Implementing a Blockchain, Smart Contract, and NFT Framework for Waste Management Systems in Emerging Economies: An Investigation in Vietnam

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Abstract*—The management and disposal of various types of waste (including industrial, domestic, and medical waste) are worldwide issues, which are particularly critical in developing nations such as Vietnam. Given the extensive population and inadequate waste treatment facilities, addressing this challenge is of utmost importance. Predominantly, the majority of such waste is not processed for composting but is instead subjected to elimination, thereby posing severe threats to public health and environmental safety. Furthermore, insufficient standards in existing waste treatment plants contribute to the rising volume of environmental waste. Emphasizing the process of waste recycling instead of total elimination is an alternate strategy that needs to be considered seriously. However, the implementation of waste segregation in Vietnam is still not sufficiently prioritized by individuals or organizations. This study presents a unique model for waste segregation and treatment, leveraging the capacities of blockchain technology and smart contracts. We also scrutinize the adherence or non-compliance to waste segregation mandates as a mechanism to incentivize or penalize individuals and organizations, respectively. To address this, we employ Non-Fungible Token (NFT) technology for the storage of compliance proofs and associated metadata. The paper's primary contributions can be delineated into four components: i) presentation of a waste segregation and treatment model in Vietnam, utilizing Blockchain technology and Smart Contracts; ii) application of NFTs for storage of compliance-related content and its metadata; iii) offering a proof-of-concept implementation rooted in the Ethereum platform; and iv) executing the proposed model on four EVM and ERC721 compliant platforms, namely BNB Smart Chain, Fantom, Polygon, and Celo, to identify the most suitable platform for our proposition.

***Keywords*—Vietnam waste management; blockchain; smart contracts; NFT; Ethereum; Fantom; Polygon; Binance Smart Chain**

I. INTRODUCTION

The challenges associated with the management and disposal of various types of waste, including domestic, industrial, and medical, pose a substantial hindrance to the economic advancement of nations [1] and a significant threat to environmental sustainability [2]. Established economies have developed stringent protocols for the inspection, categorization, and eradication of waste arising from these sources [3]. A notable portion of hazardous waste is efficiently transformed into electricity at incineration plants.

Nonetheless, in emerging economies such as the Philippines and Vietnam, where the economic potential is yet to be fully realized and the population size is considerable, methodical approaches to waste categorization and treatment have not been given the necessary attention. Predominantly, traditional waste management methods, which lack the crucial step of waste segregation at the origin sources such as residential areas, hospitals, or industrial sites, are still prevalent [4]. Investment and emphasis on pre-treatment and waste separation stages at these initial sources are considerably lacking. This neglect results in a majority of the waste being non-segregated and dumped directly into the ecosystem, leading to severe environmental pollution and contamination of surrounding areas. This waste is then conventionally collected and eliminated with no specific attention paid to the treatment of smoke and odors, thereby contributing to air and water pollution around the disposal sites.

Hazardous solid waste, for instance, rubber items like tires, and electronic components from computers and phones, need to be methodically sorted and treated via specialized procedures that safeguard the environment. To illustrate, a thermal power plant in Germany efficiently utilizes old tires as a fuel source. In order to tackle this issue, the initial step of waste segregation, also known as pre-treatment, is paramount. In the context of developed countries, industrial areas, and households, waste is typically segregated into four categories, namely i) paper-based items such as boxes and packaging; ii) recyclable waste including rubber, glass, and metal cans; iii) organic food waste; and iv) other types of waste. Each waste category is subjected to a distinctive treatment and categorization process, allowing for reuse or safe disposal to prevent harm to environmental and human health.

However, the transposition of these processes into the context of developing countries is met with challenges due to cultural differences and varying operational procedures. Notably, the constraints in waste management in these emerging economies are not merely infrastructural but also deeply rooted in public awareness and attitudes towards waste segregation and treatment. For instance, in Vietnam, wastes are often not separated and are mostly disposed of using a singular method, which involves casting them into the environment (further details on traditional waste management processes can be found in the approach section).

The conclusion of the Covid-19 pandemic has highlighted several deficiencies in global health systems [5]. Health infrastructure, medical supplies, and equipment worldwide were already strained due to a massive influx of patients, affecting the delivery of care and treatment services. This has led to the difficulty in controlling the spread of the disease, resulting in increased mortality. Particularly for emerging economies like Vietnam, which witnessed a dramatic surge in positive cases from the end of 2020 to the beginning of 2021, this issue was exacerbated by limited healthcare infrastructure, especially concerning the waste treatment process. Numerous studies, such as that conducted by [6], have concluded that unsafe procedures for handling medical waste during the pandemic have significantly contributed to the propagation of Covid-19.

To address the waste categorization and treatment problem, several models have been proposed that leverage Blockchain technology and Smart Contracts. Specific to each waste type and treatment scope, these models propose a unique treatment and transportation process for different waste types like medical waste [7], solid waste (e.g., electronic components, computers, phones) [8], household waste [9], and industrial waste [10] (see Related work for details). There is also considerable research focusing on developing waste treatment processes tailored to developing countries (e.g., India [11]; Brazil [10]; and Vietnam [12]). Regarding the Covid-19 pandemic, these approaches propose waste management and classification models for different stages (e.g., hospital/isolation zone - transportation company or transport company - waste processing company). However, these studies primarily enable governments to track and trace different types of waste (e.g., weight, waste type, etc) with ease.

In response to these issues, our goal is to design a waste categorization and treatment model rooted in Blockchain technology, Smart Contracts, and Non-Fungible Tokens (NFTs), customized to the context of Vietnam. Specifically, our proposed model empowers stakeholders to assess waste treatment levels at the output, with all relevant information processed, validated, and stored on-chain [13]. This method of on-chain storage enhances transparency compared to traditional storage methods. Additionally, we ensure system efficiency and prevent overloading through a decentralized storage approach (i.e., distributed ledger). Our model utilizes Smart Contract technology, assisting stakeholders in managing the waste treatment process, from segregation to transportation and treatment. NFT technology facilitates the storage of information regarding a garbage bag, making it easier to ascertain weight, timing, origin, and waste type (i.e., garbage, industrial, medical, domestic). Furthermore, we utilize NFTs to identify compliance or non-compliance with waste classification requirements, enabling the implementation of sanctions or rewards accordingly.

Our paper makes four primary contributions: i) we introduce a waste categorization and treatment model tailored to Vietnam, utilizing Blockchain technology and Smart Contracts; ii) we leverage NFTs to store compliance-related content and associated metadata; iii) we offer a proof-of-concept implementation based on the Ethereum platform; and iv) we execute the proposed model on four EVM and ERC721 compatible platforms, namely BNB Smart Chain, Fantom, Polygon, and Celo, to identify the most suitable platform for our proposition.

This paper comprises eight sections. After this introduction, we delve into related works that address similar research problems. The background section considers the key technologies underpinning our work, i.e., blockchain, EVM, NFT, Smart Contracts, and the four EVM-supported blockchain platforms. We then present our approach and proposed model implementation (i.e., Execution Blueprint) in Sections IV and V. To demonstrate the efficacy of our approach, Section VI outlines our evaluation steps in various scenarios, followed by a discussion of our findings in Section VII. Finally, Section VIII provides a summary and outlines potential directions for future development.

II. Related Work

Modern advancements in technology have led to the emergence of numerous innovative solutions for waste management and classification. Among these, Blockchain-based approaches have demonstrated significant potential. This section reviews a selection of notable studies in the field, broadly divided into two categories: i) Blockchain-based waste sorting and treatment solutions, and ii) region-specific waste management methodologies.

A. Blockchain-based Waste Sorting and Treatment Solutions

A plethora of studies has proposed distinctive approaches to manage different types of waste in our day-to-day lives. For instance, electronic waste (e-waste), which includes discarded electronic devices, has been addressed by Gupta et al. [8]. They proposed an Ethereum-based waste management system tailored for electrical and electronic equipment. Their model engages three key user groups: manufacturers, consumers, and retailers. Smart contracts in the system demonstrate direct constraints between these interacting entities. Retailers serve as the mediators, distributing new products to users and collecting the used items to return to manufacturers. Successful execution of these activities leads to a reward in Ether (ETH). This system eliminates the need for manufacturers to retrieve their used products directly.

In the context of solid waste, like old computers and smartphones, a model that tracks the journey of waste from its source to the treatment centers is crucial. Addressing this, Laura et al. [14] introduced a waste management system leveraging the synergy between Ethereum and QR codes. Their approach emphasizes a system that supports four stakeholders: a collection manager, a record manager, a transaction manager, and a processing manager. To determine the type of waste for disposal, each garbage bag is assigned a QR code that links to the corresponding data stored on-chain. This facilitates stakeholders to trace and ascertain the current location and estimated processing completion time of each garbage bag. By anticipating the extraction date from the garbage bag, transportation companies can determine the daily capacity for waste processing, mitigating overloading issues at waste treatment sites.

For the monitoring of cross-border waste movements in a secure, tamper-proof, and privacy-preserving manner, Schmelz et al. [15] presented an Ethereum-based study. Their approach ensures that only authorized parties can access information based on encryption technology. For authorities overseeing cross-border waste transport, they can trace location, volume, and estimated transit times of waste units (e.g., vehicles, bags) through data stored on distributed ledgers. Shipping processes can be automated by predefined smart contracts. A limitation of this approach is the lack of mechanisms to penalize violations in waste transportation and disposal.

In another study, Francca et al. [16] proposed an Ethereum-based model for managing solid waste in small municipalities.

For models utilizing the Hyperledger Fabric platform, Trieu et al. [12] proposed a medical waste treatment model called MedicalWast-Chain. The model targets the management of medical waste from healthcare facilities, including the reuse of tools, the process of transferring medical supply waste (e.g., protective gear, gloves, masks), and waste treatment processes in factories. The objective is to enable traceability of waste origins and toxicity levels, especially crucial during a pandemic. Similarly, Ahmad et al. [17] aimed to trace personal protective equipment for healthcare workers (i.e., doctors, nurses, testers) during the pandemic. They also identified compliant and non-compliant behaviors in waste classification and collection by comparing photographs of medical waste collection sites.

To validate waste treatment processes (i.e., stakeholder interactions), Dasaklis et al. [18] proposed a blockchain-based system operable via smartphones.

B. Region-Specific Waste Management Methodologies

While Blockchain technology has proven effective in managing waste, its applications remain largely unexplored in specific regions. In light of this, we present a review of traditional waste treatment methodologies.

The efficiency of waste collection, a crucial preliminary step in waste management, is heavily influenced by the chosen travel route. Several studies have attempted to optimize this process by calculating time and cost implications (i.e., vehicle route) that influence the path of the garbage collection vehicle. Some solutions have adopted Geographic Information System (GIS) technology to manage the routes of garbage collection vehicles. For instance, Ghose et al. [19] developed a solid waste collection and treatment route for the city of Asansol in India by optimizing the path based on GIS.

On a larger scale, encompassing more than just cities, Nuortio et al. [20] proposed a well-scheduled and routed waste collection method for Eastern Finland, utilizing the neighborhood threshold metadata approach. In another example, a truck planning model for solid waste collection was proposed by Li et al. [21] for the Brazilian city of Porto Alegre.

For the European context, Gallardo et al. [22] proposed a Municipal Solid Waste (MSW) management system for the Spanish city of Castellón. The system integrated ArcGIS[1] with a planning approach to optimize travel times between locations when collecting waste in the city. This approach has shown greater efficiency compared to traditional methods [23], [24].

C. Analysis of Blockchain-based Approaches for Vietnam

The aforementioned models do not devote substantial attention to the process of recycling or refurbishing. Also, these studies do not provide a well-rounded solution for rewarding compliance and penalizing non-compliance in waste sorting behavior of users (e.g., households, companies, businesses, or medical centers).

When considering Blockchain technology and smart contracts-based models, the existing solutions (both for Hyperledger Eco-system and Ethereum platforms) primarily focus on waste management from the initial stage up to the waste treatment plant. They lack comprehensive consideration of specific geographical characteristics, like those of Vietnam. This leaves a significant gap for a solution that incentivizes proper waste sorting habits not only for companies, businesses, medical centers but also households.

For traditional waste classification and treatment methods applied to a specific region, there has been minimal application of modern technologies to alleviate labor-intensive tasks and address current gaps (e.g., overloading, shipping process, information validation).

The present study aims to address these shortcomings. Not only do we propose a model to manage waste sorting, but we also offer a solution for rewarding compliance and handling violations of users/companies/enterprises based on NFT technology. The subsequent sections detail the background information related to our topics before elaborating on the proposed processing steps and implementation.

III. Background and Theoretical Foundation

A. Blockchain Technology: An Overview

Blockchain, famously associated with Bitcoin's success [25], is a distributed ledger system. It operates on a peer-to-peer network and maintains transaction records across various computers simultaneously. This decentralized approach ensures a transparent and trustworthy data management system, eliminating the need for a central authority or intermediary for validation [26], [27], [28]. The key advantages of employing blockchain-based systems are outlined below.

- Security: Blockchain incorporates digital signatures and encryption to ensure a secure environment. This robust design prevents data manipulation and unauthorized access [29].
- Fraud Prevention: As data is replicated across multiple nodes, blockchain-based systems are resilient to hacking attempts. Moreover, the decentralized nature of blockchain allows for efficient recovery of all records [30].
- Transparency: With blockchain, both parties involved in a transaction receive instantaneous notifications upon completion, ensuring a seamless and reliable experience.
- Cost-effectiveness: Since the blockchain is a decentralized system, it bypasses intermediaries and avoids associated fees, thus reducing overall costs [31].
- Access Control: Blockchain provides the option to choose between a public network, accessible to all, and a permissioned network, which requires authentication for access [32].

[1] A command-line based GIS system for manipulating data https://www.arcgis.com/index.html

- Efficiency: Transactions are processed faster in a blockchain-based system since it eliminates the need for integration with conventional payment systems [33].
- Integrity Verification: Blockchain inherently fosters a consensus-based environment, wherein the validity of participants is checked and confirmed by other network participants, further ensuring data authenticity [34].

B. Smacockchain

Smart contracts, also known as chaincode, are self-executing contracts containing the terms and conditions of an agreement directly written into code. Leveraging blockchain technology, these contracts automate transaction executions without requiring an external intervention or intermediary. Here, we delineate the salient features of smart contracts.

- Distributed: Smart contracts are replicated and distributed across all nodes of a blockchain network, distinguishing them from centralized server-based solutions.
- Deterministic: Smart contracts only perform predefined actions when specific conditions are met. Furthermore, regardless of the executor, the outcome of smart contracts remains consistent.
- Automated: Smart contracts can automate a wide range of tasks and function as self-executing programs. However, unless activated, they remain "inactive" and do not perform any action.
- Immutable: Once deployed, smart contracts cannot be altered. They can only be "deleted" if a provision for deletion was included prior to deployment, giving them an anti-forgery attribute.
- Customizable: Prior to deployment, smart contracts can be coded in different ways, making them suitable for creating diverse decentralized applications (DApps). Platforms like Ethereum are Turing complete, meaning they can solve any computational problem.
- Trust-free Environment: Smart contracts facilitate interactions between parties without requiring mutual trust, while blockchain technology ensures data accuracy.
- Transparent: Since smart contracts are based on a public blockchain, their source code remains unalterable and can be viewed by anyone.

C. Blockchain Platforms

1) Ethereum: Ethereum [35] is a decentralized open-source blockchain platform, renowned for its support of Turing-complete programming languages and smart contracts. It operates on the Ethereum Virtual Machine (EVM) and supports high-level programming languages such as Solidity, Serpent, LLL, and Mutan. Ethereum enables a variety of use-cases such as withdrawal limits, loops, financial contracts, and gambling markets, making it a preferred platform for smart contract development.

2) Hyperledger fabric: Hyperledger Fabric [36] is a permissioned, open-source, enterprise-grade distributed ledger technology (DLT) platform, tailored for large-scale commercial use. Unlike Ethereum that executes smart contracts on virtual machines, Hyperledger Fabric runs code in Docker containers, providing optimal execution speed at the expense of isolation. It supports traditional high-level programming languages such as Java and Go (Golang) over Ethereum's exclusive smart contract languages.

D. Reasons for Choosing the Ethereum Ecosystem

The Ethereum ecosystem, underpinned by the Ethereum Virtual Machine (EVM), was chosen for our deployment due to its significant benefits. Ethereum supports smart contracts and DApps, providing a Turing-complete environment that facilitates the creation of a wide range of applications. Furthermore, Ethereum's robust community support, rich developer tools, and high-level programming language compatibility make it a prime choice for blockchain-based development.

In addition, Ethereum's interoperability is a significant factor. Its ecosystem includes various blockchain platforms that operate with EVM-compatible blockchains. This allows applications built on Ethereum to be easily ported to other EVM-compatible blockchains, offering flexibility in deployment options.

E. Selected Platforms for Deployment

Given the interoperability of Ethereum and the distinct advantages of EVM-compatible blockchains, we have chosen four platforms for deployment: Binance Smart Chain (BNB Smart Chain), Polygon, Fantom, and Celo.

1) Binance smart chain: Binance Smart Chain [2] is a high-performance, low-fee blockchain platform. It supports smart contracts and is compatible with EVM, making it a viable option for deploying DApps. It also offers a dual-chain architecture with Binance Chain, allowing users to seamlessly transfer assets from one blockchain to another.

2) Polygon: Polygon [3] is a protocol and a framework for building and connecting Ethereum-compatible blockchain networks. It effectively transforms Ethereum into a full-fledged multi-chain system, often referred to as the "Internet of Blockchains". Polygon combines the best of Ethereum and sovereign blockchains into a full-fledged multi-chain system.

3) Fantom: Fantom [4] is a high-performance, scalable, and secure smart-contract platform. It is designed to overcome the limitations of previous-generation blockchain platforms. Fantom's primary proposition is its capability to perform instantaneous transactions and process large volumes at an extremely low cost, making it ideal for decentralized applications (DApps).

4) Celo: Celo [5] is an open platform that makes financial tools accessible to anyone with a mobile phone. Its mission is to build a monetary system that creates the conditions

[2]https://github.com/bnb-chain/whitepaper/blob/master/WHITEPAPER.md
[3]https://polygon.technology/lightpaper-polygon.pdf
[4]https://whitepaper.io/document/438/fantom-whitepaper
[5]https://celo.org/papers/whitepaper

of prosperity for everyone. Celo's lightweight identity and high throughput make it an optimal choice for mobile-first applications and services.

These platforms were chosen because they offer scalability, security, and efficiency while being cost-effective. Their EVM compatibility ensures smooth portability of applications built on Ethereum, providing a flexible and efficient deployment environment. For detailed understanding of these platforms, readers are referred to the respective white papers provided.

IV. Approach Devised

A. Conventional Waste Management in Vietnam: An Overview

Upon surveying waste management practices across Vietnam, we find that strategies differ considerably between urban areas (cities, for example) and rural locales (Cho Lach district in Ben Tre province serves as a good case study). Urban communities, especially those densely populated, gather waste at designated spots for waste disposal firms to handle. In contrast, rural communities typically dispose of their waste directly, often impacting the natural environment adversely.

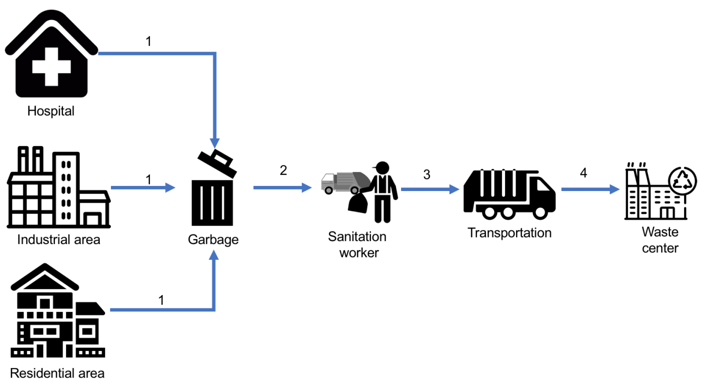


Fig. 1. Conventional waste management method in Vietnam.

Additionally, industrial and medical sectors follow their unique waste management protocols. They accumulate waste at certain locations for waste disposal companies to collect daily or semi-daily. Considering the disparities in waste segregation between urban and rural landscapes, we've formulated a waste classification and management model apt for urban settings, inspired by procedures adhered to in industrial and healthcare domains.

Fig. 1 illustrates a typical five-step waste management cycle followed in urban environments, industrial estates, and hospitals. Initially, waste is amassed at a designated location (step 1). Collection procedures (step 2) vary depending on the waste type. For instance, sanitation workers dealing with household waste (food waste) need fewer protective measures than those handling medical waste. Post collection, the waste is taken to waste sorting (step 3) and recycling centers (step 4). Depending on the waste type, these centers will either recycle or dispose of the waste (step 5).

Our study primarily focuses on the waste management process at the source (residential areas, factories, or hospitals). If individuals can segregate their waste appropriately at the source (into paper, bio, metal, and glass), it aids the subsequent recycling and waste treatment process. However, this practice is not widely observed in Vietnam, causing difficulties for waste collectors who struggle to segregate unsorted waste. To address this, we propose using Non-Fungible Tokens (NFTs) to document instances of compliance or non-compliance with waste segregation norms. The following subsection provides a detailed description of our proposed model.

B. Waste Management Model Utilizing Blockchain Technology, Smart Contracts, and NFTs

Fig. 2 represents a six-step waste segregation and management process that integrates blockchain technology, smart contracts, and NFTs. The key distinction from the traditional model (Fig. 1) comes into play in step 2. After segregation, waste should be categorized into four groups (paper, bio, metal, and glass), each corresponding to uniquely labeled or color-coded bins.

Sanitation personnel then scrutinize the segregation process undertaken by an individual or an organization to establish whether it's compliant or non-compliant (step 3). This verification is updated onto appropriate functions within the smart contracts (step 4).

In step 5, NFTs corresponding to the individual's or organization's waste segregation actions (either compliant or non-compliant) and pertinent information (metadata; see Implementation section for additional details) are generated. Finally, the entire process is updated and archived on a distributed ledger, facilitating easy validation by concerned parties.

V. Execution Blueprint

Our practical model is established on two primary objectives: i) administration of data, specifically waste - originating, seeking, and revising - within a blockchain platform, and ii) fabricating Non-Fungible Tokens (NFTs) that acknowledge, reward or penalize users, which could be individuals or institutions, based on their conduct in the management and disposal of waste.

A. Origination of Data and NFTs

Fig. 3 presents the steps necessary to set up waste data. The waste data can be of different categories such as industrial, household, or medical waste. They need to be properly divided into groups like discard or repurpose, according to their toxicity levels. Detailed descriptions about each kind of waste are then affixed to each unique garbage bag.

Each bag carries a unique identifier to distinguish it by the waste type it holds. Moreover, metadata about each garbage bag is augmented to include details about the individual or organization doing the sorting, the household or company generating the waste, as well as the time and location of waste sorting. A distributed ledger-based service enables concurrent data storage from several users, hence diminishing system latency. Broadly, the waste data is structured in the following way:

```
wasteDataObject = {
"wasteID": industrialWasteID,
"sorterID": sorterID,
```

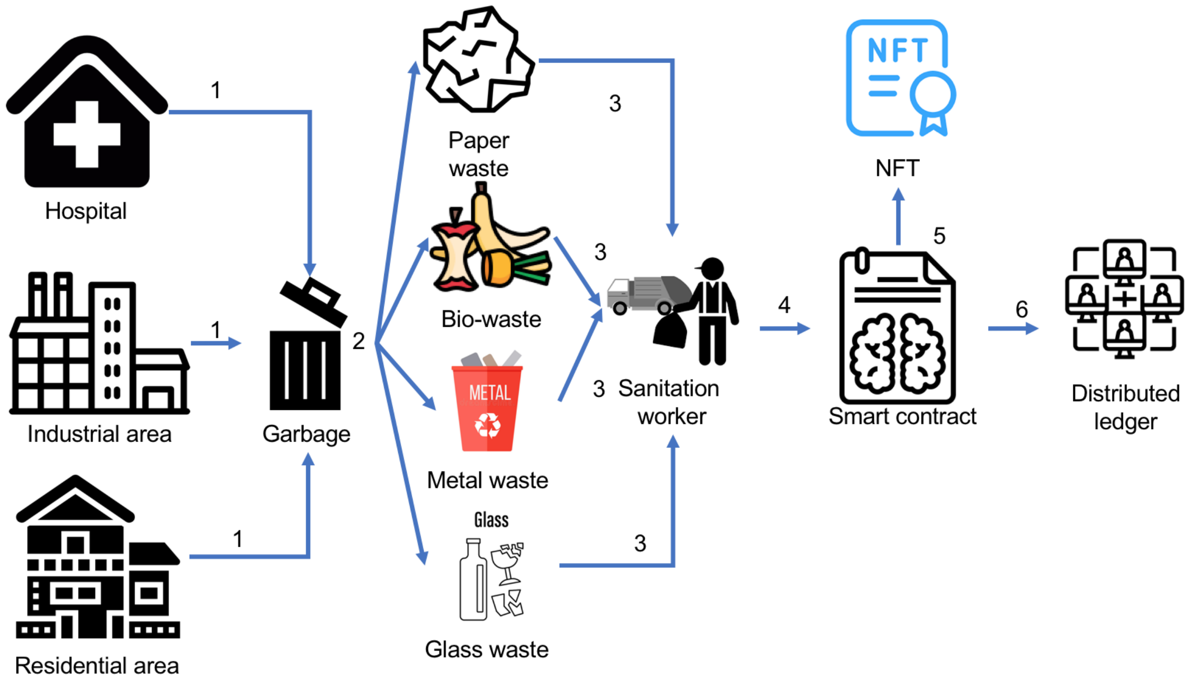


Fig. 2. Waste management framework utilizing blockchain technology, smart contracts, and NFTs.

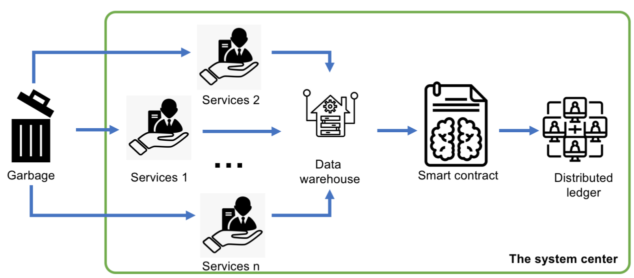


Fig. 3. Origination of data and NFTs.

```
"kind": wasteKind,
"place": place,
"amount": amount,
"unit": unit,
"bagID": bagID,
"timestamp": timestamp,
"sortingLocation": sortingLocation,
"status": null,
"repurpose": Null
};
```

Besides information about the waste's origin, weight, and kind, the system keeps track of the status of waste bags in residential areas, factories, hospitals, etc. Specifically, the "status" switches to 1 if the relevant waste bag has been moved from its original collection location for treatment or disposal; if not, it remains at 0 (pending). The "repurpose" tag indicates 1 when the waste type is reused and 0 when pending, and is applicable to non-hazardous waste.

Post the waste sorting process, sanitation workers verify the sorted waste for compliance with set standards. The data is then stored temporarily in a data repository, waiting for validation before being synchronized on the blockchain. This is achieved by invoking certain predefined constraints in the Smart Contract via the Application Programming Interface (API). In the process of initiating NFTs, the content of the NFT is defined as follows:

```
NFT WASTE = {
"wasteID": wasteID,
"sorterID": sorterID,
"place": place,
"bagID": bagID,
"kind": true/false,
"amount": true/false,
"timestamp": timestamp,
"inspector": cleanerID
};
```

If the values on the sorted waste bags are verified to be correct, the sorter is rewarded. In contrast, if there are discrepancies, penalties are applied. If the inspector provides incorrect information, they are the ones to be penalized.

B. Data Seeking

The data seeking procedure, much like data origination, is capable of handling multiple concurrent participants, courtesy of the distributed model on which the system operates. The services facilitate requests from the sanitation staff or any individual or organization to access the data.

The intent behind seeking data varies. Sanitation staff might be looking to review the waste sorting process or to transfer waste to the disposal companies, whereas individuals or organizations might want to gather information about the waste treatment process.

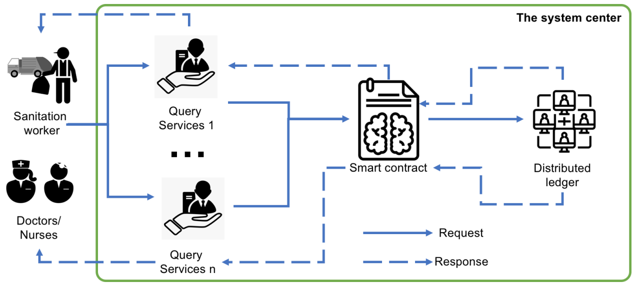


Fig. 4. Data seeking.

Fig. 4 outlines the data seeking steps. Requests are sent from the user to the smart contracts embedded within the system before retrieving data from the distributed ledger. All such requests are logged as a history for each individual or organization. If the sought information is not found (e.g., due to a wrong ID), the system responds with a 'not found' message. Regarding NFTs, all supporting services are rendered via APIs.

C. Data Revision

Data revisions are only allowed after validating that the data exists on the blockchain, following the execution of the respective data seeking procedure. In the discussion that follows, we will operate under the assumption that the sought data is indeed present on the blockchain. If not, the system will return a 'not found' message (see V-B for details).

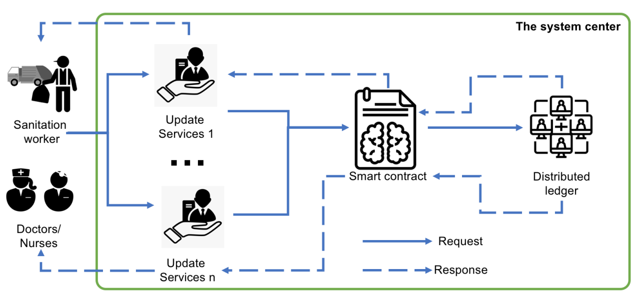


Fig. 5. Data revision.

In line with the data seeking and origination processes, the system provides revision services in the form of APIs to receive user requests before processing them via smart contracts. The primary aim of this process is to keep the time and location of waste bags updated as they move through the transportation and sorting/disposal stages. This enables the administrator to monitor the progress of waste management, right from its generation at medical centers/residential areas/factories to its final destination at waste treatment companies.

Fig. 5 outlines the waste data revision process. In the case of NFTs, the revision process only entails moving the NFT from the owner's address to a new one. If any information on an existing NFT is updated, it is stored as a new NFT (see V-A for details).

VI. Deployment Assessment

A. Deployment Process on Four Blockchain Platforms

The deployment process of our proposed model comprises four critical steps which are applied across all four Ethereum Virtual Machine (EVM) supporting platforms (Binance Smart Chain (BNB Smart Chain), Polygon, Fantom, and Celo). These steps include:

1) Preliminary Setup: This step primarily involves setting up the development environment. Solidity, the programming language for Ethereum smart contracts, is used for writing the contracts. These smart contracts include rules and instructions that govern the behavior of the blockchain.
2) Contract Creation: Once the preliminary setup is complete, the first smart contract is created. This contract encapsulates all the rules defined in the model, such as the reward or penalty mechanism for waste sorting. The smart contract is then compiled to ensure there are no errors in the code.
3) NFT Generation: After the contract has been successfully compiled, it's time to generate the Non-Fungible Tokens (NFTs) that would be issued as rewards or penalties. The NFTs are created via the smart contract that has been deployed on the blockchain. Each NFT is unique and represents a real-world object, in this case, the behavior of individuals or organizations in the waste management process.
4) NFT Retrieval/Transfer: The final step involves updating the NFT's ownership address (i.e., transferring the NFT). This transfer is done through an operation in the smart contract. The updated NFT information is then recorded on the blockchain.

These procedures are executed in a testnet environment for each platform to evaluate their cost-effectiveness. The cost of each operation - contract creation, NFT generation, and NFT retrieval/transfer - is evaluated using the following parameters: Transaction Fee, Gas Limit, Gas Used by Transaction, and Gas Price.

B. Implementation on BNB Smart Chain (Sample Deployment)

Fig. 6 outlines the steps involved in our implementation on the BNB Smart Chain. Like the general process described above, the implementation begins with setting up the development environment and writing the contract in Solidity.

Once the smart contract is written and compiled successfully, it is deployed on the BNB Smart Chain testnet. This step creates a transaction, with details of this transaction recorded and accessible via a unique transaction hash.

Upon successful deployment of the contract, NFTs are created as per the rules defined in the smart contract. Fig. 7 shows an instance of an NFT being created.

The final step involves updating the NFT's ownership address. This involves invoking the appropriate function in the smart contract, and once executed, the NFT transfer can be seen as shown in Fig. 8.

The cost of these operations is calculated and presented in terms of the Transaction Fee, Gas Limit, Gas Used by

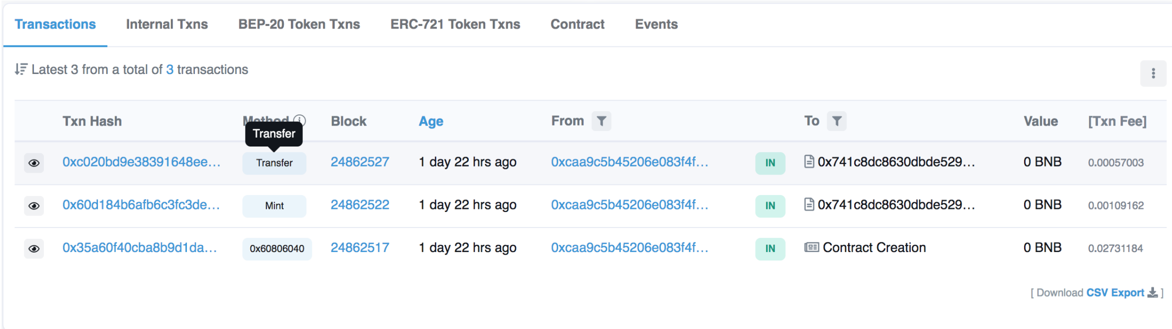


Fig. 6. The transaction info on BNB smart chain.

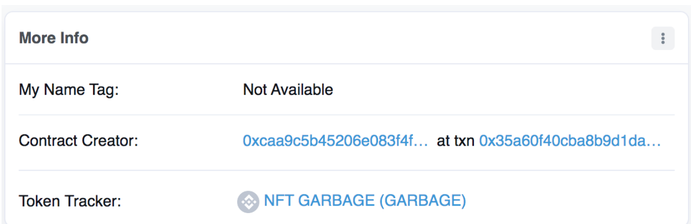


Fig. 7. NFT creation on BNB smart chain.

Transaction, and Gas Price. These costs provide valuable insights into the effectiveness and efficiency of deploying our model on the BNB Smart Chain. The same deployment process and cost assessments are followed for the other platforms (Polygon, Fantom, and Celo) to evaluate their performance and cost-effectiveness. For more details, we refer the readers follow our deployment on the test-net system of the corresponding platform, namely BNB[6]; MATIC[7]; FTM[8]; and CELO[9].

C. Transaction Fee

Table I provides a comprehensive comparison of the transaction fees incurred for various operations on the four considered blockchain platforms: BNB Smart Chain, Fantom, Polygon, and Celo.

The transaction fee is calculated for three key operations:

1) Contract creation: This operation involves creating and deploying the smart contract on the respective blockchain. The fee varies significantly across the platforms, with BNB Smart Chain being the most expensive at 0.02731184 BNB (approximately \$8.43). Fantom has the lowest cost for contract creation, amounting to 0.009576994 FTM (equivalent to approximately \$0.001837).

2) Create NFT: This operation refers to the cost of generating a Non-Fungible Token (NFT) on the blockchain. The BNB Smart Chain again appears as the most expensive option, with a fee of 0.00109162 BNB (about \$0.34). On the contrary, the Polygon platform records the least cost, at 0.000289405001389144 MATIC (approximately \$0.00).

3) Transfer NFT: This refers to the cost of transferring ownership of the NFT from one address to another. BNB Smart Chain remains the most expensive platform, with a transfer fee of 0.00057003 BNB (roughly \$0.18). Conversely, the Fantom platform provides the most cost-effective solution for NFT transfer, charging a mere 0.0002380105 FTM (\$0.000046).

This table, therefore, provides a detailed overview of the cost dynamics across various platforms for different operations. BNB Smart Chain consistently shows the highest fees for all operations, while the other platforms vary in their cost-effectiveness for different operations. These insights can guide the selection of an optimal platform for deploying the recommendation model based on financial constraints and operational priorities.

D. Gas Limit

Table II presents an in-depth comparison of the gas limits on the four blockchain platforms evaluated: BNB Smart Chain, Fantom, Polygon, and Celo. The gas limit refers to the maximum amount of gas that a user is willing to spend on a transaction. Gas in blockchain is a measure of computational effort required to execute certain operations.

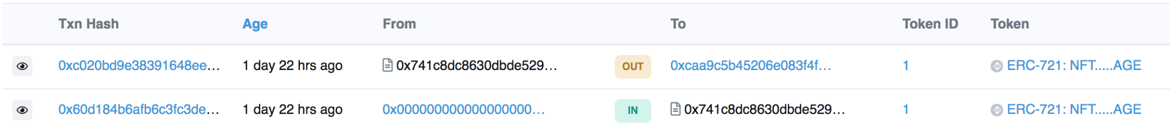
The table provides data for three crucial operations:

1) Contract creation: This column details the gas limit for creating and deploying a smart contract on the respective blockchain. Among the four platforms, Celo demands the highest gas limit for contract creation at 3,548,719, which reflects its higher computational requirements. The BNB Smart Chain has the lowest gas limit for this operation, requiring just 2,731,184.

2) Create NFT: This column indicates the gas limit necessary for generating a Non-Fungible Token (NFT) on each platform. Celo once again shows the highest gas limit at 142,040, demonstrating that generating an NFT on this platform is relatively computationally intensive. On the contrary, the BNB Smart Chain requires a lower gas limit, at 109,162.

3) Transfer NFT: This column represents the gas limit needed to transfer the ownership of an NFT from one address to another. The Celo platform necessitates the highest gas limit for NFT transfers, at 85,673, indicating a higher computational

[6] https://testnet.bscscan.com/address/0x741c8dc8630dbde529466eec066fe5f98b1f6ee4
[7] https://mumbai.polygonscan.com/address/0x3253e60880ce432dded52b5eaba9f75b92ca530a
[8] https://testnet.ftmscan.com/address/0x3253e60880ce432dded52b5eaba9f75b92ca530a
[9] https://explorer.celo.org/alfajores/address/0x3253e60880cE432DdeD52b5EAba9f75b92Ca530A/transactions



	Txn Hash	Age	From		To	Token ID	Token
	0xc020bd9e38391648ee...	1 day 22 hrs ago	0x741c8dc8630dbde529...	OUT	0xcaa9c5b45206e083f4f...	1	ERC-721: NFT.....AGE
	0x60d184b6afb6c3fc3de...	1 day 22 hrs ago	0x000000000000000000...	IN	0x741c8dc8630dbde529...	1	ERC-721: NFT.....AGE

Fig. 8. NFT transfer on BNB smart chain.

TABLE I. TRANSACTION FEE

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	0.02731184 BNB ($8.43)	0.00109162 BNB ($0.34)	0.00057003 BNB ($0.18)
Fantom	0.009576994 FTM ($0.001837)	0.000405167 FTM ($0.000078)	0.0002380105 FTM ($0.000046)
Polygon	0.006840710030099124 MATIC($0.01)	0.000289405001389144 MATIC($0.00)	0.000170007500884039 MATIC($0.00)
Celo	0.0070974384 CELO ($0.004)	0.0002840812 CELO ($0.000)	0.0001554878 CELO ($0.000)

TABLE II. GAS LIMIT

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	2,731,184	109,162	72,003
Fantom	2,736,284	115,762	72,803
Polygon	2,736,284	115,762	72,803
Celo	3,548,719	142,040	85,673

TABLE III. GAS USED BY TRANSACTION

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	2,731,184 (100%)	109.162 (100%)	57,003 (79.17%)
Fantom	2,736,284 (100%)	115,762 (100%)	68,003 (93.41%)
Polygon	2,736,284 (100%)	115,762 (100%)	68,003 (93.41%)
Celo	2,729,784 (76.92%)	109.262 (76.92%)	59,803 (69.8%)

effort for this operation. Both BNB Smart Chain and Fantom have lower requirements, with gas limits set at 72,003 and 72,803, respectively.

This comparative data provides valuable insights into the computational demands of each blockchain platform for different operations. It highlights the variance in the computational resources needed across different platforms and operations. This information can help in selecting the most efficient platform for deploying the recommendation model based on computational and resource constraints.

E. Gas Used by Transaction

Table III provides an exhaustive analysis of the "Gas Used by Transaction" on the four blockchain platforms under examination: BNB Smart Chain, Fantom, Polygon, and Celo. This metric represents the actual amount of gas consumed to process a transaction on the blockchain.

The table breaks down the consumed gas for three different operations:

1) Contract creation: This is the process of deploying a smart contract on the blockchain. On BNB Smart Chain, Fantom, and Polygon, the gas used is the same as the gas limit (100%), implying that the entire computational resource allocation was utilized for this operation. However, on Celo, the gas used is 76.92% of the gas limit, suggesting a more efficient contract creation process on this platform.

2) Create NFT: This operation involves generating a Non-Fungible Token (NFT) on the blockchain. Again, BNB Smart Chain, Fantom, and Polygon utilize 100% of the allocated gas limit. On Celo, this operation uses 76.92% of the gas limit, indicating better computational efficiency.

3) Transfer NFT: This operation involves changing the ownership of an NFT from one address to another. The BNB Smart Chain platform uses 79.17% of the gas limit, while Fantom and Polygon platforms consume 93.41%. This suggests that BNB Smart Chain might be more efficient in handling NFT transfers. Conversely, Celo utilizes 69.8% of the gas limit for this operation, making it the most efficient platform among the four in terms of NFT transfer.

The table ultimately provides valuable insights into the computational efficiency of each platform. Notably, while some platforms use the entire gas limit for their operations (indicating that they are maximally utilizing the allocated resources), others use a portion of it, indicating that they are more computationally efficient. This data is critical in selecting a suitable platform for the deployment of the recommendation model, taking into account the trade-off between resource allocation and computational efficiency.

F. Gas Price

Table IV represents the "Gas Price" for executing transactions on four different Ethereum Virtual Machine (EVM) compatible blockchain platforms: BNB Smart Chain, Fantom, Polygon, and Celo. Gas prices are expressed in each blockchain platform's native token (BNB, FTM, MATIC, and CELO, respectively) and in Gwei, where 1 Gwei equals 10^{-9} Ether.

Gas price, determined by the market conditions on the blockchain, is the cost per computational step required to execute a specific transaction or smart contract on the network.

The table breaks down the gas price for three different actions:

Contract Creation: The process of deploying a smart contract on the network. The gas prices for this action are 10 Gwei for BNB Smart Chain, 3.5 Gwei for Fantom, around 2.5 Gwei for Polygon (specifically, 2.500000011 Gwei), and 2.6 Gwei for Celo with a maximum fee per gas of 2.7 Gwei.

TABLE IV. GAS PRICE

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	0.00000001 BNB (10 Gwei)	0.00000001 BNB (10 Gwei)	0.00000001 BNB (10 Gwei)
Fantom	0.0000000035 FTM (3.5 Gwei)	0.0000000035 FTM (3.5 Gwei)	0.0000000035 FTM (3.5 Gwei)
Polygon	0.000000002500000011 MATIC (2.500000011 Gwei)	0.000000002500000012 MATIC (2.500000012 Gwei)	0.000000002500000013 MATIC (2.500000013 Gwei)
Celo	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)	0.0000000026 CELO (Max Fee per Gas: 2.7 Gwei)

Create NFT: The action of creating a Non-Fungible Token (NFT) on the network. The gas prices are identical to those for contract creation, except for Polygon, where it's slightly higher at 2.500000012 Gwei.

Transfer NFT: The operation of transferring the ownership of an NFT. Again, the gas prices are the same as for the other two operations, with the exception of Polygon, where the gas price is slightly higher at 2.500000013 Gwei.

This table is essential for understanding the costs involved in performing different actions on these platforms. It also helps in selecting a platform that balances the trade-off between computational needs and transaction costs. BNB Smart Chain has the highest gas price at 10 Gwei, while Polygon offers the most competitive gas price, hovering around 2.5 Gwei, with Celo and Fantom offering intermediate rates.

VII. DISCUSSION

A. Analysis of Transaction Costs across Different Blockchain Platforms

In our deployment assessment (VI), we detailed the transaction costs on four different EVM-enabled blockchain platforms—Binance Smart Chain (BNB), Polygon (MATIC), Fantom (FTM), and Celo (CELO)—considering three primary activities: contract creation, NFT creation, and NFT transfer. Our comprehensive examination highlighted not only the distinct monetary costs associated with each platform but also the computational costs (gas used) and gas prices.

Crucially, it is observed that the transaction value on a blockchain platform is directly influenced by the market capitalization of the platform's respective coin. As of our last observation on June 26, 2023, the total market capitalization of the four platforms—BNB, MATIC, FTM, and CELO—stood at $50,959,673,206; $7,652,386,190; $486,510,485; and $244,775,762, respectively. This market capitalization directly impacts the coin's value of each platform, although the number of coins issued at the time of system implementation is another significant factor. At the time of our evaluation, the total issuance of BNB, MATIC, FTM, and CELO was 163,276,974/163,276,974 coins; 8,868,740,690/10,000,000,000 coins; 2,541,152,731/3,175,000,000 coins; and 473,376,178/1,000,000,000 coins, respectively. Consequently, the value per coin, based traditionally on the number of coins issued and the total market capitalization, stood at $314.98 for BNB, $0.863099 for MATIC, $0.1909 for FTM, and $0.528049 for CELO.

B. Selection of Optimal Blockchain Platform for Proposed Model Deployment

Our assessments demonstrated that deploying our proposed model on Fantom offers significant advantages concerning system operating costs. Specifically, the generation and reception of NFTs incurs almost negligible fees on Fantom. Furthermore, the cost associated with creating contracts that carry a transaction execution value is extremely low, less than $0.002.

C. Future Work

Building upon our findings, our future work will aim to implement more complex methods and algorithms, such as encryption and decryption processes, as well as more complex data structures. This will allow us to better observe the transaction costs associated with these advanced operations.

Additionally, deploying the proposed model in a real-world environment presents a compelling avenue for further research—specifically, implementing the recommendation system on the Fantom mainnet. In our current analysis, we have not taken into consideration issues related to user privacy policies, such as access control [37], [38] or dynamic policies [39], [40]. These are critical considerations that will need to be addressed in upcoming research activities.

Lastly, infrastructure-based approaches, such as gRPC [41], [42], Microservices[43], [44], dynamic transmission messages [45], and Brokerless systems [46], can be integrated into our model to enhance user interaction. For instance, we can introduce an API-call-based approach that allows for more dynamic and efficient communication between different components of the system.

VIII. CONCLUSION

In conclusion, this paper addressed the challenges of waste management and disposal in emerging economies like Vietnam by proposing a waste categorization and treatment model based on Blockchain technology, Smart Contracts, and Non-Fungible Tokens (NFTs). We highlighted the deficiencies in traditional waste management methods, particularly the lack of waste segregation and treatment at the source, leading to environmental pollution and health risks. The COVID-19 pandemic further emphasized the importance of proper waste treatment, especially in the healthcare sector. Unsafe handling of medical waste during the pandemic contributed to the spread of the disease. To address these issues, various waste management models leveraging Blockchain technology have been proposed, but they primarily focus on tracking and tracing waste rather than comprehensive waste treatment processes.

Our proposed model aims to enhance waste categorization and treatment in Vietnam by providing stakeholders with a transparent and efficient system. The use of Smart Contracts enables automated and secure waste management processes, while NFTs store essential information related to waste classification and compliance. This allows for better monitoring and implementation of sanctions or rewards based on waste management behavior.

We implemented the proposed model on four EVM-compatible platforms, namely BNB Smart Chain, Fantom, Polygon, and Celo, and evaluated their performance in terms of transaction fees, gas limits, gas used, and gas prices. Through our evaluation, we found that the Fantom blockchain platform offers the most cost-effective environment for deploying the waste management model, with negligible fees for NFT generation and low costs for contract creation. This study contributes to the field by introducing a waste categorization and treatment model customized for Vietnam and demonstrating its feasibility through a proof-of-concept implementation. The findings provide insights into the suitability of different blockchain platforms for waste management applications.

Future work includes implementing more complex methods and algorithms, considering privacy policies, and deploying the proposed model in real-world settings. Additionally, integrating infrastructure-based approaches, such as gRPC and microservices, can enhance user interaction and further optimize the waste management system.

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