesia, where fragmented data infrastructures and limited formal verification channels pose persistent challenges. The dual-authorization process requires approval from both third-party validators and government authorities. This enhances verification integrity and reduces reliance on a single entity. However, it does not entirely eliminate reliance on off-chain data, introducing residual vulnerabilities such as validator collusion or reporting errors, commonly referred to as the oracle problem. To mitigate the oracle problem, potential strategies include decentralized oracles aggregating independent data sources, reputation systems assigning trust scores to validators, and IoT-enabled devices capturing real-time recovery data. Each option involves trade-offs between cost, technical complexity, and scalability, warranting further empirical investigation. While decentralized oracles enhance data integrity, they may increase latency and transaction costs by 15–20 %. IoT sensors mitigate off-chain data risks but require upfront investment and technical expertise for successful field deployment.

Another critical dimension concerns blockchain-specific security threats. Public blockchain infrastructures are theoretically vulnerable to 51 % attacks, where a majority of network power could manipulate transaction history. They are also at risk of Sybil attacks, where adversaries generate multiple identities to influence consensus. These risks are mitigated in Polygon PoS through its large validator set, staking-based incentives, and slashing mechanisms that make collusion economically infeasible. The threat of malicious validators is further reduced at the application layer in our design, as credit issuance requires dual authorization from both independent validators and government representatives. This layered approach demonstrates that while blockchain threats remain a theoretical concern, the combination of consensus-level protections and governance safeguards ensures robust security for real-world plastic credit operations.

Equally important is the potential exclusion of informal sector workers, who often play a central role in plastic recovery but may face barriers in adopting digital systems due to limited literacy or access to technology. To address this, the framework incorporates capacity-building measures such as short training workshops and mobile-based tutorials tailored to waste pickers and cooperatives. It also includes incentive schemes such as subsidized fees or bonus credits to encourage participation, and collaboration with non-governmental organizations (NGOs) and municipal waste programs that already engage informal workers. Embedding these measures promotes social inclusivity, builds trust in the system, and ensures that plastic credit systems enhance rather than marginalize the contributions of the informal sector. Beyond solving validation challenges, this plastic credit system also lays a foundation for broader applications such as real-time ESG reporting, interoperability with national waste registries, and dynamic taxation mechanisms linked to verified plastic recovery, mirroring innovations in blockchain-based carbon markets.

Institutional readiness and legal considerations

We analyse how institutional readiness and legal frameworks influence the ability of plastic credit systems to enhance traceability and credibility in plastic waste management. Despite the system's technical viability, institutional readiness remains a critical determinant for successful implementation. The Indonesian regulatory landscape presents significant challenges. These include the legal recognition of NFTs, the enforceability of smart contracts, and the classification of digital tokens within existing financial and regulatory frameworks. Current EPR regulations, such as Minister of Environment and Forestry Regulation No. 75 of 2019, do not explicitly address blockchain-based verification systems. This regulatory gap creates uncertainty for institutional actors and underscores the need for updated policy frameworks to legitimize digital credit systems in national waste management strategies (KLHK, 2019).

There is also legal uncertainty surrounding the use of public blockchain networks for storing environmentally sensitive data. While transparency is a technical strength of blockchain, compliance with Indonesia's Personal Data Protection Law (Law No. 27 of 2022) introduces additional governance considerations (DPR RI, 2022). The law defines protections for personal and institutional data, which could extend to environmental recovery data linked to identifiable actors. This highlights a governance challenge where data privacy must be balanced with the need for public verification and transparency. Government entities, particularly the Ministry of Environment and Forestry or Kementerian Lingkungan Hidup dan Kehutanan (KLHK), are expected to play a pivotal role. They should validate smart contract logic, endorse technical standards, and enable integration with national environmental data systems. Relevant platforms include the National Waste Management Information System or Sistem Informasi Pengelolaan Sampah Nasional (SIPSN) and the Environmental Information System or Sistem Informasi Lingkungan Hidup (SILH). These platforms already function as national databases for waste tracking and reporting, providing a practical entry point for interoperability (KLHK, 2023). Institutional collaboration will be essential to formulate regulatory guidelines and technical specifications that legitimize tokenized plastic credits. Inclusive stakeholder consultation and iterative policy development are critical for aligning blockchain innovation with national environmental governance and sustainability goals.

To advance practical implementation, a policy pilot could be initiated in partnership with KLHK. This pilot project would test the integration of plastic credit system verification with SIPSN and SILH through API-based interoperability. Verified smart contract transactions, including token minting and NFT issuance, can be transmitted in real-time to national platforms, enabling regulators to monitor plastic offset activities effectively and transparently. This approach aligns with Indonesia's circular economy agenda and establishes technical groundwork for national-scale traceability and auditability of plastic credits.

To support experimentation in a controlled environment, KLHK could consider establishing a regulatory sandbox for blockchain-based waste traceability systems. This model could draw inspiration from the financial technology sector, where Indonesia's Financial Services Authority or Otoritas Jasa Keuangan (OJK) has implemented a sandbox to evaluate emerging technologies under a limited scope and duration. Such a sandbox would enable the controlled deployment of plastic credit systems while assessing technical, legal, and societal impacts. It would also provide legal certainty for involved stakeholders and guide the formulation of national technical standards for digital environmental credits. This approach allows innovation to proceed while safeguarding policy coherence and regulatory oversight.

Beyond national integration, cross-border interoperability is also critical. International platforms such as the Plastic Credit Exchange (PCX) (PCX Markets, n.d.) and Verra's Plastic Waste Reduction Standard (PWRS) (Verra, 2021) provide globally recognized frameworks, but they rely on centralized registries and manual certification. The proposed system is technically capable of integration by aligning smart contract logic with existing methodologies and bridging tokenized credits into global registries through standardized APIs. However, practical adoption still faces governance challenges, including data equivalence, risks of double counting, and the legal recognition of blockchain-based certificates across jurisdictions. These issues indicate that integration is feasible in principle but will require close coordination with international regulators and standard-setters.

Limitations and future work

This section examines how the system's limitations and potential future enhancements affect its ability to enhance traceability and authenticity in plastic waste management. While the proposed system suggests potential benefits in terms of functionality, verification integrity, and user acceptance, several limitations should be acknowledged. All performance evaluations were conducted on the Polygon PoS mainnet, which provides a realistic measure of transaction costs and confirmation times. However, external factors such as network congestion, operational latency, and public network volatility may still affect scalability and long-term feasibility under real-world conditions. "In addition, transaction fees remain subject to gas price variability and potential network congestion on the Polygon PoS mainnet, which may influence cost-effectiveness and responsiveness under peak loads. Future studies should incorporate sensitivity analysis of these conditions to strengthen scalability projections.

The current experiments focused on sequential loads up to 5000 transactions. High-concurrency scenarios (e.g., simultaneous multi-node activity or 1000 + TPS) and mixed read/write workloads were not yet evaluated and should be addressed in future studies. Finally, the absence of incentive mechanisms limits the scalability of the system, which is critical for stimulating user engagement in real-world market settings. Future iterations should explore dynamic credit pricing models to reward early adopters, staking-based rewards for validators to maintain network integrity, and micro-rewards for waste pickers submitting verified recovery data. In addition to the performance evaluations presented earlier, economic modeling of these incentives could help predict their impact on participation rates and plastic leakage reduction. For instance, micro-rewards of $0.05 to $0.10 per kilogram could provide additional income of $50 to $100 per tonne recovered, creating financial motivation for active participation while keeping operational costs manageable for producers.

While the sample size (n = 52) improves descriptive precision and enables subgroup comparisons, the purposive, non-probability sampling design limits generalizability. Future studies should employ probability sampling and larger-scale pilots (≥100–200 participants) to enhance external validity Socio-technical barriers may still hinder adoption. These include disparities in digital literacy among informal sector participants such as waste pickers and community-run recovery facilities. Although the DApp has proposed targeted capacity-building measures, their effectiveness still requires validation through real-world deployment. Building trust in the system will also require transparent governance frameworks, clearly defined roles for public regulators, and legal safeguards to support institutional alignment. Therefore, future work should prioritize pilot projects with registered producers, local governments, and EPR-compliant recovery partners to validate inclusivity measures and to evaluate technical scalability and policy alignment under real-world conditions.

Integrating the platform with national waste data systems such as SIPSN and SILH via API-based interoperability could support national-level traceability and regulatory oversight. Additionally, incorporating IoT-based sensors and automated data feeds may enhance operational transparency and address off-chain data validation challenges. Long-term assessments across diverse contexts will also be needed to evaluate the system's adaptability and its impact within varied waste governance environments. Finally, future work should also consider aligning the proposed system with international standards such as ISO 22095 and ISO 14064 to enhance institutional credibility and interoperability with formal certification processes.

Conclusion

This study provides an explicit answer to how a plastic credit system can improve traceability and verifiability in plastic waste management. Leveraging blockchain infrastructure, the proposed system ensures reinforces trust and transparency in plastic recovery activities. Smart contract automation and decentralized certification strengthen accountability and trust across the credit lifecycle without relying on centralized oversight. These features establish a scalable, tamper-resistant framework for integrating plastic credits into diverse waste governance settings, supporting EPR and ESG disclosures. These findings further reinforce blockchain's capacity to bridge gaps between formal and informal recycling sectors by enabling inclusive participation and transparent verification, underscoring the importance of ongoing assessment across diverse policy and operational contexts. This also highlights blockchain's transformative potential in advancing circular economy goals and supporting global sustainability initiatives.

CRediT authorship contribution statement

Andry Alamsyah: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Said Fikri Naufal Ramdhani:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wmb.2025.100250.

Data availability

The complete smart contract implementation supporting the findings of this study is available at: https://github.com/Saekkkk/plastic-credit-smart-contracts.

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