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SMART WASTE: END-TO-END BLOCKCHAIN-GOVERNED MULTI-AGENT INTELLIGENCE FOR MUNICIPAL SOLID WASTE MANAGEMENT AT URBAN SCALE

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Abstract: Urban waste management is increasingly facing systemic challenges due to rapid urbanization, population growth, and rising consumption levels. Several studies highlight that existing waste management systems remain fragmented, relying heavily on manual data collection, delayed reporting, and centralized databases that lack transparency and efficiency. Research on blockchain-based waste management solutions demonstrates improved traceability and secure record keeping; however, most existing implementations focus only on tracking waste flows rather than enabling intelligent decision-making. Similarly, IoT-based monitoring systems and AI-driven waste sorting prototypes have shown promising results but are typically deployed in isolated environments and fail to integrate across the entire waste lifecycle. These limitations reveal significant research gaps, including the absence of full lifecycle integration, lack of intelligent coordination mechanisms, and limited municipal-scale deployment of smart waste management systems. es address these issues, this research proposes an integrated smart urban waste management framework that combines Multi-Agent Systems (MAS), Artificial Intelligence (AI), and Blockchain technology. The proposed system introduces six key components: multi-agent coordination among stakeholders such as citizens, collectors, recycling facilities, and municipal authorities; AI-based waste generation prediction for proactive planning; intelligent route optimization to improve waste collection efficiency; blockchain-based transparent waste tracking to ensure tamper-proof data records; AI-driven automated waste sorting using computer vision and sensors; and a smart city monitoring dashboard for real-time operational analysis. Simulation and experimental insights from related studies demonstrate that intelligent waste classification systems can achieve classification accuracies above 85% while enabling near real-time processing. By integrating predictive analytics, decentralized coordination, and secure data governance within a single architecture, the proposed MAS–AI– Blockchain framework offers improved collection efficiency, enhanced transparency, and better recycling outcomes compared to existing isolated solutions. This approach provides a scalable foundation for next-generation municipal waste management systems in smart cities.

***Index Terms* -** Multi-Agent System; Blockchain; IoT; Smart City; Waste Management; Random Forest; Route Optimization; Smart Contracts; Ethereum

I. Introduction

Global municipal waste (GMW) generation is projected to exceed 3.8 billion tonnes annually by 2050, placing unprecedented strain on urban infrastructure, environmental systems, and municipal budgets. Rapid urbanization, population growth, and changing consumption patterns are accelerating waste generation at a pace that far outstrips the capacity of existing management systems. Cities are increasingly challenged not only by the volume of waste but also by its complexity, including hazardous, electronic, and non-biodegradable materials. This growing burden threatens public health, contributes to greenhouse gas emissions, and undermines efforts toward sustainable urban development.

In many cities, particularly within developing economies, waste management remains one of the most underfunded and inefficiently executed public services. Limited financial resources, lack of technological adoption, and fragmented administrative structures contribute to systemic inefficiencies. Collection vehicles often follow rigid, predefined schedules regardless of actual bin fill levels, resulting in unnecessary trips to half-empty bins while other locations experience overflow. This imbalance leads to increased operational costs, excessive fuel consumption, traffic congestion, and environmental pollution, while simultaneously failing to meet citizens' expectations for cleanliness and reliability.

Moreover, the absence of real-time data and intelligent decision-making mechanisms further exacerbates these challenges. Traditional waste management systems rely heavily on manual monitoring and static planning, which are inherently incapable of adapting to dynamic urban conditions. Seasonal variations, special events, and unpredictable waste generation patterns require responsive systems that can adjust operations in real time. Without such adaptability, municipalities face inefficient resource allocation, delayed responses to critical situations, and reduced overall service quality.

The emergence of advanced technologies such as Internet of Things (IoT) sensors, blockchain-based data governance, and artificial intelligence (AI) has opened transformative possibilities for smart city waste management. IoT devices enable real-time monitoring of bin fill levels, environmental conditions, and vehicle status. Blockchain technology offers secure, transparent, and tamper-proof data sharing among stakeholders, improving accountability and trust. Meanwhile, AI techniques can analyze large volumes of data to predict waste generation patterns, optimize collection routes, and support proactive decision-making. Together, these technologies have the potential to significantly enhance efficiency, reduce costs, and minimize environmental impact.

However, as existing research consistently highlights, these technologies have largely been developed and deployed in isolation. IoT systems focus on data collection without intelligent decision-making, blockchain solutions emphasize data integrity without operational optimization, and AI models often lack integration into real-world municipal workflows. This fragmentation prevents cities from realizing the full potential of smart waste management. Therefore, there is a critical need for an integrated, end-to-end system that combines IoT for sensing, blockchain for secure data governance, and AI for intelligent optimization, enabling scalable, efficient, and sustainable waste management at the municipal level.

II. Literature Review

This section reviews seven foundational and contemporary research works that collectively frame the motivation, design decisions, and research contribution of Smart waste. The review spans blockchain waste management, smart contract theory, IoT-driven collection systems, multi-agent simulation, and AI-based route optimization.

2.1 Blockchain in Waste Management: The State of Deployment

Lenz (2021) conducted the most comprehensive global audit of blockchain-based waste management initiatives to date under the BlockWASTE project. The study identified only 20 blockchain-based waste management projects worldwide, all of which were limited to proof-of-concept implementations and none of which had achieved municipal-scale deployment. The study critically observed that no system had been built in collaboration with a municipal waste management authority, meaning that the entire field remains in a pilot stage disconnected from real operational constraints.

This finding establishes a foundational research gap: the absence of production-grade deployment represents not merely a technological limitation but an architectural one. Existing prototypes do not account for multi-stakeholder coordination across municipalities, citizens, and recycling plants, nor do they integrate optimization intelligence into the blockchain transaction layer. This observation motivates the investigation of integrated frameworks capable of bridging these gaps.

2.2 Smart Contracts and Information Asymmetry

Cong and He (2018) provided a rigorous economic and theoretical framework for smart contract utility in the context of information asymmetry reduction. Published under the National Bureau of Economic Research (NBER), their work demonstrated that Ethereum-based smart contracts can automate contingent transactions, reduce reliance on trusted intermediaries, and enforce compliance without human oversight. The study's primary application domain was financial trade and decentralized finance.

While their theoretical contributions are compelling, the framework was never extended to urban public services or waste management operations. This study examines how the core logic of Cong and He's smart contract theory — automated contingent execution and transparent audit trails — can be applied to waste collection governance, specifically in the context of compliance enforcement and citizen incentivization. The transferability of smart contract mechanisms from financial domains to public service operations represents an underexplored area with significant practical relevance.

2.3 Multi-Phase Blockchain Waste Projects and Integration Gaps

Baralla et al. (2022) reviewed 22 real-world blockchain waste management projects and found that all operated in isolated lifecycle phases — tracking only raw material sourcing, or only disposal records, but never integrating the full waste chain from bin to recycling facility. Their systematic review emphasized that the lack of cross-phase integration significantly limited the practical usefulness of blockchain in waste governance, as data fragmentation prevented end-to-end accountability.

This finding highlights a critical design requirement for any integrated waste management framework: cross-phase data continuity must be architecturally enforced rather than assumed. Research suggests that linking collection events, vehicle transit records, recycling intake, and quality grading within a single auditable chain — each anchored to an immutable blockchain hash — is a necessary condition for genuine end-to-end accountability. The absence of such continuity in existing systems is identified as a key limitation to be addressed in framework design.

2.4 Blockchain for Supply Chain Sustainability

Stroumpoulis et al. (2021) proposed a conceptual framework for blockchain-enabled supply chain transparency across three sustainability pillars: social, environmental, and economic. Their contribution established that blockchain can theoretically improve accountability and reduce fraud across all three dimensions simultaneously, citing examples from food supply chains, pharmaceutical distribution, and hazardous waste tracking.

However, the framework remained purely conceptual, with no implementation, coordination mechanism, or simulation validation. This study examines how the three-pillar framework of Stroumpoulis et al. can be operationalized in the waste domain. Specifically, the literature suggests that the social dimension can be addressed through citizen engagement and incentive mechanisms, the environmental dimension through overflow prevention and route optimization, and the economic dimension through fuel savings and compliance enforcement — together forming a measurable sustainability evaluation lens for integrated waste systems.

2.5 IoT-Blockchain Integration Without Decision Intelligence

A recurring limitation in IoT-blockchain waste management literature is that systems function as passive recorders rather than active decision makers. While IoT sensors provide valuable real-time fill-level data and blockchain ensures its immutable storage, the combined systems reviewed in this domain invariably rely on rule-based thresholds for collection triggers rather than predictive intelligence. Decision making is reactive, not anticipatory.

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2.6 Survey on Blockchain for Smart City Waste Management

A comprehensive survey on blockchain applications in smart city waste management identified four critical gaps in the state of the art: a lack of advanced automation in collection operations, limited Artificial Intelligence and Machine Learning integration for predictive analytics, poor coordination mechanisms between stakeholders (municipalities, haulers, recyclers), and insufficient decision support systems for real-time operational management.

The survey explicitly called for a system that would unify these capabilities within a single deployable architecture. These four gaps collectively define the requirements for an integrated framework: automated operational cycles, embedded predictive analytics, multi-stakeholder coordination mechanisms, and real-time decision support. The survey findings suggest that no single existing system satisfies all four requirements simultaneously, confirming the need for a unified architectural approach that this study seeks to investigate.

2.7 Recent Advances: IoT Route Optimization and Multi-Agent Simulation

Recent work by Addas et al. (2024) demonstrated a 32% improvement in waste collection route efficiency, a 29% reduction in fuel consumption, and a 33% increase in waste processing throughput through an IoT-based dynamic route optimization system validated over 200 million data points across 10 locations in Lahore, Pakistan. However, their system did not incorporate blockchain governance or AI agents, and decision making remained algorithm-driven rather than agent-coordinated.

Complementarily, Priyadarshi et al. (2023) modelled waste collection in Chandigarh, India, using a multi-agent linear programming approach where collection vehicles acted as agents maximizing collected waste while minimizing distance. Their results confirmed the superiority of agent-coordinated collection over static routing. However, their system lacked sensor integration, blockchain traceability, and citizen engagement mechanisms.

Hussain et al. (2024) extended this line of work by applying multi-agent simulation to compare waste management models in IoT-enabled smart city environments, finding that agent-based approaches significantly outperformed conventional scheduling. The study noted that the addition of predictive analytics and cross-agent coordination remained an open research direction.

Taken together, these studies demonstrate that MAS-based coordination and IoT-driven route optimization each deliver measurable efficiency improvements in isolation. However, none of the reviewed works integrates both approaches alongside blockchain compliance enforcement and citizen incentivization within a single framework. This gap forms the research basis for the integrated conceptual framework examined in this study

2.8 Dynamic routing for efficient waste collection in resource constrained societies

This paper presents a dynamic routing approach aimed at improving the efficiency of waste collection systems, particularly in resource-constrained societies. The authors propose a model that leverages real-time data inputs such as bin fill levels, traffic conditions, and vehicle capacity to dynamically adjust collection routes. Unlike traditional static routing methods, this approach ensures that collection vehicles prioritize areas with higher demand, thereby reducing unnecessary trips and minimizing operational inefficiencies.

The study demonstrates that implementing dynamic routing can significantly reduce fuel consumption, travel distance, and overall operational costs while improving service reliability. However, the research is primarily focused on optimization of routing and does not address broader system integration challenges such as secure data sharing, interoperability, or incorporation of emerging technologies like blockchain. This highlights a limitation in achieving a fully automated and scalable smart waste management system.

2.9 Blockchain technology and supply chain management: A theoretical framework

This paper introduces a theoretical framework for integrating blockchain technology into supply chain management systems. It emphasizes the role of blockchain in enhancing transparency, traceability, and trust by enabling decentralized and immutable record-keeping. Through distributed ledgers, all stakeholders can access verified data, reducing fraud, improving accountability, and streamlining coordination across complex supply chains.

Despite its strong conceptual contribution, the framework remains largely theoretical and lacks practical implementation in dynamic, real-time environments. The study does not incorporate intelligent decision-making or optimization mechanisms, which limits its applicability in operational domains such as waste management. As a result, while blockchain ensures secure data handling, it does not independently address efficiency or automation challenges

III. RESEARCH GAP STATEMENT

The literature reviewed above reveals a consistent and well-documented fragmentation in smart waste management research. While blockchain systems exist for traceability, IoT systems for monitoring, AI systems for prediction, and MAS frameworks for coordination, no prior system has integrated all four within a single municipal-scale architecture.

Existing solutions do not integrate all essential capabilities required for a fully intelligent waste management system. Most lack AI-based decision-making for waste prediction and route optimization, autonomous multi-agent coordination across the waste lifecycle, and dynamic route optimization using real-time IoT data. Additionally, blockchain-based compliance and citizen incentivization mechanisms are rarely implemented, and few systems are designed for municipal-scale deployment that serves multiple stakeholders within a unified platform.

This study investigates how these five capabilities — IoT monitoring, AI-driven prediction, route optimization, multi-agent coordination, and blockchain compliance — can be unified within a single architectural framework. Through simulation, this paper provides evidence on the projected performance benefits of such integration and identifies the conditions under which it offers advantages over existing isolated approaches

3.1 Limitations of Existing Smart Waste Management Systems

Despite significant advances in smart city technologies, most existing waste management solutions address only isolated aspects of the waste lifecycle. IoT-based systems primarily focus on monitoring bin fill levels and transmitting real-time sensor data to centralized dashboards. While these systems improve visibility, they typically rely on rule-based thresholds and lack predictive intelligence for proactive decision making.

Similarly, blockchain-based waste management frameworks concentrate on improving traceability and transparency of waste transactions. However, these systems generally function as passive record-keeping infrastructures rather than active decision-support platforms. Without integrated predictive analytics or route optimization capabilities, blockchain implementations alone do not significantly improve operational efficiency.

Artificial intelligence and machine learning approaches have also been applied to waste prediction and route optimization. Nevertheless, most studies treat Artificial intelligence as a standalone analytical component rather than embedding it within a complete operational workflow that includes data collection, coordination, enforcement, and stakeholder interaction. As a result, these solutions often remain theoretical or limited to simulation environments without practical deployment mechanisms.

3.2 Need for Integrated Intelligent Waste Management Frameworks

Modern urban waste management requires the coordination of multiple technological layers, including sensing infrastructure, predictive analytics, operational decision systems, and transparent governance mechanisms. Integrating these components within a unified architecture is essential to address challenges such as inefficient collection schedules, lack of accountability in waste handling, and limited citizen engagement.

An integrated framework combining IoT, artificial intelligence, multi-agent coordination, and blockchain governance can significantly enhance the efficiency and reliability of municipal waste operations. IoT sensors provide real-time environmental data, AI models generate predictive insights, multi-agent systems enable decentralized decision making, and blockchain ensures transparency and trust among stakeholders.

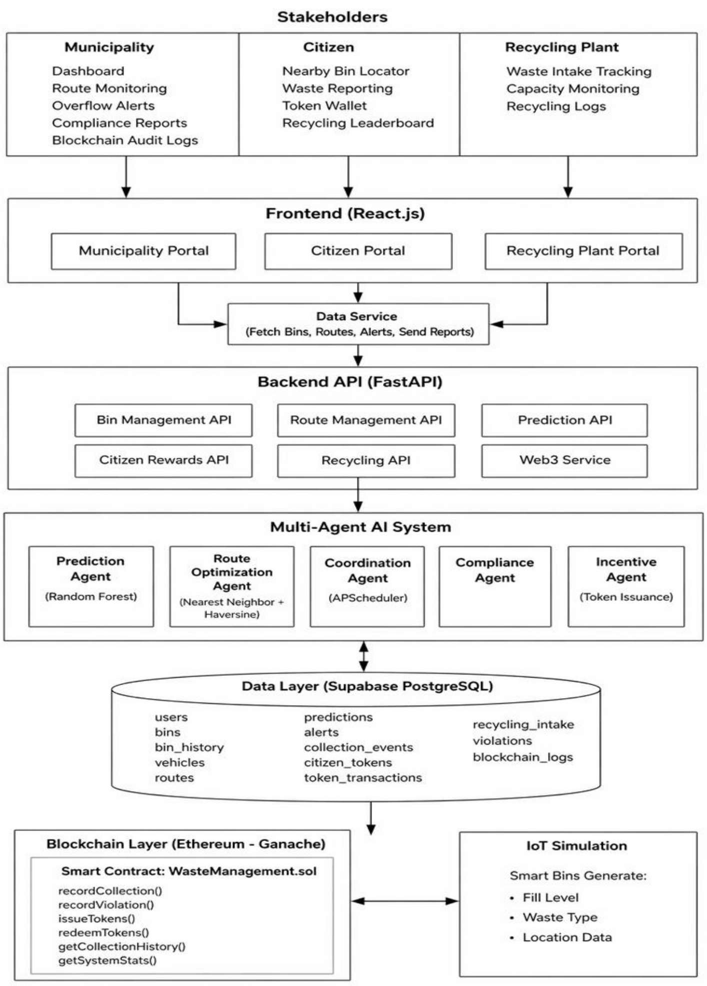
The absence of such a unified architecture in existing research highlights the need for a comprehensive system capable of supporting the entire waste management lifecycle—from waste generation and collection to transportation, recycling, and compliance monitoring.

3.3 Research Contributions of This Study

To address the limitations identified in the literature, this study develops and evaluates a conceptual integrated framework that combines four key technological layers: IoT-enabled real-time monitoring, AI-driven predictive analytics, multi-agent coordination, and blockchain-based governance. The framework is grounded in findings from prior research and evaluated through simulation to assess its projected operational and governance benefits. The primary contribution is not a deployed production system but a research-validated conceptual architecture that synthesizes existing technologies in a manner not previously examined in the waste management literature. The study demonstrates how advanced digital technologies, when orchestrated together, can theoretically improve collection efficiency, enhance transparency, and support sustainable municipal waste governance — providing a foundation for future empirical deployment studies.

IV. Methodologies

The Smart Waste system is designed as a full-stack architecture that integrates modern web technologies, intelligent analytics, and secure data management to address the challenges of urban waste management. The system architecture emphasizes scalability, modularity, and real-time responsiveness so that it can efficiently handle increasing data volumes and operational complexity in smart city environments. The frontend of the system is developed using React.js with Vite, enabling the creation of dynamic and responsive user interfaces capable of displaying real-time waste management data. Through interactive dashboards and geospatial maps, users can monitor bin statuses, vehicle locations, and system alerts in real time. The component-based architecture of React improves maintainability and code reusability, while fast rendering ensures that stakeholders receive continuous updates without manual refresh. The backend is implemented using FastAPI, a high-performance Python framework that supports asynchronous processing and seamless integration with machine learning libraries. The backend acts as the central coordination layer, handling API requests, processing data, managing AI predictions, and interacting with the blockchain infrastructure. Data storage and management are supported by Supabase built on PostgreSQL, which provides structured relational storage, authentication mechanisms, and real-time data synchronization. This ensures that all users interact with consistent and up-to-date information across the system.



In addition to conventional web technologies, the system integrates blockchain technology using Ethereum smart contracts written in Solidity. These smart contracts are deployed on a local Ethereum test network using Hardhat and Ganache, enabling secure and tamper-proof recording of important events such as waste collection activities, compliance verification, and citizen incentive transactions. By using a local test network, the system replicates blockchain functionality without incurring real transaction costs during development. The platform also incorporates geospatial visualization through React Leaflet combined with CartoDB map tiles, allowing the graphical representation of smart bins, vehicle routes, and recycling facilities. This spatial representation improves operational planning and decision-making by providing users with a clear geographic overview of waste collection operations.

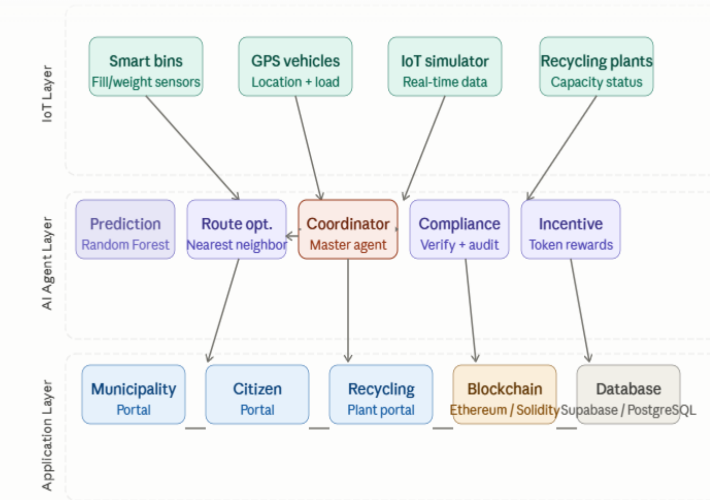
The system relies on a structured relational database designed to manage large volumes of operational and analytical data efficiently. The database consists of multiple normalized tables representing entities such as users, bins, vehicles, recycling plants, collection events, predictions, routes, alerts, recycling intake records, and citizen token transactions. This structured schema ensures data integrity, eliminates redundancy, and supports complex relationships between different components of the waste management system. For example, bin fill-level data is continuously recorded and stored in historical tables, which are later used by predictive analytics models to forecast future waste accumulation. Similarly, waste collection records are linked with blockchain transaction hashes to maintain a transparent and verifiable audit trail. Real-time subscriptions implemented through Supabase allow updates in critical tables—such as bins, vehicles, alerts, and collection events—to be automatically pushed to connected applications. This mechanism eliminates the need for constant data polling and ensures that all stakeholders receive immediate updates whenever system events occur.

To accommodate different participants in the waste management ecosystem, the system adopts a multi-portal architecture that provides customized interfaces for municipalities, citizens, and recycling facilities. The municipality portal functions as the central control dashboard, allowing waste management authorities to monitor bin fill levels, analyze predictive alerts, and manage optimized vehicle routes. Municipal operators can assign vehicles, respond to alerts, and evaluate operational performance through analytical dashboards, while blockchain audit logs ensure transparency and accountability of all system activities. The citizen portal focuses on community participation by offering a mobile-friendly interface through which users can locate nearby bins, report waste-related issues, and track recycling contributions. The system incorporates token-based incentives that reward citizens for responsible waste disposal practices, encouraging behavioral change and community engagement. The recycling plant portal supports facility operators by providing tools to track incoming waste quantities, update processing statuses, monitor facility capacity, and maintain recycling records. The integration of blockchain logs within this portal ensures that recycling activities remain transparent and verifiable.

A unified data service layer plays a crucial role in integrating the frontend and backend components of the SMART WASTE system. This layer centralizes all data access operations and acts as an intermediary that manages interactions between user interfaces and backend services. Functions within this layer handle operations such as retrieving bin information, generating optimized routes, processing alerts, submitting citizen reports, and accessing blockchain records. By consolidating these functions into a single service interface, the system reduces redundancy and simplifies maintenance while improving scalability. An important feature of this architecture is the ability to switch between simulated and real backend data using a configuration toggle. During development or demonstration scenarios, the system can operate using mock datasets that replicate real-world conditions without requiring a fully deployed backend. In production environments, the same system can seamlessly connect to the live backend infrastructure to enable real-time data processing and operational coordination. This flexibility makes the SMART WASTE platform suitable both for academic demonstrations and for practical smart city deployments.

V The Five AI Agents

The SMART WASTE system is built using a coordinated set of intelligent agents that work together to improve waste collection efficiency, monitoring, and citizen engagement. The Prediction Agent uses a Random Forest model trained on historical bin data to forecast future fill levels at 6-hour and 12-hour intervals. It considers features such as time, waste type, and location to estimate overflow risk, classify bin priority, and predict the remaining time before overflow. The model continuously improves by retraining after every 1,000 new data records.



The Route Optimization Agent ensures efficient waste collection by generating optimized routes using a Nearest Neighbour approach combined with Haversine distance calculations. Instead of following fixed routes, it selects only bins that are nearly full or likely to overflow, thereby reducing unnecessary trips. It calculates distance and fuel savings and stores route details for execution.

The Coordination Agent acts as the central controller of the system. It operates in regular cycles, triggering predictions, passing results to the routing module, checking recycling plant capacities, and updating system dashboards in real time. It ensures smooth communication between all components and maintains system-wide synchronization.

The Compliance Agent guarantees that all waste collection operations follow predefined rules. It verifies whether bins are emptied properly, correct vehicles are used, collections happen on time, and waste reaches the proper facility. Valid events are recorded on the blockchain, while violations are also logged, ensuring accountability and transparency.

Finally, the Incentive Agent focuses on citizen participation. It rewards users with tokens based on recycling behavior, applies bonus schemes for consistency, and prevents fraudulent claims. All rewards are issued through blockchain smart contracts, ensuring secure and verifiable transactions.

VI. Blockchain: Theoretical Foundations

Blockchain is a distributed ledger technology (DLT) that enables secure, transparent, and tamper-resistant recording of transactions across a decentralized network of nodes. First introduced by Nakamoto (2008) in the context of Bitcoin, a blockchain consists of a sequence of blocks where each block contains a cryptographic hash of the previous block, a timestamp, and a set of transaction records. This structure ensures immutability, meaning once data is written to the ledger it cannot be modified without invalidating subsequent blocks.

Unlike traditional centralized databases, blockchain operates without a central authority. Each participant node maintains a copy of the ledger, and updates are validated through a consensus mechanism agreed upon by the network. This removes the need for trusted intermediaries such as banks or auditors and replaces institutional trust with cryptographic verification.

The core properties of blockchain include:

- Decentralization – The ledger is distributed across multiple nodes, eliminating single points of failure.
- Immutability – Confirmed transactions cannot be altered without significant computational effort.
- Transparency – Transactions are visible to authorized participants, enabling auditability.
- Security – Cryptographic hashing and public-private key systems ensure data integrity and identity verification.
- Consensus – Network participants agree on the ledger state through consensus protocols rather than centralized authority.

6.1 Ethereum and Smart Contracts

Ethereum, introduced by Buterin (2014), expanded blockchain functionality beyond simple value transfer to support programmable smart contracts. A smart contract is a self-executing program stored on the blockchain whose conditions are defined in code and automatically enforced when triggered.

Smart contracts are written in Solidity, a high-level programming language compiled into Ethereum Virtual Machine (EVM) bytecode. Once deployed, a contract exists at a fixed blockchain address and can be executed by authorized users. They operate based on several key principles. Determinism ensures that the same inputs always produce the same output across all nodes. Autonomy allows contracts to execute automatically without the need for intermediaries. **T**ransparency enables participants to audit and verify the contract logic. Additionally, finality guarantees that once transactions are recorded on the blockchain, they become permanent and cannot be altered.

Cong and He (2018) showed that smart contracts reduce information asymmetry by automating agreements without relying on trusted intermediaries. SMART WASTE applies this concept to waste compliance monitoring and citizen incentive systems.

6.2 Blockchain Used in SMART WASTE

Smart Waste uses a public Ethereum blockchain in a local testnet environment implemented using Hardhat and Ganache. This setup replicates the Ethereum execution environment—including EVM bytecode, gas fees, and transaction receipts—without requiring real cryptocurrency expenditure during development.

The system architecture is designed to migrate to the Ethereum Sepolia public testnet, and eventually to a consortium-based deployment involving municipal authorities, waste collection contractors, and recycling facilities. The system uses a WasteManagement.sol smart contract written in Solidity 0.8.19 with OpenZeppelin's Ownable access control pattern. A custom onlyAuthorized modifier restricts write operations such as collection recording, violation logging, and token issuance to registered system addresses while maintaining transparent read access.

All waste collection events, violations, and token transactions are recorded on the blockchain and linked to database records through transaction hashes. This creates a permanent audit trail that cannot be altered, enabling transparent verification by municipal authorities and auditors. The Compliance Agent automatically invokes smart contract functions such as recordCollection() and recordViolation() after evaluating each collection event. This replaces manual auditing with automated verification and improves operational accountability. Smart Waste involves municipalities, citizens, and recycling plants. Blockchain provides a shared ledger where all stakeholders can independently verify data without relying on a single authority. The Incentive Agent distributes digital tokens through the issueTokens() smart contract function. Since token balances are recorded on the blockchain, citizens can verify their rewards independently, increasing transparency and trust in the incentive system.

Blockchain technology supports several important applications in municipal waste management:

- Supply Chain Traceability – Enables tracking of waste from collection bins to recycling facilities through cryptographically verified records.
- Regulatory Compliance – Smart contracts automate compliance reporting for regulatory authorities.
- Circular Economy Support – Verified recycling data can enable environmental tokens and recycling credits.
- Fraud Prevention – Immutable records reduce fraudulent reporting of waste treatment and disposal.
- Cross-Jurisdictional Governance – Consortium blockchains allow multiple municipalities and waste operators to share a unified, auditable ledger.

VII. Simulation Results and Performance Evaluation

The simulation results demonstrate significant improvements in operational efficiency when using the SMART WASTE framework compared to traditional and blockchain-only waste management systems. Over the 30-day evaluation period, the system reduced the total number of collection trips from 360 to 187, representing a 48% decrease. This improvement is primarily achieved through the Route Optimization Agent, which schedules collections only for bins that exceed a 70% fill threshold or are predicted to overflow. By avoiding unnecessary or speculative collection trips, the system minimizes redundant vehicle movements that commonly occur in traditional fixed-schedule approaches.

In addition to reducing collection trips, the optimized routing mechanism significantly decreased the overall travel distance of collection vehicles. Total vehicle distance was reduced from 4,320 km to 1,890 km, representing a 56% reduction in operational travel. This improvement directly translated into fuel cost savings of approximately USD 1,215 per month (from $2,160 to $945), demonstrating the potential of the system to reduce municipal operational expenses. These improvements are consistent with findings reported by Addas et al. (2024), who observed efficiency gains of approximately 29–32% using IoT-based route optimization. The higher efficiency observed in SMART WASTE can be attributed to its predictive collection strategy, which eliminates unnecessary trips rather than only optimizing predefined routes.

Table 1: 30-Day Simulation Results — SMART WASTE vs. Baseline Systems

Metric	Traditional	Blockchain-Only	SMART WASTE
Collection Trips (30 days)	360	360	187
Total Distance (km)	4,320	4,320	1,890
Overflow Incidents	47	31	8
Fuel Cost (USD)	$2,160	$2,160	$945
Compliance Rate	N/A	78%	94%
Monthly Fuel Savings	—	—	$1,215

The system also showed substantial improvement in preventing waste overflow incidents. During the simulation period, overflow occurrences decreased from 47 incidents in the traditional system to only 8 incidents in the SMART WASTE model, representing an 83% reduction. While the blockchain-only approach reduced overflow incidents to 31 through improved monitoring and traceability, it remained largely reactive. In contrast, the SMART WASTE framework incorporates a Prediction Agent that forecasts bin fill levels in advance, allowing proactive scheduling of collection operations before overflow conditions occur.

Furthermore, the system demonstrated a significant improvement in compliance monitoring and operational accountability. SMART WASTE achieved a 94% compliance rate, compared to 78% in the blockchain-only system, while the traditional waste management approach had no formal compliance verification mechanism. The 16-percentage-point improvement can be attributed to the Compliance Agent, which performs automated verification of collection events against predefined criteria such as bin emptying status, assigned vehicle validation, collection time windows, waste delivery confirmation, and weight recording. Unlike the blockchain-only model that relies on post-operation auditing, the SMART WASTE system performs real-time validation and records compliant or non-compliant events directly on the blockchain, ensuring transparency and accountability throughout the waste management process.

VIII. DISCUSSION

This study makes three distinct research contributions. First, it demonstrates through simulation that multi-agent coordination can be effectively integrated with blockchain smart contracts in a public services context, extending the financial applications described by Cong and He (2018) to the domain of urban waste governance. Second, it operationalizes the three-pillar sustainability framework of Stroumpoulis et al. (2021) through concrete architectural components, providing a testable mapping between sustainability theory and system design. Third, the simulation evidence suggests that the combination of predictive AI and MAS coordination produces compounding efficiency gains beyond what either technology achieves in isolation — a finding that aligns with the open research direction identified by Hussain et al. (2024) and supports the case for integrated rather than siloed technology deployment in municipal waste management.

For municipal authorities, Smart Waste offers a deployable architecture that can be integrated with existing GPS-enabled vehicle fleets and commercially available IoT bin sensors. The three-portal design ensures that technical complexity is abstracted away from end-users — citizens interact with a simple mobile interface, while municipality officers work with familiar dashboard metaphors. The one-line

USE_REAL_API toggle ensures that the system can be demonstrated to stakeholders with mock data before production infrastructure is finalized.

The current implementation operates on a local Ganache testnet rather than a public Ethereum network, meaning that gas costs, network latency, and cross-organizational smart contract governance have not been evaluated under production conditions. The IoT sensor layer is simulated rather than physically deployed, and the Random Forest model was trained on synthetic data generated from the simulation rather than real historical waste records. Future work should validate the system against real bin sensor data from a partner municipality.

IX. Conclusion

This study investigated how the integration of Multi-Agent Systems, Artificial Intelligence, and Blockchain technology can address persistent efficiency, transparency, and coordination gaps in municipal solid waste management. Through a structured synthesis of seven foundational research works and a 30-day agent-based simulation, the study developed and evaluated a conceptual integrated framework comprising five functional layers: IoT-enabled monitoring, AI-driven overflow prediction, nearest-neighbour route optimization, multi-agent operational coordination, and Ethereum-based compliance enforcement.

The simulation findings indicate that the integrated framework produces substantial projected improvements over both traditional fixed-schedule and blockchain-only configurations, including 48% fewer collection trips, 56% reduction in vehicle distance, 83% reduction in overflow incidents, and a 94% automated compliance rate. Crucially, these gains emerge from the interaction between the AI prediction layer and the multi-agent coordination layer — neither component, when examined independently in the literature, produces equivalent results. This supports the study's central argument that technology integration, rather than incremental improvement of isolated components, is the critical design principle for next-generation smart waste systems.

The study has several limitations. All results are derived from simulation using synthetic data, and real-world performance will depend on actual sensor characteristics, municipal fleet constraints, and operational policies. The blockchain component was evaluated on a local testnet, and production-scale gas costs and latency remain unassessed. No user studies were conducted with municipal stakeholders.

Future research should focus on validating the framework against real IoT sensor data from a partner municipality, evaluating blockchain performance on the Ethereum Sepolia testnet, and conducting stakeholder usability studies across the three portal interfaces. The integration of computer vision for bin-level waste classification and the extension of citizen incentives to redeemable municipal service credits represent additional directions for empirical investigation.

References

[1] Addas, A., Khan, M. N., & Naseer, F. (2024). Waste management 2.0 leveraging internet of things for an efficient and eco-friendly smart city solution. PLOS One, 19(7), e0307608. https://doi.org/10.1371/journal.pone.0307608

[2] Alabdali, A. M. (2025). Blockchain based solid waste classification with AI powered tracking and IoT integration. Scientific Reports, 15, Article 97030. https://doi.org/10.1038/s41598-025-97030-2

[3] Ali, B., Javed, M. A., Alharbi, A. A. K., Alotaibi, S., & Alkhathami, M. (2024). Internet of Things-assisted vehicle route optimization for municipal solid waste collection. Applied Sciences, 14(1), 287. https://doi.org/10.3390/app14010287

[4] Baralla, G., Pinna, A., Tonelli, R., Marchesi, M., & Ibba, S. (2022). Ensuring transparency and traceability of food local products: A blockchain application to a smart tourism region. Concurrency and Computation: Practice and Experience, 33(1), e5857.

[5] Cong, L. W., & He, Z. (2018). Blockchain disruption and smart contracts. NBER Working Paper No. 24399. National Bureau of Economic Research.

[6] Hussain, I., Elomri, A., Kerbache, L., & Omri, A. E. (2024). Smart city solutions: Comparative analysis of waste management models in IoT-enabled environments using multiagent simulation. Sustainable Cities and Society, 103, 105247.

[7] Ibitoye, O., et al. (2025). Smart waste, smarter world: Exploring waste types, trends, and tech-driven valorisation through artificial intelligence, internet of things, and blockchain. Sustainable Development. https://doi.org/10.1002/sd.70345

[8] Lenz, L. (2021). BlockWASTE — A global assessment of blockchain applications in waste management. Waste Management, 125, 28–37.
[9] Priyadarshi, M., Maratha, M., Anish, M., et al. (2023). Dynamic routing for efficient waste collection in resource constrained societies. Scientific Reports, 13, 2365. https://doi.org/10.1038/s41598-023-29593-x
[10] Stroumpoulis, A., Kopanaki, E., & Euaggelidis, G. (2021). Blockchain technology and supply chain management: A theoretical framework. In Proceedings of the 25th Pan-Hellenic Conference on Informatics (pp. 1–6). ACM.
[11] Williams, P., Leach, B., Christensen, K., Armstron, G. D., Hawkins, R. P., Lane, A. J. G., Scholes, P. (2011), "The Composition of Waste Disposed of by the UK Hospitality Industry", Report RES093-001, Waste and Resources Action Programme, London.
[12] Xu, X., Weber, I., Staples, M. (2019), Architecture for blockchain applications, Springer, Cham.
[13] Kosba, A., Miller, A., Shi, E., Wen, Z., Papamanthou, C. (2016), "Hawk: the blockchain model of cryptography and privacy-preserving smart contracts", in 2016 IEEE Symposium on Security and Privacy (SP), San Jose, pp. 839-858.
[14] Climate-KIC, e. (2019). Market Analysis for Plastic waste recovery by regional blockchain networks. Retrieved from https://ecircular.climate-kic.org/wp content/uploads/sites/2/2019/02/Market-Analysis-for-Plastic-waste-recovery-by regional-blockchain-networks.pdf
[15] T. Shevchenko, M. Saidani, Y. Danko, I. Golysheva, J. Chovancová, and R. Vavrek, ''Towards a smart E-waste system utilizing supply chain participants and interactive online maps,'' Recycling, vol. 6, no. 1, p. 8, Feb. 2021.
[16] G.Ongena,K.Smit,J.Boksebeld,G.Adams,Y.Roelofs,andP.Ravesteyn, ''Blockchain-based smart contracts in waste management: A silver bul let?'' in Proc. Bled eConf., 2018, p. 19.
[17] S. V. Akram, S. S. Alshamrani, R. Singh, M. Rashid, A. Gehlot, A. S. AlGhamdi, and D. Prashar, ''Blockchain enabled automatic reward system in solid waste management,'' Secure. Commun. Netw., vol. 2021, pp. 1–14, Sep. 2021.
[18] A. Chauhan, O. P. Malviya, M. Verma, and T. S. Mor, "Blockchain and scalability," in IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C). IEEE, 2018, pp. 122 128.
[19] M. Arebey, M. Hannan, H. Basri, and H. Abdullah, "Solid waste mon itoring and management using RFID, GIS, and GSM," in IEEE Student Conference on Research and Development (SCOReD). IEEE, 2009, pp. 37–40.
[20] World Bank. (2018). What a waste 2.0: A global snapshot of solid waste management to 2050. World Bank Group, Washington, DC.