Design and implementation of an AI, IoT, and blockchain-based system for circular economy transition in landfill management: a case study of Quilmaná, Peru

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ABSTRACT

This study presents the design and implementation of an integrated system based on artificial intelligence (AI), internet of things (IoT), and blockchain to support circular economy practices in landfill management. The system addresses the lack of integrated and validated digital solutions for environmental monitoring, resource optimization, and social inclusion in resource-constrained contexts. Developed under a design science research (DSR) approach, the system combines IoT sensors for real-time monitoring, machine learning models (LSTM for methane prediction, CNN for waste classification, and reinforcement learning (RL) for biogas optimization), and a blockchain-based platform for transparent transactions and recycler formalization. The system was implemented and evaluated over 12 months using operational data. The LSTM model achieved 95% prediction accuracy, while the CNN model demonstrated high classification performance. Results indicate a 35% reduction in landfill waste, a 40% decrease in CH_4 emissions, and a 30% increase in recycler income, with 60% of informal workers formalized. These findings demonstrate that integrating AI, IoT, and blockchain enables the transformation of landfill systems into scalable circular economy platforms for sustainable waste management.

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1. INTRODUCTION

Globally, municipal solid waste (MSW) generation has reached approximately 1.4 billion tons annually, with an average of 1.2 kg per person per day. Latin America contributes nearly 10% of this volume, reflecting increasing pressure on waste management systems. In Peru, around 7.5 million tons of MSW are generated each year; however, only about 15% is recycled, indicating significant inefficiencies in waste treatment and recovery processes. The district of Quilmaná produces approximately 2,288.55 tons annually and lacks adequate sanitary landfill infrastructure, reflecting a broader national deficit of legally compliant disposal facilities.

Despite regulatory frameworks such as ISO 14001:2015 and ISO 26000:2010, their implementation remains limited in developing regions. Existing landfill management approaches are predominantly based on conventional monitoring and operational practices, with limited integration of digital technologies. Recent studies have explored the use of artificial intelligence (AI) for waste classification and prediction, internet of things (IoT) for environmental monitoring, and blockchain for improving transparency in recycling systems. However, these approaches are typically developed in isolation and lack validation in real-world landfill environments, particularly in resource-constrained contexts. This fragmentation reveals a critical research gap: the absence of integrated, scalable, and empirically validated systems that combine AI, IoT, and blockchain technologies to simultaneously address environmental performance, resource recovery, and social inclusion in landfill management.

To address this gap, this study proposes the design and implementation of an integrated system that combines IoT-based environmental monitoring, AI-driven predictive and optimization models (including LSTM, CNN, and reinforcement learning (RL)), and a blockchain-based platform for transparent transactions and formalization of informal recyclers. The system is developed following a design science research (DSR) approach and validated through a 12-month real-world deployment at the Quilmaná landfill in Peru.

The main contributions of this study are as follows: (i) the design of a modular and integrated architecture combining AI, IoT, and blockchain technologies; (ii) the implementation and empirical validation of the system in a real landfill environment; (iii) the quantitative evaluation of environmental, economic, and social impacts using defined performance indicators; and (iv) the establishment of a scalable framework linking digital technologies with circular economy principles in resource-limited settings.

The remainder of this paper is organized as follows: section 2 reviews related work; section 3 describes the research methodology and system architecture; section 4 presents the results; section 5 discusses the findings and implications; and section 6 concludes the study and outlines future research directions.

2. RESEARCH METHOD

This study follows a DSR approach, focusing on the design, development, and evaluation of an integrated system based on AI, IoT, and blockchain technologies. The DSR methodology is widely used for building and evaluating information systems artifacts in real-world contexts [1]. The research was conducted over 12 months at the Quilmaná landfill in Peru. The methodology is structured into four main stages: (i) system design, (ii) data collection and preprocessing, (iii) model development and training, and (iv) system evaluation.

2.1. System architecture

The proposed system consists of three main components as shown in Figure 1.

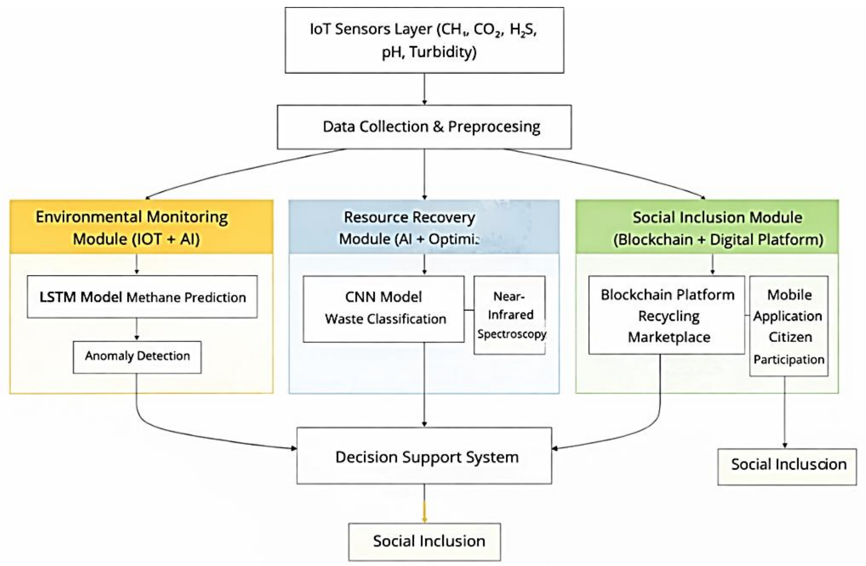

Figure 1. System architecture of the proposed integrated AI–IoT–Blockchain framework for environmental monitoring, resource recovery, and social inclusion at the Quilmaná landfill (Peru)

2.1.1. Environmental monitoring module (IoT+AI)

This module includes 20 IoT sensor nodes (LoRaWAN-compatible) deployed across the landfill to monitor methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), leachate pH, and groundwater quality. IoT-based environmental monitoring has been widely applied for real-time data acquisition in waste management systems [2]. The collected data are processed using long short-term memory (LSTM) neural networks to predict methane emissions and detect anomalies. LSTM models are effective for time-series forecasting and environmental prediction tasks [3].

2.1.2. Resource recovery module (AI+Optimization)

Waste classification is performed using convolutional neural networks (CNNs) based on near-infrared (NIR) spectroscopy data to identify material composition. CNNs have demonstrated high performance in image-based and spectral waste classification tasks [4]. Biogas production is optimized using RL models that dynamically adjust biodigester parameters to maximize methane generation efficiency. RL techniques are commonly used for process optimization in dynamic systems [5].

2.1.3. Social inclusion module (Blockchain+Digital Platform)

A decentralized marketplace is implemented using blockchain technology (Ethereum) to enable transparent transactions between recyclers and recycling companies. Blockchain has been proposed as a solution for improving traceability and transparency in recycling systems [6]. Additionally, a mobile application supports citizen participation through real-time environmental data visualization and gamification mechanisms, which have been shown to enhance user engagement in sustainability initiatives [7].

2.2. Implementation and data collection

2.2.1. System implementation

The IoT infrastructure was deployed at key locations within the landfill [8]-[11], including gas vents, leachate storage tanks [12]-[14], and waste disposal cells. A total of 20 sensor nodes were installed to continuously monitor environmental parameters such as methane (CH_4), leachate pH, and turbidity. Similar sensor deployment strategies have been reported in smart landfill monitoring systems [15]-[18]. To ensure high-fidelity environmental data acquisition, the specific operational ranges, measurement accuracies, and academic baselines for each deployed IoT component are detailed in Table 1.

Table 1. Technical specifications of IoT sensors

Parameter	Sensor	Range	Accuracy	Reference
Methane (CH_4)	Figaro TGS2600	0-10.000 ppm	±2%	[12]
Leaching pH	Hanna HI98107	pH 0-14	±0,1 pH	[19]
Turbidity	Campbell OBS500	0-1.000 NTU	±5%	[19]

2.2.2. Data collection and model training

The AI models were trained using a dataset collected over 6 months, comprising environmental measurements (gas emissions, leachate characteristics), waste composition data, and economic variables such as market prices of recyclable materials [20]. Data preprocessing included normalization, removal of outliers, and interpolation of missing values. The dataset was divided into training and testing subsets following a 70/30 split.

2.2.3. System validation

The integrated system was evaluated over an additional 6-month period using key performance indicators (KPIs), including waste diversion rate, methane (CH_4) emission reduction, and recycler income. These indicators are commonly used to assess environmental and socio-economic performance in waste management systems [21].

2.3. Ethical and social considerations

This study involved human participants, specifically informal recyclers and local community members interacting with the digital platform. Informed consent was obtained from all participants through online forms in accordance with applicable data protection and ethical guidelines [22]. Capacity-building activities were conducted to support the adoption of the system, including training sessions for recyclers on digital tools and for citizens on the use of the mobile application. These initiatives aimed to enhance digital literacy and promote active participation in circular economy practices [23].

3. RESULTS AND DISCUSSION

The proposed AI-based system produced quantifiable impacts across environmental, economic, and social dimensions after a 12-month evaluation period, including 6 months of training and 6 months of operational deployment.

3.1. Environmental performance

3.1.1. Methane emission reduction

The LSTM model achieved a prediction accuracy of 95%, with RMSE = 118 ppm and MAE = 84 ppm, enabling early detection of methane (CH_4) peaks and proactive biogas capture. As a result, CH_4 emissions were reduced by 40% compared to baseline conditions, equivalent to approximately 5,000 tons of CO_2e per year [24].

3.1.2. Leachate monitoring

Real-time pH monitoring enabled the identification of contamination events up to 48 hours earlier than conventional manual methods, significantly reducing the risk of groundwater contamination [19], [25].

3.1.3. Waste diversion

The CNN model improved waste classification efficiency, achieving precision = 0.92, recall = 0.90, and F1-score = 0.91. This led to a 35% increase in waste diversion from landfill disposal, contributing to improved material recovery rates. The comprehensive behavior and the specific monthly trajectory of these environmental enhancements, highlighting the contrast between the baseline and post-implementation phases, are illustrated in Figure 2.

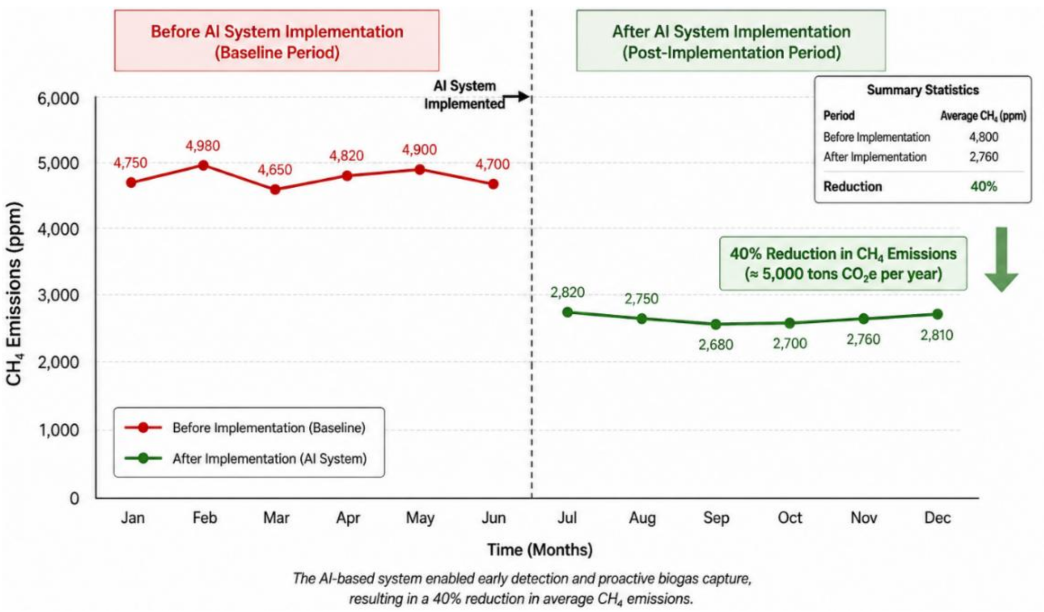

Figure 2. CH_4 emission reduction before and after system implementation (Pre vs. Post-AI)

3.2. Economic impact

3.2.1. Resource valorization

The RL model optimized biodigester operations, resulting in a 40% increase in biogas production. The system generated approximately 80 m^3/day of energy, sufficient to supply around 300 households [26].

3.2.2. Revenue streams

The implementation of the system enabled multiple revenue sources:

- Recyclable material sales reached approximately $15,000 per month [27].
- Carbon credits generated approximately $8,000 annually, verified through blockchain mechanisms [28].

Operational costs were reduced by 25% due to predictive maintenance strategies [29]. To systematically evaluate the economic viability of these streams against the expenditures, a comprehensive cost-benefit analysis detailing the investments, savings, and payback periods is structured and presented in Table 2.

Table 2. Cost-benefit analysis

Concept	Initial investment	Savings/Month	ROI
IoT Sensors	$8,000	-	-
AI Platform	$12,000	-	-
Operational savings	-	$5,000	6 months
Residual income	-	$15,000	4 months

3.3. Social impact

3.3.1. Inclusion of recyclers

Approximately 60% of informal recyclers were integrated into the blockchain-based marketplace, resulting in a 30% increase in income due to fair pricing mechanisms [30]. Formalization also enabled access to social benefits such as healthcare and social security [31].

3.3.2. Community participation

The mobile application reached 500 active users, representing approximately 30% of the local population [32]. Gamification features increased participation in recycling activities by 70% [33]. Citizen approval increased from 50% to 90% based on post-implementation surveys [34]. To better understand these dynamics, the chronological evolution of both social inclusion and community participation indicators is graphically displayed in Figure 3.

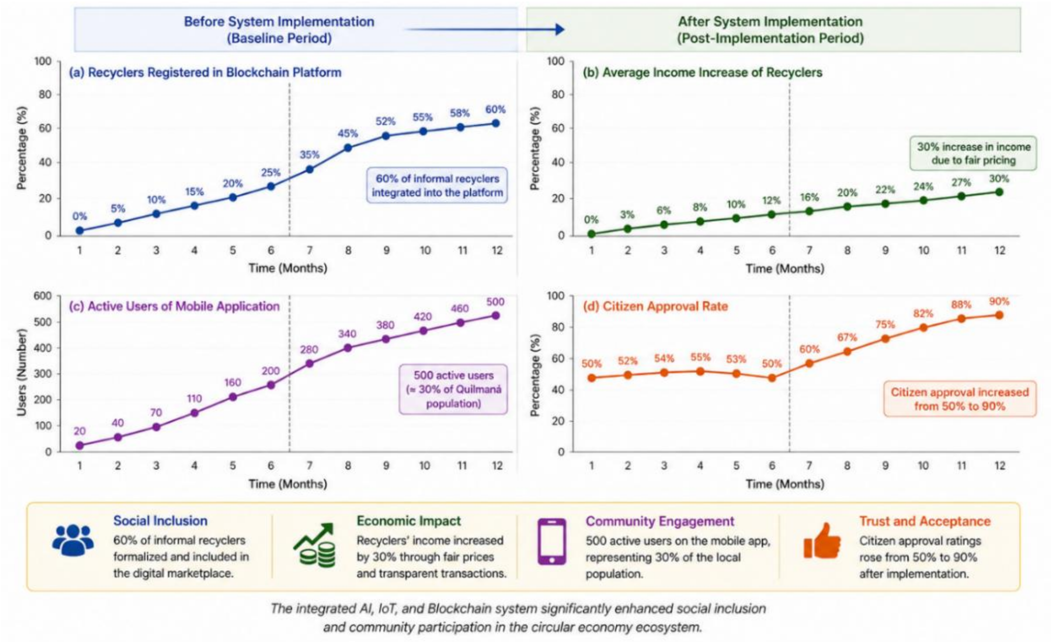

Figure 3. Evolution of social inclusion and community participation indicators

3.4. Challenges and lessons learned

Technical challenges included connectivity limitations in remote landfill areas, which were mitigated through the implementation of edge computing solutions [35]. From a social perspective, initial resistance from recyclers was addressed through participatory co-design workshops, improving system adoption [36]. Overall, the results demonstrate that the integration of AI, IoT, and blockchain technologies can significantly enhance landfill management performance, supporting environmental sustainability, economic viability [37]-[39], and social inclusion within a circular economy framework [40].

4. CONCLUSION

This study presented an integrated system based on AI, IoT, and blockchain to support circular economy practices in landfill management, using Quilmaná (Peru) as a case study. The results showed significant improvements: methane (CH_4) emissions were reduced by 40%, waste diversion increased by

35%, and operational costs decreased by 25%. The AI models demonstrated strong performance (RMSE = 118 ppm, MAE = 84 ppm), enabling accurate prediction and optimization processes. Additionally, 60% of informal recyclers were formalized, increasing their income by 30%, while citizen participation improved substantially through the mobile platform. These findings demonstrate that the integration of AI, IoT, and blockchain can effectively transform landfill systems into scalable circular economy models, contributing to environmental sustainability, economic efficiency, and social inclusion. However, the study is limited to a single case and a 12-month evaluation period. Future work should focus on scaling the system to other regions and improving AI model robustness with larger datasets.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study were collected through research and are available in the SCOPUS database and from the corresponding author.

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