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Blockchain Model for Tracking Plastic Waste Using Smart Contracts to Reduce Emissions

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Abstract: This research focuses on the design and development of a blockchain-based plastic waste tracking system aimed at enhancing transparency, efficiency, and accountability in plastic waste management. The system utilizes Hyperledger Fabric as a permissioned blockchain platform and integrates smart contracts to manage transactions between organizations, including waste generators, collectors, sorting warehouses, and final processing warehouses. This system records each stage of the plastic waste journey, from creation to final processing, in a permanent, transparent, and immutable manner. The testing results demonstrate that the system can accurately record the status and history of waste, manage transfers between organizations, and process plastic waste into recycled products. Moreover, the system shows a significant potential for carbon emission reduction, with an estimated reduction of up to 50% compared to traditional plastic waste management methods, such as incineration or landfilling. The study also explores how the implementation of blockchain can support global efforts in mitigating the environmental impacts of plastic waste. The blockchain-based system also provides real-time monitoring, ensuring that each transaction is verified and recorded immediately, contributing to more effective management. The implementation of smart contracts further guarantees that waste-related activities are executed automatically when predefined conditions are met, reducing administrative overhead. The study also explores how the implementation of blockchain can support global efforts in mitigating the environmental impacts of plastic waste. Ultimately, this system presents a scalable solution that could be adopted in various regions to improve global waste management strategies.

Keywords: Blockchain; Carbon Emissions; Plastic Waste; Recycling; Smart Contracts.

INTRODUCTION

Climate change is an urgent global challenge, driven largely by rising greenhouse gas emissions, particularly carbon dioxide (CO_2), which significantly accelerates global warming and poses a severe threat to ecosystems and human health (Masson-Delmotte et al., 2021). A critical but often overlooked contributor to these emissions is plastic waste, which continues to accumulate globally and is increasingly difficult to manage. Annually, approximately 400–450 million tons of plastic waste are produced worldwide, yet only 9% of it is recycled. The rest is either incinerated, landfilled, or disposed of improperly, releasing harmful carbon emissions into the atmosphere (Geyer et al., 2017; Ritchie et al., 2023; Tsakona et al., 2021; Tumu et al., 2023). The incineration of plastic not only produces CO_2 but also releases other hazardous compounds that degrade air quality and endanger human health (Bardales Cruz et al., 2023; Environment, 2021). In some regions, recycling rates have dropped to as low as 5–6%, with most single-use plastics ending up in landfills (Wakefield, 2022).

Plastic production and disposal account for about 3.3%-4.5% of global greenhouse gas emissions, equating to 1.8 billion tonnes in 2019 (Ritchie, 2023). Additionally, the refinement of plastics emits 184-213 million metric tons of greenhouse gases annually, and landfills contribute more than 15% of global methane emissions, mostly from single-use plastics. If left unaddressed, plastic production and waste management could consume up to 13% of the global carbon budget by 2050, exacerbating climate change (Sharma et al., 2023).

Improperly managed plastic waste worsens the environmental crisis by polluting oceans, land, and air, and contributing to more severe climate change impacts (Hakim, n.d.). Efficient and transparent plastic waste

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management is therefore essential to mitigate these negative consequences (Ayu Wulandari & Sultan Aji Muhammad Idris Samarinda, 2023). Traditional waste management systems often lack transparency and are vulnerable to data manipulation, making it difficult to verify whether plastic waste is properly recycled or processed (Vargas, 2025). As a solution, the implementation of a traceability system that tracks the journey of plastic waste from its creation to final processing offers a promising way forward (M. Fajar Wirayudha & Paniran Paniran, 2024).

Blockchain technology presents a promising solution to this problem. By offering decentralized, immutable, and transparent transaction records, blockchain enhances transparency and accountability in waste management (Bułkowska et al., 2024). This technology ensures that every step in the plastic waste journey—from collection to final processing—is accurately recorded and verifiable, preventing data manipulation (Kouhizadeh & Sarkis, 2018). Smart contracts (chaincode), integrated into blockchain systems, automate processes, minimize human error, and ensure compliance with regulatory guidelines, making them crucial in optimizing plastic waste management (Desy Apriani et al., 2023).

This research proposes to design and develop a blockchain-based plastic waste tracking system, integrating smart contracts to improve transparency and accountability (Ahmad et al., 2021). The study was conducted in Parepare and Makassar, South Sulawesi, focusing on plastic waste management practices in these regions. While existing research has focused on plastic waste management, traditional systems still fail to provide the transparency and efficiency necessary to address this global issue effectively. Given the urgent need to reduce carbon emissions and combat climate change, it is evident that more sophisticated solutions are necessary. By leveraging Hyperledger Fabric, a permissioned blockchain platform, this system aims to enable secure and transparent interactions between stakeholders—waste producers (users), collectors, sorting facilities, and final processing warehouses (Le et al., 2022). Each transaction will be recorded on the blockchain, ensuring an immutable audit trail and safeguarding data integrity from tampering (Inayatulloh, 2024).

This blockchain solution will advance existing research on waste management by integrating innovative technology and improve the efficiency of plastic waste management in Parepare and Makassar. By promoting environmentally friendly practices and reducing carbon emissions, the system aligns with global sustainability efforts (Pradhana et al., 2022). Furthermore, this study will explore how blockchain technology can support global efforts to mitigate the environmental damage caused by improperly managed plastic waste, offering a significant step forward in overcoming the limitations of current systems and achieving environmental goals. The findings of this research will benefit local authorities, waste management companies, and policymakers in Parepare and Makassar who are working to improve plastic waste management practices.

METHOD

This study adopts the Design and Development Research (DDR) approach to design, develop, and evaluate a blockchain-based plastic waste tracking system. The DDR approach was chosen because it provides a systematic framework for developing and validating practical technological solutions to address challenges in plastic waste management and reduce carbon emissions from inadequate plastic disposal. As defined by Richey and Klein (2007), DDR comprises structured phases: needs analysis, design and development, and evaluation, enabling other researchers to easily replicate and extend the method (Hanis et al., 2025; Padzil et al., 2021).

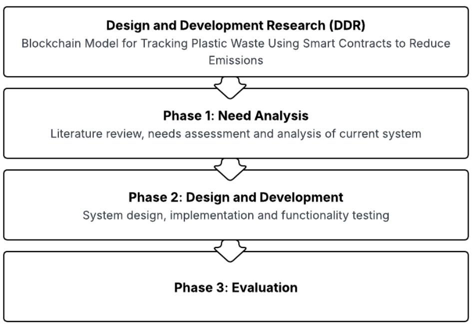

Fig. 1 Method Research Flow Chart

Literature Review

This research begins with a comprehensive review of existing literature on blockchain-based plastic waste tracking models, smart contract applications, and carbon emissions measurement approaches in waste management. Prior studies have shown the potential of blockchain to improve transparency and traceability in plastic waste supply chains, ensuring data integrity and accountability (Bułkowska et al., 2024; Inayatulloh, 2024).

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Smart contracts automate transactions, minimize human error, and ensure compliance with waste management regulations (Desy Apriani et al., 2023; Kouhizadeh & Sarkis, 2018).

However, while significant progress has been made, most existing research has focused on pilot studies or specific waste sectors, such as paper recycling or marine plastics, without integrating blockchain and smart contracts into a comprehensive plastic waste management system. Research on carbon emission reductions resulting from plastic waste management using blockchain remains limited, particularly in regional contexts like Parepare and Makassar, South Sulawesi. Therefore, this study aims to fill this gap by designing a blockchain-based plastic waste tracking model that integrates smart contracts for automated management, although the real-world implementation of the model has not yet been conducted.

This study aims to design a model that can measure carbon emission reductions based on local practices in Parepare and Makassar, with comprehensive stakeholder engagement.

Needs Analysis

This phase focuses on understanding the flow of plastic waste and identifying the system's technical requirements. Observations and direct interviews are conducted with stakeholders, including residents, collectors, and final processors. The results of this analysis ensure that the system design aligns with real-world conditions and operational needs.

System Design

The system design phase involves the creation of a blockchain-based plastic waste tracking system, which is developed in the following steps:

1. Blockchain Architecture
   The design of the Hyperledger Fabric architecture is crucial for the system. The architecture consists of four key organizations:
   a. User (Waste Generator): The entity producing the plastic waste.
   b. Collector (Waste Collector): The organization responsible for collecting the waste.
   c. Sorting Warehouse (Sorting Warehouse): The facility where the waste is sorted.
   d. Final Processing Warehouse (Final Processing Warehouse): The location where the waste is processed into recyclable materials.
2. Smart Contracts
   Smart contracts (chaincode) are designed to manage the status of plastic waste throughout its lifecycle, including its creation, transfer between organizations, and final processing. These contracts ensure that each transaction is automated and secure, facilitating seamless communication between organizations.
3. Waste Tracking Transaction Flow
   This step defines the transaction flow for recording the status of plastic waste, including its transfer history between organizations and the results of its final processing. All transactions are logged on the blockchain to guarantee transparency, immutability, and data integrity.

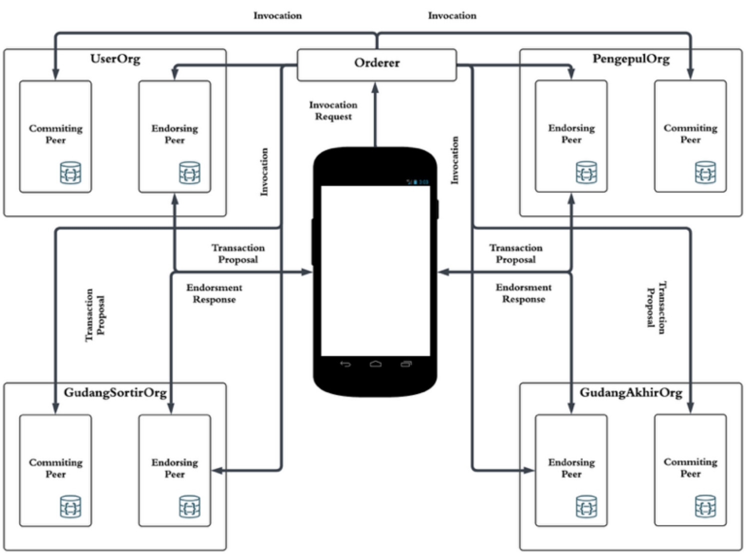

Fig. 2 Blockchain-Based Plastic Waste Tracking System Architectur (Illustrated by the author based on the research findings)

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The system design in Figure 1 is based on the author's research findings and the development of the Hyperledger Fabric architecture, which involves four key organizations: user, collectors, sorting warehouses, and final processing warehouses.

System Implementation

Once the system is designed, the next phase focuses on implementing the blockchain-based plastic waste tracking system. The implementation consists of the following key steps:

1. Blockchain Network Setup
   The Hyperledger Fabric blockchain network is set up to establish a peer-to-peer network among the four organizations involved. Each organization will maintain a peer node to record and verify transactions within the network.
2. Smart Contracts (Chaincode) Development
   Smart contracts are developed to manage the full lifecycle of plastic waste, from its creation and transfer between organizations to its final processing. These contracts are essential for ensuring that all operations are performed automatically when predefined conditions are met.
3. API Layer Development
   A Node.js-based backend API is developed to facilitate communication between users and the blockchain. This API ensures smooth interaction with the blockchain, enabling users to submit data, track transactions, and retrieve information related to plastic waste.

Table 1. API Endpoints Table

Endpoint	Description
[POST] /waste	Create a new plastic waste record
[PUT] /waste/:id/transfer	Change the status of plastic waste by transferring it to another organization
[PUT] /waste/:id/process	Process the plastic waste in the final warehouse and record the processing results
[GET] /waste/:id	Retrieve information about a specific plastic waste record

Functionality Testing

Functionality testing is performed to verify that the system operates as expected. This includes conducting simulation tests and limited trials within a single plastic waste supply chain to confirm the transaction flow and waste processing functionality.

Evaluation

The system will be evaluated based on its ability to reduce carbon emissions from recycled plastic waste. The emission reduction will be calculated using the following formula:

$$Emissions\ Avoided = Plastic\ Waste\ Mass\ x\ Plastic\ Emission\ Factor\ (kg\frac{CO_2e}{kg}waste) \quad (1)$$

Where, Plastic Waste Mass: The amount of recycled plastic waste (kg) and Plastic Emission Factor: The carbon emitted per kilogram of recycled plastic waste, obtained from environmental agency reports or related research.

RESULT

This section presents the results of testing the blockchain-based plastic waste tracking system model, developed using Hyperledger Fabric and smart contracts. The goal is to assess the model's functionality and evaluate its potential impact on plastic waste management and carbon emission reduction.

System Model Testing

The system was tested through several stages to ensure its functionality, focusing on three primary processes: waste creation, transfer between organizations, and processing. The system's effectiveness was evaluated by simulating the full lifecycle of plastic waste within the tracking system.

1. System Functionality
   Testing the system functionality showed that the model can accurately record the status and history of plastic waste throughout its lifecycle. The following are the results of the tests conducted:
   a. Waste Creation

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The system successfully recorded plastic waste with a unique ID, photo, type of plastic, weight, and an initial status of "created".


```json
{
    "result": [
        {
            "Key": "WASTE_20250725_034305_001",
            "Record": {
                "id": "WASTE_20250725_034305_001",
                "photo": "base64encodedphoto1",
                "processedResult": {
                    "outputProducts": "",
                    "processedBy": "",
                    "processedDate": "",
                    "qualityGrade": "",
                    "recyclingRate": 0
                },
                "status": "created",
                "transactionTime": "2025-07-25T03:43:05Z",
                "transferHistory": [],
                "user": {
                    "userID": "USER001",
                    "userName": "Alice Johnson"
                },
                "waste": {
                    "id": "PLASTIC_WASTE_20250725_034305_001",
                    "plasticType": "PET",
                    "weight": 2.5
                }
            }
        }
    ],
    "error": null,
    "errorData": null
}
```


Fig. 3 Waste Transaction Record

b. Waste Transfer
The transfer of waste between organizations has been successfully recorded with a clear history, including the identification of the party conducting the transfer and the time of the waste transfer.

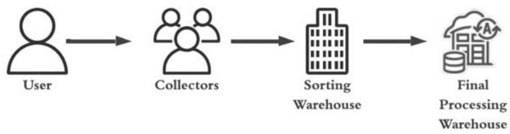

Fig. 4 Waste Transfer Flow Between Organizations

c. Waste Processing
The system can record the processing of waste at the final warehouse, with the resulting recycled products, such as plastic flakes or pellets, and the status "processed".


```json
{
    "result": [
        {
            "Key": "WASTE_20250725_034305_001",
            "Record": {
                "id": "WASTE_20250725_034305_001",
                "photo": "base64encodedphoto1",
                "processedResult": {
                    "outputProducts": "Cacah (plastic flakes) - 2.5kg",
                    "processedBy": "admin",
                    "processedDate": "2025-07-25T11:04:07Z",
                    "qualityGrade": "Standard",
                    "recyclingRate": 0
                },
                "status": "at_gudangakhir",
                "transactionTime": "2025-07-25T05:11:52Z",
                "transferHistory": [
                    {
                        "from": "user",
                        "timestamp": "2025-07-25T05:27:38Z",
                        "to": "pengepul",
                        "transferBy": "admin"
                    },
                    {
                        "from": "pengepul",
                        "timestamp": "2025-07-25T09:45:23Z",
                        "to": "gudangsortir",
                        "transferBy": "admin"
                    },
                    {
                        "from": "gudangsortir",
                        "timestamp": "2025-07-25T11:05:10Z",
                        "to": "gudangakhir",
                        "transferBy": "admin"
                    }
                ],
                "user": {
                    "userID": "USER001",
                    "userName": "Alice Johnson"
                },
                "waste": {
                    "id": "PLASTIC_WASTE_20250725_034305_001",
                    "plasticType": "PET",
                    "weight": 2.5
                }
            }
        }
    ],
    "error": null,
    "errorData": null
}
```


Fig. 5 Waste Transaction Processed

2. Reliability of Smart Contract
The smart contract (chaincode) was evaluated to determine its reliability in automating transactions and ensuring compliance. The following aspects were tested:
a. Transparency and Reliability
All transactions are well recorded on the blockchain and can be verified by authorized parties, without data manipulation.
b. Accuracy of Waste Status

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The system automatically changes the status of the waste according to its stages, from "created" to "processed".

Table 2. Waste Status in the System

Status	Description	Related Organization
created	The waste has just been registered in the system	User
at_pengepul	The waste has been moved to the collector	Collectors
at_gudangsortir	The waste is being sorted and cleaned at the sorting warehouse	Sorting Warehouse
at_gudangakhir	The waste is processed at the final warehouse into recycled products	Final Processing Warehouse
processed	The waste has been processed and converted into recycled products	Final Processing Warehouse

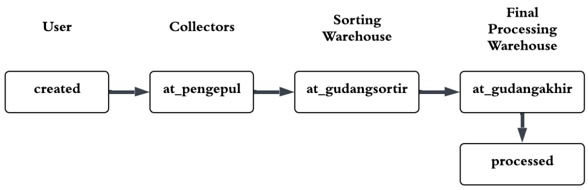

Fig. 6 Waste Transaction Flow in the Blockchain System

3. Performance Testing
   The testing results show that the system can handle transactions with low latency and adequate scalability, even as the number of transactions increases. The performance test results of the system are as follows:
   a. Waste Creation Process Speed
      The time required to record waste in the blockchain is approximately 200 ms per waste item, indicating the system's efficiency in handling data.
   b. Waste Transfer Speed
      The transfer process between organizations takes approximately 150 ms, showing that the system can operate efficiently even when multiple transactions are processed simultaneously.

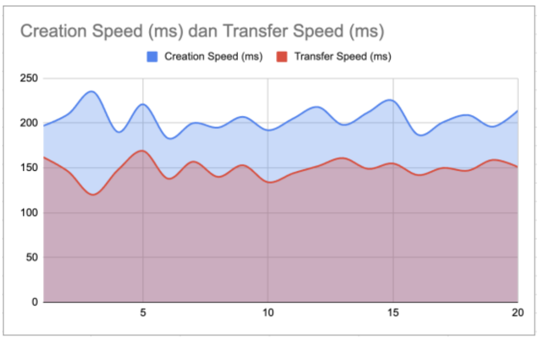

Fig. 7 Performance Testing System

Evaluation of Carbon Emission Reduction Potential

At this stage of the model, the estimation of carbon emission reduction is carried out based on simulations and theoretical calculations referring to the carbon emission factors from plastic waste incineration and recycling.

1. Carbon Emission Reduction through Recycling
   a. Emissions from Plastic Waste Incineration
      Burning plastic waste generates large amounts of carbon dioxide (CO_2) emissions. According to recent data, burning PET plastic can produce CO_2 emissions ranging from 0.8 to 6.5 kg CO_2 per kilogram of plastic burned (An et al., 2022). Emissions from other plastic types are also significant, with HDPE producing between 0.8 and 6.0 kg CO_2 per kilogram of plastic burned, and LDPE between 0.8 and 5.8 kg CO_2 per kilogram of plastic (Delft, 2023). The incineration of PVC and PP plastics results in 2.0 to

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5.4 kg CO_2 per kilogram of plastic and 1.9 to 4.7 kg CO_2 per kilogram of plastic (Alsabri et al., 2022; Liang Quanwei & Yu Liming, 2023; Petrík et al., n.d.).

b. Emission Reduction with Recycling
Plastic recycling has the potential to significantly reduce carbon emissions. Based on simulations, this model can divert 50% to even 100% of plastic waste from incineration or landfills to more efficient recycling processes. Recycling processes conducted with efficient technology can result in very significant carbon emission reductions, with varying reduction figures depending on the type of plastic (Li et al., 2022; Schade et al., 2024).

Table 3
Estimation of Carbon Emission Reduction from Plastic Waste Recycling

Type of Waste	Carbon Emissions (kg CO_2) Before Recycling	Carbon Emissions (kg CO_2) After Recycling	Emission Reduction (%)
PET	0,8-6,5	-0,6 s.d. -1,9	80-100% (net-efisien)
HDPE	0,8-6,0	<1,0	50%+
LDPE	0,8-5,8	0,3-0,5	70-90%
PP	1,9-4,7	0,6-1,3	50-60%
PVC	2,0-5,4	0,18-0,34	75-79%
Mixed Plastics	2-3	0,87	60-70%

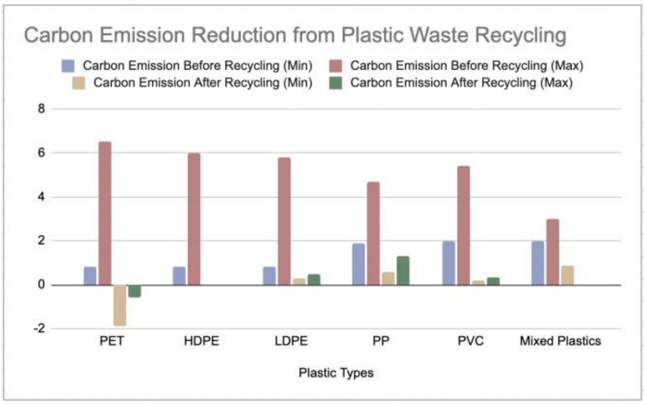

Fig. 8 Comparison of Carbon Emissions Between Traditional Waste Management and Recycling

2. Estimation of Carbon Emission Reduction Potential
Based on calculations and simulations, if plastic waste managed through the blockchain system is processed through recycling, the carbon emission reduction that can be achieved is significant. According to the latest data, types of plastic waste such as PET can divert carbon emissions by up to 100%, with an emission reduction of 6.5 kg CO_2 per kilogram becoming negative (net efficiency) in the recycling process.

DISCUSSIONS

Testing and simulation results of the blockchain-based plastic waste tracking system model demonstrate that this technology can significantly enhance transparency and efficiency in plastic waste management. By utilizing Hyperledger Fabric as the blockchain platform and integrating smart contracts to manage transactions between organizations, the system ensures that every step in the plastic waste lifecycle—from creation to final processing—is accurately recorded, with data integrity ensured through an immutable audit trail.

The results of carbon emission reduction simulations provide clear and promising insights. By diverting plastic waste from incineration or landfilling to more efficient recycling processes, the system has the potential to reduce carbon emissions by up to 50% compared to traditional waste management methods. Specifically, recycling PET (Polyethylene Terephthalate) could lead to 100% emission reduction, while HDPE (High-Density Polyethylene) waste shows reductions of around 50% or more (Li et al., 2022; Schade et al., 2024). These findings highlight the potential of blockchain technology to optimize recycling processes and drastically reduce emissions that would otherwise result from incineration or landfilling.

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A more in-depth analysis of carbon emission potential across various plastic types shows that PP (Polypropylene) can achieve 50-60% emission reductions, while PVC (Polyvinyl Chloride) recycling can lower emissions by up to 75-79% (Alsabri et al., 2022; Liang Quanwei & Yu Liming, 2023; Petrík et al., n.d.). These findings align with prior research on the carbon footprint of plastics, which demonstrates that incineration generates significant CO_2 emissions, while recycling offers substantial reductions. The integration of blockchain into plastic waste management provides a transparent and verifiable method to ensure that plastic waste is processed in a way that maximizes its recycling potential, ultimately contributing to the reduction of greenhouse gases.

The smart contracts (chaincode) embedded in the blockchain platform help automate processes and ensure that each transaction—from waste transfer to final processing—complies with established guidelines. This minimizes human error and administrative overhead, which is a major challenge in conventional waste management systems. Blockchain also enables real-time transaction verification, ensuring that waste transfers and processing are done securely and according to regulations, thus improving efficiency and accountability.

However, implementing this system on a larger scale in the real world presents several challenges. Widespread adoption of the blockchain-based system across the entire plastic waste supply chain will require overcoming regulatory, infrastructural, and collaborative barriers. This includes ensuring that existing policies are aligned with the new blockchain infrastructure and improving the current recycling infrastructure to handle large volumes of waste. Additionally, for this system to be effectively integrated into real-world waste management practices, close collaboration between governments, waste management companies, and recycling facilities will be essential.

Furthermore, although the carbon emission reduction measured in this study is based on simulation models and theoretical calculations, real-world validation through field testing is required. The accuracy of the estimated emission reductions depends significantly on how efficiently the system is integrated into actual recycling practices and the extent to which it can handle the global volume of plastic waste produced annually. Pilot implementations will be crucial to validate these estimates and provide more accurate, real-world data on the emission reductions that can be achieved.

Overall, this study demonstrates that blockchain technology, combined with smart contracts, can play a pivotal role in improving transparency, efficiency, and accountability in plastic waste management. While the technology shows great potential for reducing carbon emissions, real-world implementation requires addressing existing challenges, including integration of infrastructure, policy, and collaboration among stakeholders. Further research and collaboration with stakeholders will be essential to fully realize the environmental benefits of blockchain in managing plastic waste and reducing the impact of climate change.

CONCLUSION

This study successfully designed and developed a blockchain-based plastic waste tracking system model aimed at enhancing transparency, efficiency, and accountability in plastic waste management. By utilizing Hyperledger Fabric as the blockchain platform and smart contracts to manage transactions between organizations, this system can permanently, transparently, and immutably record every stage of the plastic waste journey. The testing results showed that the system can accurately record the status and history of waste, manage transfers between organizations, and process plastic waste into recycled products. Although this system is still in the prototype stage, initial testing indicates that the implementation of blockchain technology can improve the effectiveness of plastic waste management and has the potential to reduce carbon emissions. The estimated carbon emission reduction, based on simulations, shows that this system can potentially reduce carbon emissions by up to 50% compared to traditional plastic waste management methods, such as incineration or disposal in landfills. By ensuring that plastic waste is processed through more efficient recycling, blockchain technology can support global efforts in climate change mitigation.

Nevertheless, the greatest challenge faced is the adoption and widespread implementation of the system across the entire plastic waste supply chain. The success of this system depends on its integration with existing waste management policies, as well as the provision of adequate recycling infrastructure. Therefore, this research opens opportunities for further development in the application of blockchain technology on a larger scale, with positive impacts on the environment and a reduction in the carbon footprint.

Overall, this study demonstrates that blockchain and smart contracts can be an innovative solution in plastic waste management, which not only enhances transparency and efficiency but also plays a crucial role in supporting global efforts to reduce the environmental impact of plastic waste and climate change.

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