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Leveraging Blockchain, Smart Contracts, and NFTs for Streamlining Medical Waste Management: An Examination of the Vietnamese Healthcare Sector

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Abstract—**Medical waste is deemed hazardous due to its potential health implications and the predominant practice of discarding it post six months of utilization. Furthermore, the reusable proportion of such waste is minimal. The implications of this scenario were brought to the fore during the COVID-19 pandemic when sub-optimal medical waste management was identified as a factor exacerbating the spread of the virus worldwide. The predicament is particularly grave in developing nations, such as Vietnam, where the underdeveloped state of medical infrastructure renders efficient waste management a daunting task. The waste management challenge also stems from the significant roles played by different stakeholders (healthcare workers and patients confined to isolation wards), whose actions directly influence waste classification, impact the waste treatment process, and indirectly contribute to environmental pollution. Given that waste management involves a chain of activities requiring the coordinated efforts of medical, transportation, and waste treatment personnel, inaccuracies in the initial stages, such as waste sorting, can negatively impact subsequent processes. In light of these issues, our study puts forth a unique model aimed at enhancing waste classification and management practices in Vietnam. This model innovatively integrates Blockchain technology, smart contracts, and non-fungible tokens (NFTs) with the intent to foster an increased individual and collective consciousness towards effective waste classification within healthcare settings. Our research is notable for its four-fold contribution: (a) suggesting a unique mechanism based on blockchain technology and smart contracts, designed specifically to improve medical waste classification and treatment in Vietnam; (b) introducing a model for instituting rewards or penalties based on NFT technology to influence behaviors of individuals and organizations; (c) demonstrating the feasibility of the proposed model through a proof-of-concept; (d) executing the proof-of-concept on four prominent platforms that support ERC721 - NFT of Ethereum and EVM for executing smart contracts programmed in the Solidity language, namely BNB Smart Chain, Fantom, Polygon, and Celo.**

Keywords*—*Medical waste management; blockchain; smart contracts; NFTs; ethereum; fantom; polygon; binance smart chain

I. INTRODUCTION

The threat posed by medical waste, a hazardous byproduct of healthcare activities, is of global concern. The vast majority of medical supplies and equipment – nearly 99% – become waste within six months of initial use due to their potential for transmitting infections [1], [2]. The environmental hazards posed by single-use items such as medical gloves, protective gear, and masks, further exacerbate the issue [3]. As such, regulatory bodies worldwide have implemented stringent processes to ensure proper classification and treatment of medical waste.

A notable facet of this global waste management challenge is the intersection of environmental and economic implications [4]. Materials difficult to break down contribute to pollution, applying immense pressure on the environment [5]. This concern is particularly acute in developing nations where waste disposal processes have shown links to environmental pollution, as seen in India [6] and Brazil [7]. The urgency of the issue further intensified during the pandemic, with the surge in medical supplies leading to increased waste [8], [9].

The Vietnam context presents a unique case. Systematic studies have delved into the role of waste segregation in managing the Covid-19 crisis. However, much of the focus remains on the results or consequences of waste management rather than providing an improved, technologically advanced model aimed at enhancing transparency and decentralized data storage.

Addressing this need, recent research has pivoted towards models utilizing Blockchain technology and smart contracts for waste treatment and classification [10], [11]. Such models focus on identifying the origin and composition of waste and encompass key stakeholders – healthcare workers, patients, waste collectors, and waste treatment companies. Information related to these user groups and waste (referred to as 'bags') is validated before being recorded on the chain. This method not only helps pinpoint the source of waste but also minimizes contact between parties, thereby reducing disease transmission risks [12]. As such, these models could supersede traditional waste treatment methods, particularly during epidemic periods.

Additionally, the role of public awareness and cooperation in waste management is crucial to curbing treatment times. The process of self-classification, despite being commonplace in developed nations, only emerged in developing countries following the outbreak of the Covid-19 pandemic. In Vietnam, a large portion of waste is unclassified, significantly impacting its treatment process. Consequently, our research seeks to address this issue by proposing a model for managing medical waste using Blockchain technology and smart contracts. Simultaneously, we aim to shape public perceptions of waste classification by leveraging non-fungible token (NFT) technology.

This study focuses on evaluating existing waste treatment models in developing countries, specifically Vietnam, during the Covid-19 pandemic. It seeks to provide a suitable approach for potential future epidemics. Our main contribution lies in presenting an NFT-based (ERC 721) approach and a penalty system for violations of waste classification norms.

Thus, the four-fold contribution of our work includes: (a) proposing a medical waste classification and treatment mechanism for the Vietnamese context, leveraging blockchain technology and smart contracts; (b) introducing a reward/punishment system based on NFT technology aimed at individuals and organizations; (c) implementing a proof-of-concept of the proposed model using smart contracts; and (d) deploying the proof-of-concept on four platforms supporting ERC721 - NFT of Ethereum and EVM for executing smart contracts written in Solidity, namely BNB Smart Chain, Fantom, Polygon, and Celo.[1]

This paper is structured into seven subsequent sections. Following this introduction, we offer a brief overview of Blockchain, Smart contract, EVM, NFT, and the four EVM-supported blockchain platforms in Section II. Then we review related work exploring similar research problems in Section III. Next, we describe our proposed approach and its implementation (Sections IV, V). Section VI demonstrates the effectiveness of our model in different scenarios, followed by a discussion in Section VII. Finally, Section VIII summarizes our work and outlines potential avenues for future research.

II. BACKGROUND

A. Blockchain Technology

Originally conceived as the underlying technology for Bitcoin [14], blockchain has gained recognition for its potential beyond cryptocurrency [15], [16]. Blockchain is often characterized as a transparent, reliable, and decentralized ledger that operates on a peer-to-peer network [17], [18]. It manages transaction data across several computers concurrently, fostering a trust environment that permits autonomous interaction without reliance on a centralized authority [19]. Key benefits of blockchain-based systems include:

- Security: Through digital signatures and encryption, blockchain systems ensure data security and integrity [20].
- Fraud control: Data duplication across multiple nodes provides robust defense against hacking, enabling efficient recovery of records[21].
- Transparency: Real-time transaction status visibility fosters reliability and convenience for all parties involved [22].
- No hidden fees: The decentralized nature eliminates the need for intermediaries, thereby reducing associated costs and commissions.
- Access levels: Users can opt for a public blockchain network accessible to all, or a permissioned network, which requires user authorization for each node[23].
- Speed: Blockchain transactions are expedited due to the lack of external payment system integration, leading to cost and time efficiency[10].
- Account reconciliation: Authenticity and validity of participants are collaboratively verified by the network participants.

B. Smart Contract

Smart contracts, or chaincodes[24], [25], are self-executing contracts where terms of agreement between parties are directly written into lines of code and automated via blockchain technology. Noteworthy characteristics of smart contracts include:

- Distributed: Smart contracts are replicated and distributed across all nodes of the blockchain network, fostering decentralization.
- Deterministic: Smart contracts execute actions as designed under defined conditions, and yield consistent results irrespective of the executor.
- Automate: Capable of automating various tasks, smart contracts operate as self-actuating programs that remain idle until activated.
- Non-modifiable: Post-deployment modifications to smart contracts are impossible. Deletion is possible only if this functionality was predefined.
- Customizable: Smart contracts can be programmed diversely before deployment, enabling the creation of various types of decentralized applications (Dapps).
- Trust-less interactions: Smart contracts allow parties to interact without mutual trust, as blockchain technology ensures data accuracy.
- Transparency: As smart contracts operate on a public blockchain, their source code is immutable and publicly viewable.

C. Blockchain Platforms

1) Ethereum: Ethereum [26] is a decentralized platform that supports the development and execution of smart contracts via Turing-complete programming languages. These smart contracts are executed by the Ethereum Virtual Machine (EVM) and can be written in languages such as Solidity, Serpent, Low-level Lisp-like Language (LLL), and Mutan. Ethereum enables the creation of various applications, including financial contracts, betting markets, and withdrawal limits. As of now, it remains the most popular platform for smart contract development.

D. Ethereum Virtual Machine (EVM)

The Ethereum Virtual Machine (EVM) is a Turing-complete software that operates as a runtime environment for smart contracts in Ethereum. It is completely isolated from the main Ethereum network, which makes it a perfect sandbox for running untrusted code [27]. As such, smart contracts can't communicate with other contracts directly. Instead, they do so

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[1] We exclude ETH from our deployment because of its prohibitively high smart contract execution fee.[13]

via the EVM, preventing any potential malicious code from affecting the network.

When a smart contract is executed, each and every instruction is run on every node in the network. This redundancy helps ensure the security and robustness of the network, but it also necessitates a mechanism for restricting resource consumption on the network. To this end, Ethereum implements a system known as "gas" – each instruction requires a certain amount of gas to execute. Gas is purchased with Ethereum's native cryptocurrency, Ether, and helps to prevent spam on the network and allocate resources proportionally [28].

Smart contracts in Ethereum are typically written in a high-level programming language, such as Solidity, then compiled to EVM bytecode to be deployed to the blockchain. The EVM executes this bytecode on each node when a function from a contract is called. Due to its design, the EVM can execute untrusted code without compromising the security or performance of the network, making it a cornerstone of Ethereum's smart contract capabilities.

E. Non-Fungible Tokens (NFTs)

Non-fungible tokens (NFTs) have gained considerable attention in the digital art and collectibles space, giving individuals the ability to prove ownership of unique pieces of content on the blockchain. In contrast to fungible tokens such as Bitcoin or Ether, NFTs are not interchangeable for other tokens of the same type but represent something unique. This uniqueness and the ability to prove ownership make NFTs particularly useful for digital art, real estate, and other use cases where uniqueness is important.

NFTs are defined in a smart contract through the ERC721 standard on the Ethereum blockchain [29]. This standard outlines a minimum interface that NFTs must implement to enable their interoperability across the Ethereum ecosystem. The ERC721 standard has given rise to many unique digital assets, from digital cats in the game CryptoKitties to multi-million dollar digital artwork.

F. Blockchain Platforms

1) Binance Smart Chain (BSC): Binance Smart Chain (BSC) is a blockchain network built for running smart contract-based applications, achieving a balance between speed, security, and cost[2]. BSC runs in parallel with Binance's native Binance Chain (BC), hence enabling users to get the best of both worlds: the high transaction capacity of BC and the smart contract functionality of BSC.

BSC uses a consensus model called Proof of Staked Authority (PoSA), where participants stake BNB (the Binance native token) to become validators. If they propose a valid block, they'll receive transaction fees from the transactions included in it.

BSC supports EVM, meaning that it can run Ethereum-based applications and uses tools like Metamask, Truffle, and Remix, among others. This compatibility allows it to tap into a broad developer community and existing applications, enhancing its utility and potential for adoption.

2) Fantom: Fantom is a high-performance, scalable, customizable, and secure smart-contract platform. It is designed to overcome the limitations of previous generation blockchain platforms[3]. Fantom is permissionless, decentralized, and open-source.

The primary innovation behind Fantom is a new protocol known as the "Lachesis Protocol" used to maintain consensus within the network. This protocol is intended to be highly scalable and provide near-instant transaction confirmation, making it ideal for DeFi applications and real-world uses.

Fantom is EVM-compatible, hence it allows developers to deploy Ethereum smart contracts directly to Fantom. The network uses a Proof-of-Stake (PoS) consensus algorithm and boasts high speed and low fees, offering 2-second finality for transactions.

3) Celo: Celo is a blockchain ecosystem focused on increasing cryptocurrency adoption among smartphone users[4]. By using phone numbers as public keys, Celo hopes to introduce the world's billions of smartphone owners, including those without access to traditional banking services, to the benefits of cryptocurrency.

Celo's native token is the Celo Dollar (cUSD), a stablecoin pegged to the US Dollar. This focus on a stable digital currency separates Celo from other EVM-compatible blockchains.

Celo uses a consensus mechanism called Byzantine Fault Tolerance (BFT), derived from PBFT, to maintain network security and reach consensus efficiently. It also implements an on-chain governance system that allows token holders to vote on network changes.

4) Polygon (Matic): Polygon (previously Matic Network) is a Layer 2 scaling solution for Ethereum[5]. It is designed to provide faster and cheaper transactions on Ethereum using Layer 2 sidechains, which are blockchains that run alongside the Ethereum main chain. Users can deposit Ethereum tokens to a Polygon smart contract, interact with them within Polygon, and then later withdraw them back to the Ethereum main chain if necessary.

Polygon uses a modified version of the Plasma framework, an off-chain scaling solution originally proposed by Vitalik Buterin. The network also uses a Proof-of-Stake (PoS) consensus mechanism, and block producers are selected from the staking nodes.

Polygon is interoperable with a number of other blockchain networks. It supports a flexible framework for building various kinds of applications, including DeFi (Decentralized Finance) and dApps (Decentralized Applications).

The aforementioned platforms represent a selection of EVM-compatible blockchains with various features and capabilities. When deciding on a suitable platform for a particular use case, considerations such as transaction speed, cost, security, consensus mechanism, and the platform's overall community and ecosystem need to be factored into the decision-making process.

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[2] https://github.com/bnb-chain/whitepaper/blob/master/WHITEPAPER.md

[3] https://whitepaper.io/document/438/fantom-whitepaper

[4] https://celo.org/papers/whitepaper

[5] https://polygon.technology/lightpaper-polygon.pdf

III. RELATED WORK

This section offers a comprehensive review of the previous investigations focused on the deployment of blockchain technology and smart contracts in waste management processes. To our understanding, there remains a dearth of research examining waste segregation issues within the context of a developing country. As such, this review concentrates on two primary research domains - the application of blockchain technology in managing medical waste and household waste.

A. Implementing Waste Management Models to Realize a Circular Economy (CE)

The circular economy (CE) is an aspirational model for the future that aims for sustainability through closed-loop waste management and optimal resource utilization. It is gaining attention from numerous technology companies, one of them being Amazon. The company has embarked on an initiative known as Amazon CE [30], which creates a continuous loop of product use based on partnerships and service offerings. The program empowers customers with options to reuse, repair, and recycle their products, thus aligning with the principles of the CE model.

Despite the diversity of waste types, numerous innovative strategies have emerged to handle each one. For electronic waste, Gupta et al. [31] have conceived an Ethereum-based waste management model. This model focuses on three key user groups, namely producers, consumers, and retailers, each playing a specific role in the waste management cycle. The retailers serve a dual purpose by distributing new products to consumers and collecting used ones for return to manufacturers. The correct execution of these activities rewards the participants with Ethereum's cryptocurrency, ETH.

In the context of solid waste, such as discarded computers and smartphones, Laura et al. [32] have introduced a management system founded on a combination of Ethereum and QR codes. This approach empowers stakeholders with the ability to track and ascertain the current location of waste and predict the time needed for its processing. Similarly, Schmelz et al. [33] proposed a secure and tamper-proof system for tracking cross-border waste movements using Ethereum. However, a significant drawback of this system is its inability to support penalties for waste management violations.

B. Medical Waste Management Models

The application of the CE model in a medical environment presents unique challenges. Medical equipment and supplies, which constitute a significant proportion of medical waste, are often single-use and unrecyclable after six months from their first utilization [1]. The Covid-19 pandemic has exacerbated this problem by creating an enormous quantity of medical waste, including personal protective equipment, leading to potential infection risks [34], [35].

To address these pressing issues, Trieu et al. [10] have proposed a model called MedicalWaste-Chain based on the Hyperledger Fabric. This model focuses on the treatment and disposal of medical waste emanating from health centers, as well as the recycling of tools and medical supplies. Moreover, Ahmad et al. [36] have directed their efforts toward developing a traceability model for personal protective equipment, particularly for healthcare workers, to maintain accountability during a pandemic. To facilitate the validation of waste treatment processes and interactions between stakeholders, Dasaklis et al. [37] proposed a blockchain-based system deployable on smartphones.

C. Analysis of Blockchain Technology-based Approaches Applied to Vietnam

The approaches reviewed above, while innovative, have limitations. They tend to overlook the process of waste reproduction or refurbishment and lack comprehensive solutions for managing the behavior of end-users, particularly in terms of rewarding compliant behavior or penalizing violations. Moreover, they concentrate predominantly on managing the waste treatment chain from origin points, such as medical centers, to waste processing plants, with little consideration for household waste management.

The application and implementation of these models in a specific region like Vietnam require a holistic understanding of various socio-economic and environmental factors. As such, this study aims to instill responsible waste segregation habits among not only medical centers but also households. This research can provide a critical foundation for responding to respiratory diseases in the future, encouraging every household to adopt responsible waste disposal practices. The proposed model in this paper not only manages the waste sorting process but also incorporates a unique solution for rewarding compliant behavior and penalizing violations using Non-Fungible Token (NFT) technology. A detailed explanation of this proposed model and its implementation steps will be presented in the subsequent sections.

IV. METHODOLOGY

A. Conventional Model for Medical Waste Treatment and Classification

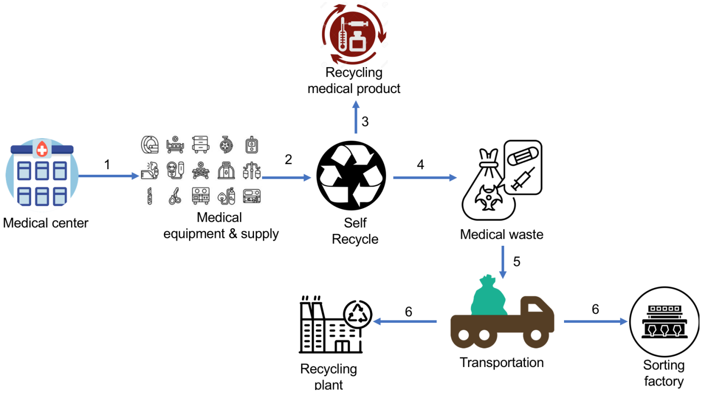


Fig. 1. Conventional model for medical waste treatment and classification.

The existing model for medical waste treatment and classification, as depicted in Fig. 1, is based on guidelines issued by the Ministry of Health in Vietnam during the Covid-19 pandemic [38]. As seen in Fig. 2, five distinct sources of medical waste are classified, which then undergo five sequential treatment steps. Medical waste is primarily generated at treatment centers (hospitals, military barracks), testing and vaccination sites, and individual locations under quarantine (like households, apartments).

The initial three steps in medical waste classification - separation, segregation, and collection - are conducted at healthcare centers. Following this, all hazardous waste is sent to disposal facilities where it undergoes the final two steps: transportation and destruction.

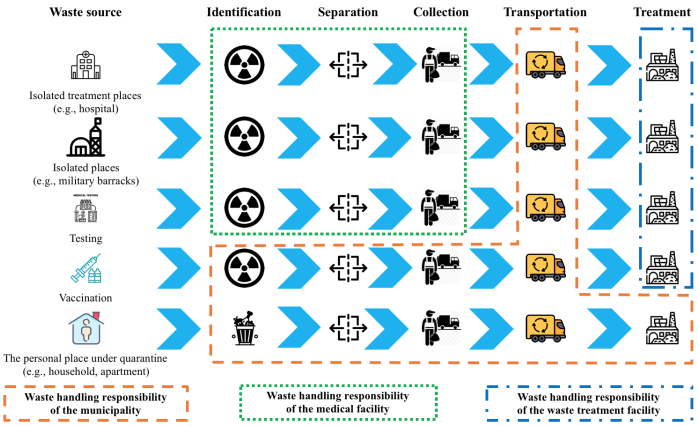


Fig. 2. Sample of medical waste treatment during the Covid-19 pandemic in Vietnam.

Under real-world circumstances, such as the care and treatment of diseases in medical centers, waste can be bifurcated into two categories: reusable and disposable. Each category warrants distinct treatment procedures.

The traditional model for waste classification and treatment, detailed in Fig. 1, is a multi-step process. Step 1 includes the collection of waste from various departments within a medical facility, primarily consisting of medical equipment and supplies. Step 2 involves the segregation of waste and identification of reusable items within the medical facility. Reusable items (Step 3) are reintegrated into the system, while disposable waste is readied for disposal (Step 4) and sent to the waste treatment area (Step 5). At this stage, waste is classified based on the requirements of treatment procedures, such as recycling or sorting (Step 6).

However, the traditional model exhibits several drawbacks, including a lack of incentive for individuals to segregate waste accurately, a deficiency of mechanisms to penalize violations, and inefficiencies in the tracking and auditing of waste treatment procedures. To address these issues, we propose a model that combines blockchain, smart contracts, and Non-Fungible Tokens (NFTs) to certify waste classification at medical centers and effectively identify compliance or violations with medical waste segregation requirements.

B. *Innovative Model for Medical Waste Treatment and Classification Leveraging Blockchain Technology, Smart Contracts, and NFT*

Fig. 3 illustrates the proposed model that integrates blockchain technology, smart contracts, and NFTs in a nine-step process for medical waste classification and treatment. Initially, medical professionals (doctors and nurses) familiarize themselves with the regulations and requirements for waste segregation (Step 1). The degree of compliance with these rules becomes a crucial metric for assessing performance and determining rewards or penalties. Subsequently, medical professionals perform the initial waste segregation (self-recycling in Step 2). Hazardous waste is segregated and placed outside the patient care and treatment areas in hospitals or medical centers (Step 3). The cleaning staff, trained in assessing the waste sorting behaviors of medical personnel, conduct an initial inspection (Step 4). The inspection involves two stages, where Step 5 includes a non-invasive observation of medical staff's waste sorting activities during treatment, while Step 6 involves assessment of reusable waste in the medical environment.

Upon confirmation of compliance or violation of waste segregation requirements, the cleaning staff updates the results in the predefined functions on the smart contract (Step 7). Following this, Non-Fungible Tokens (NFTs) are generated, corresponding to the waste segregation behavior of the individuals or organizations involved (Step 8). These NFTs encapsulate relevant evidence and information concerning the individual's or organization's compliance or violation. Finally, all evaluation and validation steps, along with their results, are recorded and stored on distributed ledgers (Step 9). This blockchain-based ledger provides a transparent, secure, and immutable record of all activities, fostering accountability, and efficient auditing of medical waste management.

V. SYSTEM EXECUTION

The practical execution of our novel model is focused on two fundamental targets: i) management of medical waste data including initialization, interrogation, and modification on a blockchain platform, and ii) production of Non-Fungible Tokens (NFTs) for each user's (entities or institutions) reward and infraction behavior stemming from their participation in waste classification/disposal.

A. *Data Input and NFT Initialization*

The diagram in Fig. 4 details the process to initiate medical waste data. This waste includes various medical apparatus (for instance, expired or damaged) or medical consumables (such as masks, PPE, injections). These waste categories are further segregated into different classes (for example, discard, reuse) based on their toxicity grading.

Every waste bag, tagged with a unique identifier, houses a particular type of waste and carries a detailed waste description. It also encompasses metadata like the sorter's details, departmental information, time stamp, and waste generation location. The storage mechanism has been designed to handle simultaneous storage on a distributed ledger - enabling multiple users for concurrent storage to optimize system latency.

The medical waste data is structured as follows:

```
medicalWasteObject = {
"wasteID": wasteID,
"staffKey": staffKey,
"category": waste category,
"deptID": deptID,
"amount": amount,
```

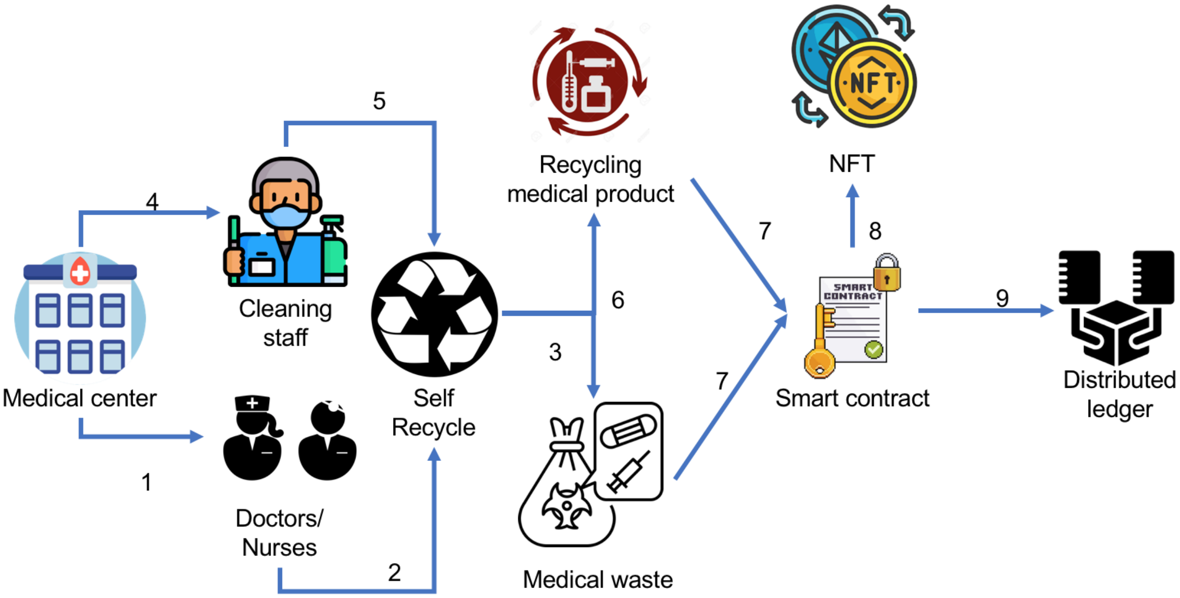


Fig. 3. Innovative model for medical waste treatment and classification leveraging blockchain technology, smart contract, and NFT.

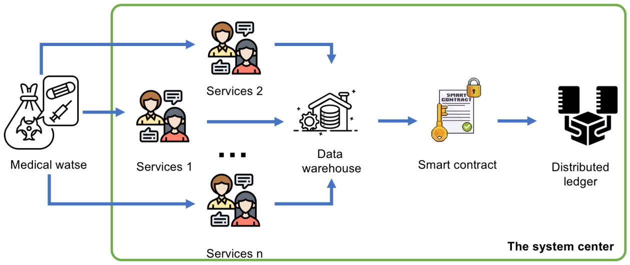


Fig. 4. Data input and NFT initialization.

```
"unitType": unitType,
"bagID": bagID,
"timestamp": timestamp,
"locale": locale,
"currentStatus": null,
"recycleStatus": Null
};
```

Alongside the essential information (such as origin, weight, waste category, etc.), we also retain information pertaining to the status of the waste bags at the medical center ("currentStatus" and "recycleStatus" - default to Null). Specifically, "currentStatus" changes to 1 if the corresponding waste bag has been dispatched out of the medical center for waste treatment; value 0 indicates a pending status. Meanwhile, "recycleStatus" becomes 1 when the waste (medical equipment) is reused (value 0 indicates pending). Non-toxic wastes pose no harm to the environment or human health.

Once the waste sorting is completed, the cleaning staff verifies the process, and upon validation, the data is synchronized onto the chain (initially stored in the data warehouse). The validation constraints embedded in the Smart Contract are activated via the API for chain synchronization. This process is crucial since it directly impacts waste treatment procedures and forms the basis for reward or penalty for individuals and organizations.

For initiating NFTs (reward, sanction), the NFT structure is defined as:

```
NFT WASTE_HANDLING = {
"wasteID": wasteID,
"staffKey": staffKey,
"deptID": deptID,
"bagID": bagID,
"typeMatch": true/false,
"quantityMatch": true/false,
"timestamp": timestamp,
"verifierKey": staffKey // Cleaning staff
};
```

If the sorted trash bags meet the expected standards, the sorter is rewarded. If they deviate, they are penalized. The verifier is penalized in cases of incorrect information verification.

B. *Data Interrogation*

The data interrogation process, demonstrated in Fig. 5, is designed to support multiple simultaneous system participants. Both cleaning staff and healthcare professionals can utilize this feature, albeit for different purposes. The cleaning staff accesses data to verify the classification process or to manage the transportation of hazardous medical waste. Healthcare professionals, on the other hand, may require data to identify reusable medical tools.

These requests are submitted via API calls from the user to the system's smart contracts, which fetch the required data from the distributed ledger. Each data retrieval request is logged as part of the query history for each individual or organization. If no match is found (e.g., incorrect ID),

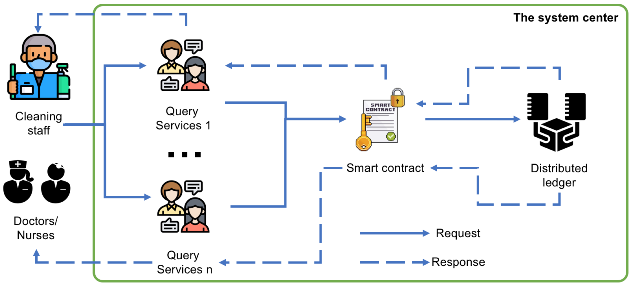


Fig. 5. Data interrogation.

the system sends an error message to the user. For NFT interrogation, APIs are provided as support services.

C. Data Modification

The data modification function, shown in Fig. 6, is activated only after data existence on the chain is confirmed. If no data is found, the system sends a corresponding error message to the user. Like data interrogation and input processes, data modification is facilitated through APIs, which process user requests and pass them onto smart contracts for execution.

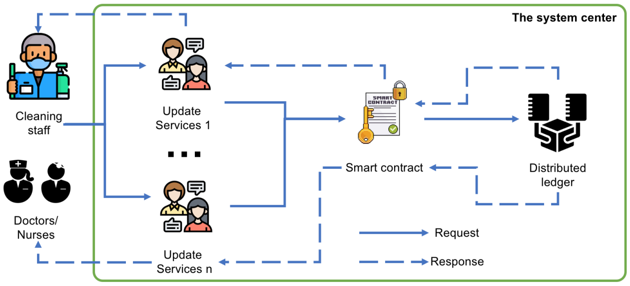


Fig. 6. Data modification.

The main objective of this function is to update the location and time stamp of waste bags during transportation and handling of medical waste. This enables administrators to trace the status of medical waste treatment/transportation from medical centers to waste treatment companies.

For NFTs, the modification process primarily involves transferring the NFT from the initial owner's address to a new one. In the event of any information update on an existing NFT, a new NFT is created.

VI. PERFORMANCE ASSESSMENT

A. Environmental Setting

The process of evaluation is a crucial aspect of our proposed model's successful deployment. It provides valuable insights about the efficiency, cost-effectiveness, and scalability of the system, particularly on Ethereum Virtual Machine (EVM)-enabled platforms. It's vital to note that the model in focus rewards or imposes penalties based on the compliance or violation of medical waste classification norms, respectively.

Earlier research publications have detailed the evaluation of system responsiveness, covering aspects like successful and failed request responses, system latency (minimum, maximum, average), among other metrics. Hence, the focus in this current analysis pivots towards identifying the most favorable platform for deploying our proposed model.

In our attempt to identify an optimal environment for implementation, we tested our system on four renowned blockchain platforms, each boasting support for the Ethereum Virtual Machine (EVM). The chosen platforms for this comparative analysis include Binance Smart Chain (BNB Smart Chain), Polygon, Fantom, and Celo.

Fig. 7 provides a snapshot of transaction details on the Binance Smart Chain, an example of one of the four platforms evaluated. The same procedure has been repeated for all four platforms, where we successfully deployed the recommendation system and obtained transaction information. It is important to note that the transaction fees were collected in the respective native tokens of each platform. This uniform approach ensures a fair and objective evaluation process across all tested platforms.

Fig. 8 illustrates the process of NFT creation. The figure highlights how our recommendation system creates a Non-Fungible Token (NFT) as a reward or penalty mechanism for compliance or violation of waste classification norms. NFTs are created upon validation of waste sorting data by cleaning staff and are synchronized onto the chain. The data stored in the NFT includes information about the waste, staff, and department, as well as the status of type and quantity matching.

Fig. 9 showcases the process of transferring an NFT. This step is fundamental to the modification process, where the ownership of an NFT is shifted from its original holder to a new one. An essential aspect of this process is the update of the NFT ownership address.

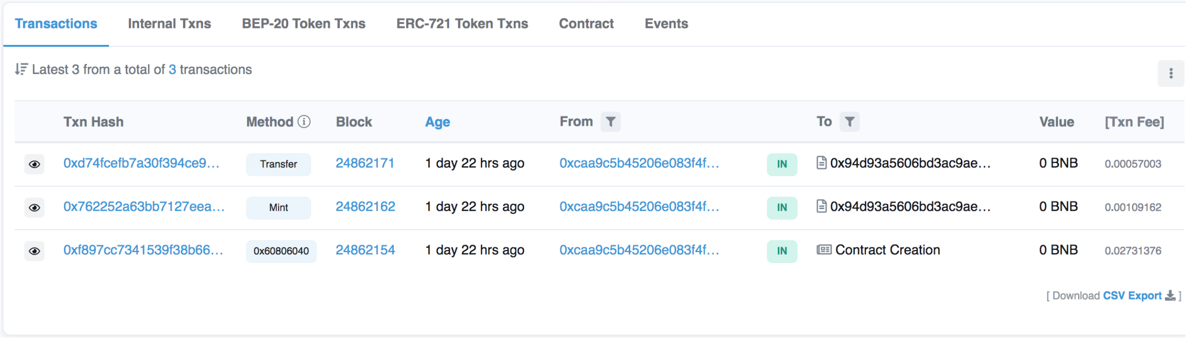
Our performance assessment extends to smart contracts designed based on the Solidity language. These contracts were deployed in the testnet environments of all four platforms to derive a comparative analysis about the cost-effectiveness of each. Specific focus areas of our evaluation revolved around transaction fees, gas limit, gas used by the transaction, and gas price. These metrics collectively assist in identifying the most cost-effective platform for deploying our model.

By meticulously assessing these parameters and documenting the outcome, we aim to shed light on the best platform for implementing our model. Such a comparative analysis can serve as a benchmark for future implementations and modifications of the model.

B. Our Deployment in the Four Blockchain Platforms

Our evaluation encompasses four primary EVM-supported platforms, namely Binance Smart Chain, Polygon, Fantom, and Celo. For each of these platforms, we've effectively executed the deployment of our recommendation model and documented the corresponding transaction details. The relevant links that provide access to our implementation on each platform are shared below:

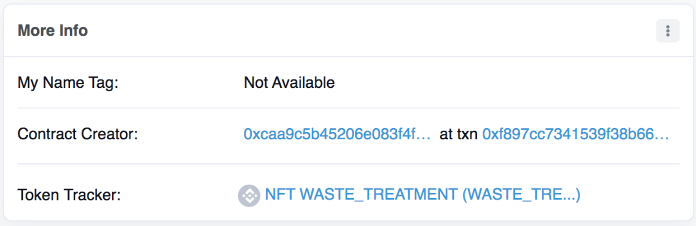
1) Binance Smart Chain (BNB Smart Chain): This platform is an independent blockchain that runs in parallel to Binance Chain, maintaining the performance of the original



Latest 3 from a total of 3 transactions

Txn Hash	Method	Block	Age	From		To	Value	[Txn Fee]
0xd74fcefb7a30f394ce9…	Transfer	24862171	1 day 22 hrs ago	0xcaa9c5b45206e083f4f…	IN	0x94d93a5606bd3ac9ae…	0 BNB	0.00057003
0x762252a63bb7127eea…	Mint	24862162	1 day 22 hrs ago	0xcaa9c5b45206e083f4f…	IN	0x94d93a5606bd3ac9ae…	0 BNB	0.00109162
0xf897cc7341539f38b66…	0x60806040	24862154	1 day 22 hrs ago	0xcaa9c5b45206e083f4f…	IN	Contract Creation	0 BNB	0.02731376

Fig. 7. Transaction details on the Binance Smart Chain.



More Info

My Name Tag:	Not Available
Contract Creator:	0xcaa9c5b45206e083f4f… at txn 0xf897cc7341539f38b66…
Token Tracker:	NFT WASTE_TREATMENT (WASTE_TRE...)

Fig. 8. Process of NFT creation.

chain while also possessing the capability to support complex applications like decentralized apps (dApps). Our implementation of the recommendation model on the Binance Smart Chain can be viewed using the link: BNB[6].

2) Polygon: A multi-chain Ethereum scaling solution that aims to provide secure, scalable, and instant transactions powered by PoS side chains. We deployed our model on the Polygon platform, and the smart contract details can be accessed at the following link: MATIC[7].

3) Fantom: Known for its high-speed, low-cost transactions and secure execution of smart contracts, Fantom provides a conducive environment for deploying our recommendation model. The Fantom implementation details can be found at the subsequent link: FTM[8].

4) Celo: This platform is a mobile-first platform that makes financial dApps and crypto payments accessible to anyone with a mobile phone. Our model's deployment on the Celo platform can be examined at the subsequent link: CELO[9].

Each of these links directs the user to the respective testnet environments where the detailed implementation of our recommendation model on each platform is available. The information presented includes an overview of the transactions associated with our smart contracts, including transaction hash, status, block, timestamp, from, to, value, and transaction fee, among others. It provides a comprehensive snapshot of the process of deploying our model and the associated costs for each of the four platforms.

C. Transaction Fee

Table I, titled "Transaction fee", presents a comparative overview of the transaction fees associated with various operations conducted on four distinct blockchain platforms: Binance Smart Chain (BNB), Fantom, Polygon (MATIC), and Celo.

The operations encapsulate:

- Contract Creation: This signifies the process of deploying a novel smart contract onto the blockchain network. A smart contract represents a self-executing contract with the agreement terms being inscribed directly into the code, subsequently stored and replicated on the blockchain.
- Create NFT: This operation encompasses the generation of a Non-Fungible Token (NFT) on the blockchain. NFTs constitute a genre of digital asset created to showcase ownership or authentication proof of unique items or content.
- Transfer NFT: This operation details the procedure of transferring the ownership of an NFT from one entity to another within the blockchain.

For every operation, the transaction fees are delineated for each blockchain platform in their specific cryptocurrency (BNB, FTM, MATIC, CELO), alongside their equivalent value in USD ($) within brackets.

- For Binance Smart Chain (BNB), the costs for Contract Creation, Create NFT, and Transfer NFT operations are 0.02731376 BNB ($8.41), 0.00109162 BNB ($0.34), and 0.00057003 BNB ($0.18) respectively.
- For Fantom, the corresponding costs stand at 0.009577666 FTM ($0.001840), 0.000405167 FTM ($0.000078), and 0.0002380105 FTM ($0.000046).
- For Polygon (MATIC), the costs are calculated as 0.006841190030101236 MATIC ($0.01), 0.000289405001041858 MATIC ($0.00), and 0.000170007500612027 MATIC ($0.00).
- Lastly, for Celo, the costs are evaluated as 0.0070979376 CELO ($0.004), 0.0002840812 CELO ($0.000), and 0.0001554878 CELO ($0.000).

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[6] https://testnet.bscscan.com/address/0x94d93a5606\bd3ac9ae8b80e334dfec74d0075ece

[7] https://mumbai.polygonscan.com/address/0x48493\a3bb4e7cb42269062957bd541d52afc0d7a

[8] https://testnet.ftmscan.com/address/0x48493a3b\b4e7cb42269062957bd541d52afc0d7a

[9] https://explorer.celo.org/alfajores/address/0x48493A3bB4E7c\B42269062957Bd541D52aFc0d7A/transactions

	Txn Hash	Age	From		To	Token ID	Token
👁	0xd74fcefb7a30f394ce9…	1 day 22 hrs ago	0x94d93a5606bd3ac9ae…	OUT	0xcaa9c5b45206e083f4f…	1	ERC-721: NFT.....ENT
👁	0x762252a63bb7127eea…	1 day 22 hrs ago	0x000000000000000000…	IN	0x94d93a5606bd3ac9ae…	1	ERC-721: NFT.....ENT

Fig. 9. NFT transfer process.

TABLE I. TRANSACTION FEE

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	0.02731376 BNB ($8.41)	0.00109162 BNB ($0.34)	0.00057003 BNB ($0.18)
Fantom	0.009577666 FTM ($0.001840)	0.000405167 FTM ($0.000078)	0.0002380105 FTM ($0.000046)
Polygon	0.006841190030101236 MATIC($0.01)	0.000289405001041858 MATIC($0.00)	0.000170007500612027 MATIC($0.00)
Celo	0.0070979376 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	2,731,376	109,162	72,003
Fantom	2,736,476	115,762	72,803
Polygon	2,736,476	115,762	72,803
Celo	3,548,968	142,040	85,673

TABLE III. GAS USED BY TRANSACTION

	Contract Creation	Create NFT	Transfer NFT
BNB Smart Chain	2,731,376 (100%)	109.162 (100%)	57,003 (79.17%)
Fantom	2,736,476 (100%)	115,762 (100%)	68,003 (93.41%)
Polygon	2,736,476 (100%)	115,762 (100%)	68,003 (93.41%)
Celo	2,729,976 (76.92%)	109.262 (76.92%)	59,803 (69.8%)

This table aids in visualizing and contrasting the cost-effectiveness of deploying and managing NFTs across these platforms, thereby facilitating the decision-making process for selecting the most fitting blockchain for specific applications.

D. Gas limit

In the realm of blockchain technology, the term "Gas Limit" carries a specific significance. The gas limit can be understood as the maximum amount of computational power an individual is willing to expend for conducting a particular operation or executing a transaction on the blockchain. In essence, it acts as a cap to prevent overspending or infinite looping of operations. Since every operation, from simple to complex, on the blockchain requires a certain amount of computational resources, the gas limit ensures that these operations do not overrun their resource allocation.

Operations such as contract creation, NFT creation, or NFT transfer all necessitate different amounts of computational resources, hence different gas limits. The gas limit is explicitly set for each transaction, and if an operation exceeds this set limit, it will be terminated, ensuring the integrity of the network and the safety of its users.

In the context of the Table II, titled "Gas limit", the values detailed represent the gas limits for different operations, namely contract creation, NFT creation, and NFT transfer across four blockchain platforms: Binance Smart Chain (BNB), Fantom, Polygon (MATIC), and Celo. The gas limits are presented in units of gas.

For the Binance Smart Chain, the gas limits for contract creation, NFT creation, and NFT transfer are set at 2,731,376, 109,162, and 72,003 gas units, respectively.

Fantom and Polygon share identical gas limit values, with 2,736,476 units for contract creation, 115,762 units for NFT creation, and 72,803 units for NFT transfer.

On the other hand, Celo requires the highest amount of gas for each operation. The gas limits for contract creation, NFT creation, and NFT transfer on Celo are 3,548,968, 142,040, and 85,673 units, respectively.

This comparative analysis of gas limits across different platforms aids in assessing the computational efficiency of conducting operations on these platforms. It provides crucial insights into the operational costs involved in the deployment and management of smart contracts and NFTs, which can guide the selection of the most appropriate and cost-effective platform for specific use cases.

E. Gas Used by Transaction

In the context of blockchain transactions, "Gas Used by Transaction" refers to the actual amount of computational work done by a particular transaction on the blockchain network. Each operation or instruction in a transaction requires a certain amount of gas to execute, and the total gas used by the transaction is the sum of the gas used by each of these individual operations.

It's crucial to understand that not all set gas (defined by the gas limit) is always consumed by a transaction. The actual gas consumed depends on the computational complexity of the transaction. If a transaction finishes before reaching its gas limit, the unused gas is refunded to the sender. Conversely, if a transaction runs out of gas before it completes, it is halted, and all changes are reversed, but no gas is returned. Therefore, the gas used by transaction metric can provide an insight into the computational efficiency and cost-effectiveness of a transaction.

In Table III, titled "Gas Used by Transaction", we present the actual gas used by three different types of transactions — contract creation, NFT creation, and NFT transfer — on four different blockchain platforms: Binance Smart Chain (BNB), Fantom, Polygon (MATIC), and Celo. The values are reported in units of gas and also as a percentage of the respective gas limit for each transaction type.

For contract creation and NFT creation transactions, BNB, Fantom, and Polygon all use 100% of the gas limit, indicating that these transactions use all allocated resources. For NFT transfer, BNB uses 79.17% of the gas limit, while Fantom and Polygon use slightly more, at 93.41%.

Interestingly, Celo exhibits a different pattern. For contract creation and NFT creation transactions, Celo uses only 76.92% of the gas limit. This indicates a higher computational efficiency for these types of transactions on Celo compared to the other platforms. However, the NFT transfer on Celo uses only 69.8% of the gas limit, which is lower than the corresponding values on the other platforms.

This comparative study provides a clear picture of the computational efficiency of executing different transactions across various platforms. These insights can significantly aid in selecting the most efficient and cost-effective platform for deploying and managing smart contracts and NFTs.

F. Gas Price

In blockchain ecosystems, “Gas Price” represents the cost of each unit of gas that a user is willing to pay for a transaction. The unit for gas price is typically “gwei” (giga-wei), where 1 ETH (Ether) equals 1,000,000,000 gwei. The gas price is set by the sender of the transaction and plays a significant role in transaction prioritization. Miners, who validate and add transactions to the blockchain, have a preference for transactions with higher gas prices, as it leads to greater rewards for them. Consequently, if a user sets a higher gas price, their transaction is likely to be processed more quickly. However, setting an exceedingly high gas price can lead to unnecessary costs, while setting it too low might result in the transaction not getting processed if miners deem it unworthy of their computational effort. Therefore, users need to find a balance to ensure that their transactions are processed in a reasonable timeframe without incurring excessive costs.

In Table IV, titled “Gas Price”, we provide a detailed comparison of the gas prices for three different types of transactions — contract creation, NFT creation, and NFT transfer — across four different blockchain platforms: Binance Smart Chain (BNB), Fantom, Polygon (MATIC), and Celo.

For BNB Smart Chain, the gas price for all three transaction types is set at 0.00000001 BNB, equivalent to 10 gwei. This is a common gas price on the BNB Smart Chain and is likely to ensure a swift transaction execution. On the Fantom network, the gas price is lower at 0.0000000035 FTM, or 3.5 gwei for all three transactions. This reduced price could result in slower transaction processing times, but it also means lower transaction costs. For Polygon, the gas price for all transaction types is set even lower at 0.000000002500000011 MATIC, approximately equivalent to 2.5 gwei. Again, this could potentially lead to slower transaction times but lower costs. Finally, for Celo, the gas price for all transactions is set at 0.0000000026 CELO. Notably, this platform also specifies a “Max Fee per Gas” set at 2.7 Gwei. This is the maximum price that the sender is willing to pay per unit of gas, which gives the user more control over the transaction costs.

This comprehensive comparison across various platforms can help users to make informed decisions when choosing the optimal platform for their specific needs, taking into account both transaction costs and expected processing times.

VII. DISCUSSION

A. Threats to Validity

The evaluation carried out in this research attempts to measure and compare the performance of various blockchain platforms, focusing on transaction costs, response rates, and other metrics. However, several potential threats to validity need to be acknowledged for a comprehensive understanding of the findings.

The first and foremost issue pertains to the inherently volatile nature of cryptocurrency markets. The conversion rates and transaction costs cited in this study represent a snapshot of market conditions at a specific point in time, and do not account for the periodic and often substantial fluctuations that can drastically affect these figures. Therefore, the calculated cost-effectiveness of each platform, as presented in this research, may vary significantly depending on the market state at the time of consultation.

Secondly, the study assumes a controlled environment for all platforms without any network congestion, excessive transaction volumes, or other real-time factors that could potentially influence the performance and responsiveness of a platform. These uncontrollable real-world variables can yield different results under varying circumstances, thus impacting the generalizability of the study’s conclusions.

Finally, the evaluation was conducted on the testnet environments of the four platforms, which might not fully represent the conditions of the main networks. The responsiveness and performance on the mainnet could differ, affecting the validity of the comparisons made in this research.

B. Notable Observations

In the process of conducting this comparative study, several notable observations were made. The Binance Smart Chain (BNB) demonstrated the highest transaction costs among the four platforms evaluated. However, it also consistently provided high transaction throughput, which may be crucial for applications requiring rapid, high-volume transactions.

On the other hand, platforms such as Fantom, Polygon, and Celo displayed significantly lower transaction costs, which can be an attractive attribute for applications sensitive to cost constraints. Nonetheless, the lower costs may correspond to a slower transaction speed due to decreased miner incentives. These variations underline the trade-offs that need to be considered when choosing a blockchain platform for application deployment.

C. Limitations

This research was conducted with certain limitations which should be taken into account while interpreting the findings. Primarily, the implementations were executed in controlled test environments, which may not replicate the real-world

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)	0.000000002500000009 MATIC (2.500000009 Gwei)	0.000000002500000009 MATIC (2.500000009 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)

conditions of live networks. Variables such as network congestion, transaction volume, and changing miner incentives can significantly influence the transaction fees, gas usage, and response times experienced on the live networks.

Secondly, the study's focus is largely technical and quantitative, revolving around performance metrics and cost factors. It does not consider qualitative aspects such as ease of use, community support, or developer tools provided by the platforms, which can also influence the selection of a blockchain platform.

Furthermore, the study did not account for potential changes in the platforms themselves. Modifications or updates to the platforms' protocols, changes in the consensus mechanisms, or introduction of new features could significantly alter the performance or cost structure, rendering the current findings less relevant.

D. Future Work

Building upon this research, future studies could encompass a wider array of blockchain platforms for a more comprehensive comparison. Moreover, evaluations could be conducted under varying network conditions to capture a more accurate picture of how factors such as network congestion or increased transaction volumes affect transaction costs and performance.

Additionally, a more holistic approach could be adopted to consider qualitative aspects in addition to the technical and quantitative parameters evaluated in this study. These could include ease of use, developer support, platform maturity, and other factors that could influence the choice of a platform.

Future research could also closely monitor updates and modifications to these blockchain platforms, in order to assess how these changes affect the performance and cost effectiveness. Lastly, a deeper investigation into the security aspects of these platforms could be carried out. This is particularly important as security is a key consideration in blockchain applications, and this aspect was not the main focus of the current study.

In our future research plans, we also intend to venture further into the development and integration of sophisticated algorithms, with a particular focus on encryption and decryption methodologies. These strategies provide an additional layer of security to our model, ensuring the privacy and confidentiality of data transactions on the blockchain. More specifically, we aim to examine the transactional costs associated with implementing such complex methodologies. We hope to elucidate the correlation between the complexity of data structures and transaction costs, thus providing a more comprehensive picture of cost-effectiveness in blockchain deployment.

Simultaneously, we are exploring the idea of implementing our proposed model in a live, real-world environment. While our initial studies have taken place in controlled, simulated scenarios, a deployment on a mainnet environment such as Fantom (FTM) will expose our system to real-world dynamics. This could offer valuable insights into the practicalities of deploying blockchain systems, and the unique challenges that might arise therein.

Our current analysis, while comprehensive, does not yet fully consider the nuances of user privacy policies. Access control, a critical aspect of any system dealing with user data, has been examined in previous studies [39], [40]. Similarly, dynamic policies, which allow for flexibility and adaptability in system rules, have also been the focus of earlier research [41], [42]. In our forthcoming research activities, we plan to delve into these areas. Our aim is to establish a robust privacy framework that strikes a balance between data security and operational efficiency.

In terms of infrastructure, we are looking at the possibility of incorporating certain proven approaches into our model. Technologies such as gRPC [43], [44], a high-performance remote procedure call (RPC) framework, offer benefits in terms of speed and interoperability. Microservices architecture, too, presents a scalable and efficient way to structure applications [45], [46]. Similarly, dynamic message transmission strategies [47] and brokerless systems [48] have their respective advantages in enhancing user interaction. Incorporating these technologies via an API-call-based approach could create a more intuitive, accessible, and efficient system for users interacting with the blockchain.

VIII. CONCLUSION

In summation, this study has bestowed invaluable understanding pertaining to the selection of appropriate EVM-compatible blockchain platforms for the deployment of our proposed recommendation model. Through an exhaustive investigation and assessment of platforms including Binance Smart Chain, Polygon, Fantom, and Celo, we have unearthed detailed distinctions in costs, gas limits, gas consumption, and gas prices, each playing a critical role in the creation and transfer of Non-Fungible Tokens (NFTs) and smart contract deployments.

The comprehensive evaluation of transactional expenses, gas thresholds, gas consumed, and gas pricing has not only delivered a lucid understanding of operational expenditure associated with each platform, but also unveiled the intricacies of transactional efficiency and efficacy. Binance Smart Chain emerged as a cost-effective solution, while Fantom showed promising transactional speed and effectiveness.

Our contribution extends beyond proposing a novel recommendation model, as we have openly shared the implementation details on these blockchain platforms. This initiative is expected to stimulate further research and offer the developer community an in-depth practical insight into working with these platforms. Furthermore, we have offered an elaborate account of our evaluation procedure, ensuring its reproducibility and transparency.

Our future work is ripe with exciting opportunities, from delving into complex methodologies such as encryption and decryption, addressing privacy policy issues, and investigating infrastructure-based strategies. As we incessantly refine and augment our model, these areas will form the epicenter of our research focus.

Even though the road ahead is laden with complexities, the study reiterates the enormous potential and versatility of blockchain technology across varied applications. As we steer forward, our objective is to leverage these unique strengths to craft an efficient, robust, and secure blockchain-powered recommendation system. The exploratory journey continues, with each stride taking us closer to our ultimate goal: an equitable, secure, and accessible future propelled by blockchain technology.

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