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Enhancing Digital Asset Ownership through Decentralized NFT Applications

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Enhancing Digital Asset Ownership through Decentralized NFT Applications

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ABSTRACT

The rapid expansion of the digital ecosystem has introduced pressing challenges surrounding identity, authenticity, trust, and transparency. The ease with which digital content can be duplicated often undermines creators, whose works are distributed without consent or fair compensation. Blockchain technology offers a transformative solution through its decentralized, transparent, and tamper-resistant structure. Among its innovations, Non-Fungible Tokens (NFTs) provide a mechanism to verify the authenticity and ownership of unique digital assets. This study explores the transformative potential of NFTs in strengthening digital ownership and authenticity while identifying critical challenges such as market concentration, interoperability limitations, and security vulnerabilities within public NFT platforms. Employing the Extreme Programming (XP) methodology, this research proposes a secure framework for NFT creation outside public marketplaces to enhance the protection of smart contracts and user accounts. The findings demonstrate that this approach grants users greater control, minimizes exposure to platform-level risks, and promotes trust in decentralized asset management. Overall, this study underscores NFTs' pivotal role in reshaping digital ownership models and highlights the need for continued innovation to ensure security, transparency, and equitable value distribution in the evolving digital economy.

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1. INTRODUCTION

In today's digital age, the availability of information is abundant and easy to obtain, access, exchange, distribute, and transmit at any time, anywhere, via the internet. In addition to bringing many benefits, it has raised new challenges and problems in identity, authenticity, trust, and transparency. Through the internet, all kinds of digital media can be easily shared and copied, with or without the permission or consent of the original content's creator or owner, whose distribution is a problem for the creator because their work can be copied and distributed without consent or remuneration. There is no widely accepted way to determine a digital artwork's "original" part. Nor is there a widely accepted way of proving or diverting its ownership. It is becoming a challenge and a problem that still needs to be faced in today's digital age. One of the critical advantages of blockchain is its ability to provide a highly secure and transparent platform for transactions. This can help mitigate fraud, data manipulation, and lack of trust in various industries [1].

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Blockchain is a digital book technology whose databases are shared and replicated by many parties and can only be updated by following pre-established rules [1], [2]. A data update has been verified, approved, and distributed to all parties. It will add a new block to the chain copy. Each block has a unique hash, and if someone tries to change the data in the block, the hash in that block will change. This blockchain technology has revolutionized the creation of ownership records for digital works as exciting innovations such as creating proprietary records or books that cannot be changed and decentralized [3].

NFTs (Non-Fungible Tokens) are digital information units stored on the blockchain that authenticate digital assets as unique and, therefore, cannot be inherently exchanged for NFTs with other non-fungible assets [4]. NFT has received significant attention as a digital asset for various purposes, such as photos, videos, audio, profile images, identities and other types of digital files [5]. Ownership of an NFT can be likened to possessing a priceless masterpiece, where individuals can download it from the internet or acquire it in a printed format for personal use. However, the essential truth regarding ownership remains unaltered, with only one individual trusting its authenticity. The immutable and tamper-proof nature of blockchain technology enables the recording and interlinking of transactions related to artworks, establishing a transparent and verifiable lineage of ownership [6]. Moreover, the rise of NFTs has created a paradigm shift in how society perceives and values digital content. These tokens empower creators to assert their ownership and authenticity over digital creations in an unprecedented manner, opening up new avenues for artists, content creators, and collectors alike to participate in a digital economy underpinned by the principles of blockchain technology.

Based on research conducted by Sajjad Alizadeh shows that the NFT market has experienced a significant rise in NFT manufacturing and trading. However, only a few participants made most of the sales and purchases, while most addresses had some NFT transactions [5]. Some marketplaces provide NFT manufacturing services, but they have just supported some formats, so there are still quite limited files that can do NFT manufacturing. Furthermore, transferring ownership of an NFT within a marketplace necessitates the obligation of covering associated costs within that specific marketplace. This financial responsibility may include transaction fees incurred while transferring the NFT from one owner to another. These fees contribute to maintaining and operating the marketplace infrastructure and ensure participants' secure and efficient exchange of NFTs. NFT buyers and sellers need to be aware of and consider these costs as they engage in transactions within the marketplace ecosystem, as they can vary and impact the overall economic aspects of NFT trading and ownership transfers. Also, the vulnerability of the existing marketplace website can cause a chance of losing our NFT. Based on reports of a hack on Nifty Gateway, a popular exchange for non-fungible tokens (NFTs), there has been a security vulnerability in its system, which has resulted in the account of Michael Miraflor, a media strategist, being hacked and his entire collection of NFTs being deleted within minutes [7]. So, with the creation of NFTs themselves, whose operations are not for the public, users can ensure the security of smart contracts and user accounts because access is not like the public marketplace exists. So, by creating private NFTs, users can ensure the security of smart contracts and user accounts because access is different from the public markets.

2. METHOD

This research uses Extreme Programming (XP) as a strategic methodology, as shown in Figure 1. Extreme programming selection is supported by an established reputation as a fast, highly efficient, and exceptionally low-risk approach to software development. Extreme programming (XP) is one of the popular software development methodologies from the Agile family used for small-scale projects [8]. The adoption of XP aligns with the fundamental objectives of this research, which aim to address the complexities of developing innovative solutions in the context of decentralized and non-fungible token (NFT) applications for personal asset management. XP's emphasis on flexibility, collaboration, and iterative development makes it particularly well-suited to the dynamic nature of blockchain technology and NFT integration, providing a systematic framework for achieving research goals while minimizing potential risks. Since XP requires minimal supporting procedures, it eliminates the need for extensive project specifications and documentation [9]. The fact that it is team-oriented implies that everyone on the development team, not just the team's owner or manager, is responsible for the project's successful completion [9]. This methodology choice helps maintain consistency and reliability throughout the research process, ensuring the validity of the findings.

To ensure a comprehensive evaluation, several additional experiments will be conducted to assess the system's performance across various dimensions. These experiments will include a cost-per-mint analysis on selected blockchain networks to evaluate the financial efficiency of minting NFTs. In addition, an end-to-end latency measurement will be performed, capturing both the IPFS upload time and the mint confirmation period, providing insight into the system's responsiveness. Usability testing will also be conducted via a questionnaire administered to multiple users, enabling an evaluation of the user experience. Finally,

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interoperability testing will assess the system's ability to import external NFTs and read third-party contract metadata, ensuring compatibility with other platforms. These evaluations will generate empirical data, substantiating the findings and ensuring a thorough and multifaceted performance assessment of the system.

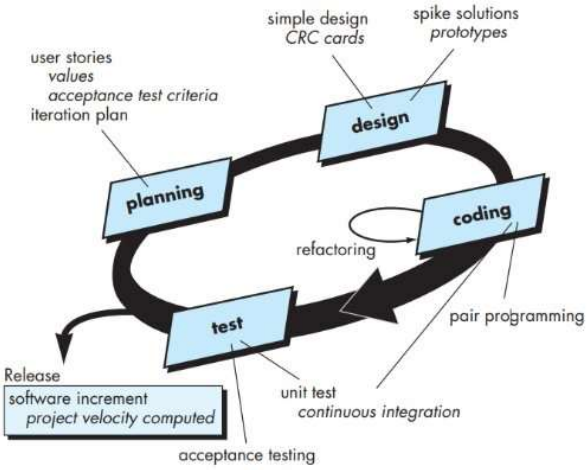

Figure 1. Extreme Programming Software Life Cycle

Figure 1 shows the planning phase, which involves identifying in-depth research objectives, careful planning strategy of application features, measurable resource allocation, and developing a structured, iterative plan. This stage serves as a solid foundation for further development. During the Design stage, a comprehensive application conceptual design process was carried out, considering comprehensively the integration of NFTs in the context of personal digital asset management. Besides that, selecting the appropriate blockchain technology and detailing an accurate initial test plan is also integral to this stage. While in the Development (Coding) stage, the research team started implementation based on the design that had been made with a high level of accuracy and thoroughness. This phase includes implementing the designed features, including the ability to create, store, and manage NFTs in the context of personal digital asset management. Finally, the Testing phase involves a series of systematic tests, including rigorous unit testing, comprehensive integration testing, and overall testing to verify the functionality of the NFT in the application and ensure that its performance and security aspects are met with a high level of confidence. With this highly structured XP-SLC approach, developing NFT applications for personal digital asset management follows strict scientific procedures and guarantees success in achieving the stated research objectives.

2.1. Blockchain

Blockchain is a type of database that is both decentralized and distributed. It is frequently used to preserve the record of every single transaction in a block, which is then secured with cryptographic hashes [10], [11], [12], [13]. When Satoshi Nakamoto published a whitepaper on the decentralized cryptocurrency Bitcoin in 2008, the first application of blockchain technology was suggested [14], [15]. By combining various pre-existing technologies, such as asymmetrical encryption, Merkle Tree Structures, and Hashcash (a cryptographic algorithm that makes verifying a proof simple but computing it complex), he managed to create a novel solution [15].

According to Ref [16], here is a possible explanation for a blockchain: A blockchain is an immutable and read-only data structure. It works by appending new entries (blocks) to the end of a ledger. These blocks are linked to the previous block's 'hash' identifier.

2.2. NFT

NFTs have emerged as a subject of rigorous examination across various interdisciplinary academic domains, such as finance, real estate economics, law (with a focus on intellectual property rights), and information technology [17]. Researchers like Sunyaev et al. have delineated two approaches for integrating tokens into an existing distributed ledger [18]. The first method involves the utilization of a private distributed ledger, which restricts access solely to authorized agents, allowing them to partake in reading transactions from and appending new transactions to the ledger. On the other hand, the second approach empowers agents to design bespoke tokens by employing smart contracts, thus offering flexibility while utilizing an existing distributed ledger to implement the token-based economy [17]. Furthermore, the research conducted by Peres et al. [19] and Taherdoost [20], has emphasized that non-fungible tokens

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(NFTs) represent cryptographic assets within the blockchain ecosystem, characterized by their possession of unique identification information and code, which sets them apart from one another. This distinctiveness is a crucial attribute contributing to the growing popularity and adoption of non-fungible tokens (NFTs). Additionally, NFTs have demonstrated their potential in mitigating fraudulent activities, primarily because each token bears the digital signature of its owner, thus ensuring its uniqueness and authenticity within the blockchain system [20]. Consequently, NFTs are gaining increasing prominence and application across various academic disciplines and industries thanks to their unique properties and versatility in use cases.

2.3. Smart Contract

Smart contracts are computer programs that are an essential part of the blockchain network. They describe the triggers, conditions, and business logic allowing intricate programmable transactions [21], [22]. A smart contract is a set of code-based instructions that can be executed automatically on a blockchain network according to predetermined agreements or conditions. These smart contracts consist of a set of pre-defined rules; if these rules are met, they trigger the automatic execution of the programmed agreement. In other words, a smart contract functions as a set of instructions written in a programming language that contains a certain logic. With smart contracts, the agreement process becomes more efficient because it does not require intermediaries or third parties to verify or enforce the agreement. For example, suppose all the terms and conditions specified in the smart contract are met in a buying and selling transaction. In that case, the transaction will be carried out automatically without human intervention. This helps facilitate, verify, and enforce agreements more efficiently in the blockchain environment.

Smart Contracts concentrate solely on the technological aspect of contracts, disregarding the social environments in which contracts function and the intricate methods individuals utilize them [23], [24], [25]. Consequently, Smart Contracts cannot be considered identical to traditional contracts [23], [26]. Smart contracts extend the utility of a blockchain from storing transactions to enforcing the terms of multi-party agreements. Smart Contracts also help enter multi-party agreements involving anything of value, be it money, property transactions, or other entities, without needing a third-party intermediary. Thus, when using it, the parties involved do not have to rely on lawyers or banks to conclude contracts, but when certain conditions are met, the smart contract will automatically run to issue payments. The implementation of smart contracts on the blockchain makes them immutable. That is, the contract used can never be canceled or deleted.

2.4. IPFS

IPFS, short for InterPlanetary File System, is an innovation developed by Juan Benet in 2014. This system is designed as a solution for the efficient storage and distribution of large files in a distributed manner. It aims to replace the currently dominant HTTP request-response protocol. IPFS was developed as open-source software and boasted the absence of a single point of failure, thereby allowing nodes in a network to operate without establishing trust between them. The infrastructure offered by IPFS can identify, verify, and transfer files using cryptographic hashes to guarantee the authenticity of files regardless of their storage location on the network [27].

The existing systems within IPFS have proven efficient and secure in document retrieval, management, and validation while preventing malicious data modification [28]. Like public blockchains, files stored on IPFS can be accessed and viewed by anyone connected to IPFS nodes. Unlike in a central server, these files are not stored. Instead, they are distributed across multiple nodes, which creates a vital decentralization feature. It is important to note that storing data in a blockchain has a different fee model depending on the size of the data, and transactions on a blockchain store only a small amount of data. Therefore, it is crucial to consider wisely which data should be placed On-Chain and which data is more appropriate to store Off-Chain. As such, IPFS becomes an essential solution for ample file storage on the blockchain, as it provides a peer-to-peer distributed file system that fragments, encrypts, and distributes files to various nodes in the network, maintaining their security and availability.

3. RESULTS AND DISCUSSION

The creation of NFT applications for these digital works and assets uses Python as a programming language and Brownie as a framework for developing smart contracts targeting the Ethereum Virtual Machine. In addition, PYQT5 is utilized as a framework for creating the application's graphical user interface (GUI), offering a wide range of pre-built design elements.

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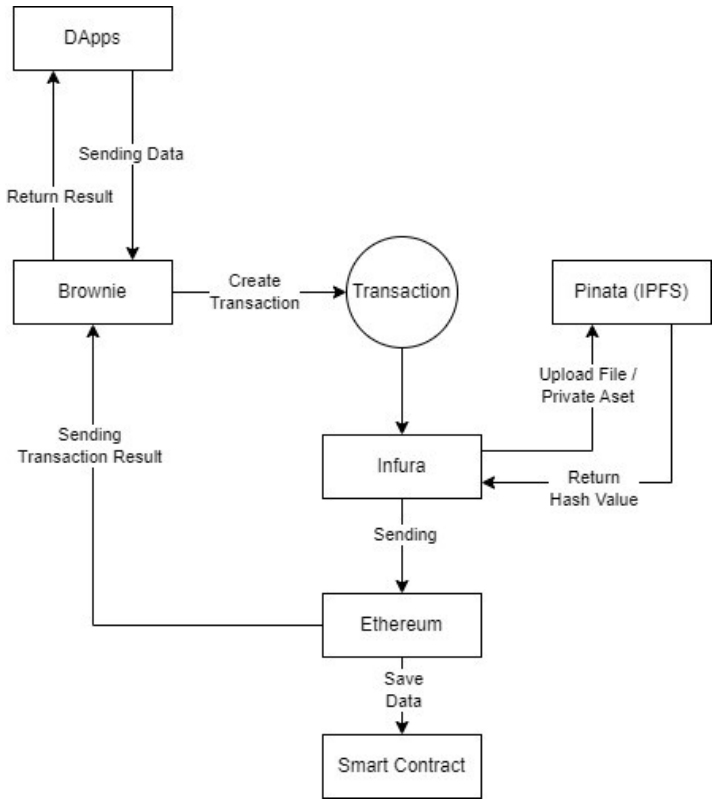

Figure 2. Proposed Model

Figure 2 is a visual representation that clearly and in detail depicts the entire process involved in designing an NFT creation application. This process starts from the initial stage, where the user uploads the data that will be converted into an NFT into the application. Once the data is uploaded, the next step is to store it in smart contracts running on the Ethereum network. Storing data in smart contracts is very important because smart contracts act as smart entities that facilitate NFT transactions and management. In smart contracts, NFT data will be assigned a unique ID token, which will then become the official identity of the NFT on the blockchain network. The token standard implemented is ERC-721, which ensures the uniqueness of each NFT. Additionally, metadata for each NFT is stored in JSON format, including information such as the token ID, name, description, and creator details. Furthermore, the royalties for each NFT are implemented using EIP-2981, which allows creators to define royalty fees for secondary sales of their NFTs. In addition, figure 2 also includes the stage where the data uploaded by users is integrated with the IPFS blockchain network. This data is uploaded to IPFS via the Infura API, which ensures secure and distributed storage. After uploading, IPFS generates a hash value reflecting the data storage location on the IPFS network. This ensures that the data remains secure and accessible across the decentralized storage network.

This entire process is reflected in Figure 2, which allows users and interested parties to quickly understand how the application works from the data upload stage to data storage in smart contracts and IPFS. This image provides a comprehensive and in-depth visual view of the mechanisms underlying the creation and management of NFTs in the context of such applications. Users must enter a private key before using the application. The private key serves as a cryptographic key used by the blockchain algorithm to encrypt or decrypt data or to sign transactions performed during the minting of NFTs. It is important that users store their private keys securely, ideally in a hardware wallet to prevent unauthorized access. After this, users will be directed to the main menu and select the desired options according to the file type for NFT creation. After filling in the form and entering the file you want to use as NFT, the application will upload the file to IPFS, returning the hash value of the file stored on IPFS. The stored hash will be re-entered into the data format as JSON, which will be uploaded back to the IPFS to obtain the hash value. The hash is put together in a link format, where the link will be sent as a transaction into the blockchain to validate the transaction.

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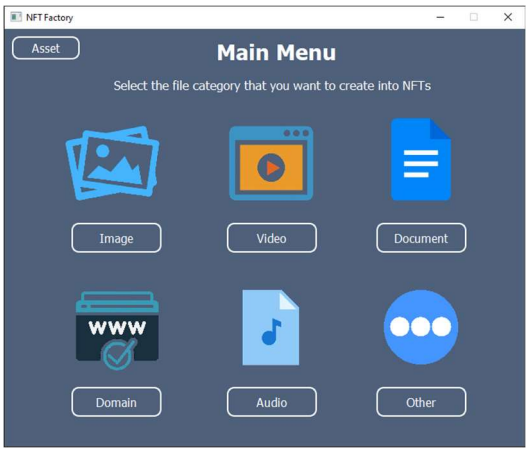

Figure 3. Application Main Menu View

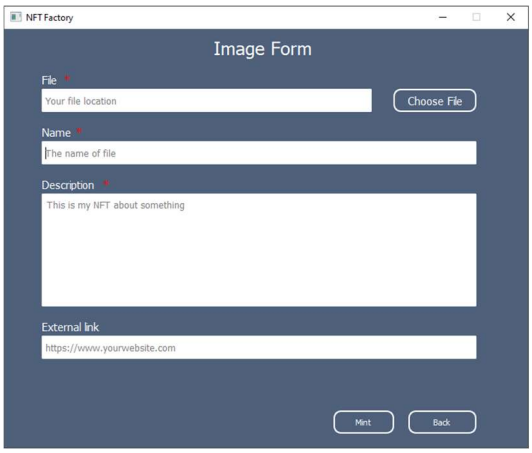

Figure 4. Application Image Menu View

Figures 3 and 4 show creating an NFT on Dapp (decentralized applications). The first stage is to choose the type of asset the NFT will be created and then fill in the detailed information on the created asset. Then, the mint process is carried out into the blockchain via a smart contract, and the assets are stored on IPFS. Once the mint process is complete and at least two blockchain nodes have validated the transaction, the application will display a pop-up message that can display the NFT created on the Opensea NFT marketplace website. Users can also view the NFT information that has been created through the Asset menu on the application, which will display a variety of information such as token ID, NFT name, description, file link NFT, information about the website, file type, creator name, artist name, registration date, date of expiration, image NFT cover link, type of NFT created, and transaction ID as a link to https://etherscan.io so that users can directly perform NFT self-checking on the Ethereum blockchain that they already have through the etherscan website.

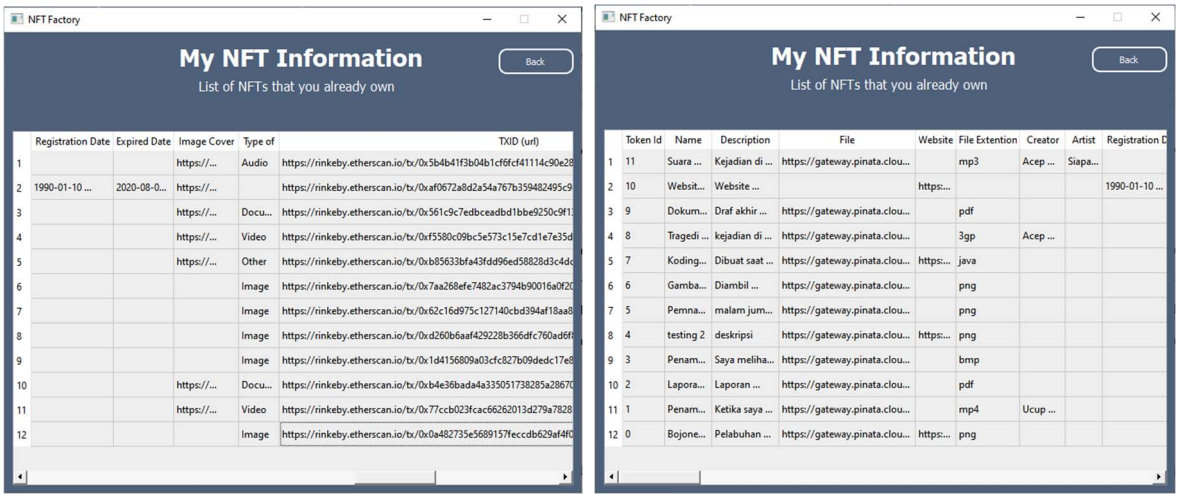

Figure 5. Assets Menu View

In its application, the Infura API is used as a node provider. In the blockchain, each node holds a copy of every significant book, then from it called the blockchain. Moreover, every interaction on the blockchain requires a node to communicate and validate a transaction. Using Infura as a node provider to access the Ethereum blockchain will be much easier and faster as users do not have to build their nodes and synchronize against the Ethereum blockchain. Also, using this blockchain node provider makes decentralized application scaling (DApp) safer and eliminates the need to develop and construct its infrastructure in the DApp infrastructure. Figure 5 shows data that has been stored on the blockchain and can be traced through the scanner on the blockchain to ensure that the data has been entered and validated by the nodes on the blockchain.

The application was tested using the Black Box testing method, and the results are obtained in Table 1 as follows:

Table 1. Black Box Testing Results

Testing	Scenario	Expected results	Results	Validity
Main Menu	Select existing menu	Displays the target	Match	✓

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	options	menu page		
Image Menu	Create NFT Image	Can Make NFT	Match	✓
Video Menu	Create NFT Video	Can Make NFT	Match	✓
Document Menu	Create NFT Document	Can Make NFT	Match	✓
Domain Menu	Create NFT Domain	Can Make NFT	Match	✓
Audio Menu	Create NFT Audio	Can Make NFT	Match	✓
Assets Menu	Create NFT Assets	Can Make NFT	Match	✓
Others Menu	Create Other NFT	Can display NFT in mint via application	Match	✓

Researchers have identified several areas for improvement in developing the proposed NFT model that hinder its features. An in-depth evaluation of these deficiencies provides valuable insights for improvement and better future development. One drawback of this proposed model is that it cannot display NFTs that did not originate or were created through this platform, which suggests the potential to improve interoperability with NFTs from various external sources. Second, this model also does not support users to import smart contract addresses directly when wanting to access NFTs, so improvements in this area will allow users to access NFTs originating from various smart contracts on the blockchain more easily. Lastly, this model does not provide an option to cancel a transaction from either the user or system perspective, which often requires repeated confirmations to confirm the desired transaction. Increasing flexibility in managing transactions would be a positive step towards improving user experience. Analysis of these shortcomings provides valuable insight into how the proposed NFT model can be improved to meet broader user needs and strengthen its position in the ever-evolving NFT ecosystem.

To ensure the reproducibility of this research, all necessary technical details for replication are provided. The code used to implement key processes, such as NFT creation, smart contract interactions, and IPFS uploads, is available in the supplementary materials. A critical section of the code, specifically the minting function, is outlined as follows: the program connects to the Ethereum network using Web3 and Infura, constructs a transaction to mint the NFT, signs it with the user's private key, and sends the transaction to the blockchain. The exact versions of the tools and libraries used in this study are: Python 3.9, Brownie v1.17.2, IPFS (ipfshttpclient v0.4.6), and the Infura API v3 for Ethereum. To further enhance reproducibility, sample transaction hashes generated during testing on the Ropsten testnet are provided. For example, the minting transaction hash 0x9c1e8927dbca99f6f1edb2bb99c7e4a1588a4bc4c5fe278bcefc4c1c47b6bcd1 and the smart contract deployment hash 0x34c9a87d3fd22d440ad5d12f322d9c3f4a37682f351e7b0290d3091da07dbba7 can be verified on the Ropsten Etherscan Explorer. This process is supported by full pseudocode in the supplementary materials, detailing the steps necessary for others to replicate the work. The exact versions of the tools used are Python 3.9, Brownie v1.17.2, IPFS (ipfshttpclient v0.4.6), and the Infura API v3 for Ethereum. In addition to the code and versions, a Threat Model has been outlined to assess potential risks associated with the application. The model identifies key assets, adversaries, attack vectors, and corresponding mitigation measures to secure the system and ensure that vulnerabilities are minimized during interactions on the blockchain.

Table 2. Threat Model

Assets	Adversaries	Attack Vectors	Mitigation Measures
NFT data (metadata, files)	Malicious users	Man-in-the-middle (MITM) attacks	Use of hardware wallets for private key storage
Smart contract interactions	Malicious smart contracts	Reentrancy attacks, overflow	Contract upgradability, input sanitization, rate-limiting
User private keys	Phishing attacks	Keylogging, social engineering	Hardware wallets, multi-signature contracts

The model outlines the risks involved, such as man-in-the-middle (MITM) attacks targeting NFT data or phishing attacks aimed at user private keys. Mitigation measures, such as the use of hardware wallets for private key storage, contract upgradability, input sanitization, and rate-limiting, are implemented to minimize potential attack vectors, as detailed in Table 2.

For experiments conducted during the research, several important metrics were measured to assess the performance and usability of the system. Gas cost per mint was measured by running the minting process 10 times, with the mean ± standard deviation (std) reported to evaluate the cost efficiency. IPFS upload and pin time via Infura was also measured, with results provided in the same format (mean ± std) to evaluate the performance of the IPFS upload process. Usability testing was carried out with a small group of 6–12 users using the System Usability Scale (SUS), providing quantitative feedback on the application's ease of use, clarity of instructions, and overall satisfaction. Additionally, the interoperability test involved importing and displaying two external NFTs, confirming that the system can effectively integrate and display NFTs from

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other sources. These experiments and their results ensure the technical reproducibility of the study, providing empirical data to evaluate the performance and usability of the system. By making these details available, other researchers can replicate the process, validate the results, and build upon the work in future studies.

4. CONCLUSION

Based on the extensive research findings in blockchain and NFTs, utilizing NFTs for personal digital assets and works within the blockchain ecosystem has demonstrated remarkable efficacy. The process of tokenizing a diverse array of file types while ensuring cross-format compatibility has exhibited robust functionality, affirming the application's capacity to create and manage NFTs seamlessly. Notably, this application showcases high interoperability by facilitating users to access and exhibit their NFTs through established channels such as the Opensea NFT marketplace website. This integration broadens the exposure of digital assets and enhances their visibility to a broader audience, underpinning the platform's potential as a valuable tool for creators within the NFT landscape. Furthermore, users can exercise real-time oversight of their NFTs on the Ethereum blockchain through platforms like Etherscan, emphasizing the application's alignment with the blockchain's core principles of transparency and decentralization. The research outcomes underscore the NFT application's role in empowering creators to tokenize and manage their digital assets within blockchain technology. This development opens new avenues for creators to harness the benefits of NFTs, thus revolutionizing private asset management within decentralized applications.

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AUTHOR CONTRIBUTIONS STATEMENT

Yusuf Kurnia contributed to the conceptualization of the study, methodology design, system implementation, data analysis, and preparation of the original manuscript draft. Rino contributed to software development, validation, and formal analysis of the application performance. Edy contributed to software engineering design, testing procedures, and quality assurance. Junaedi contributed to investigation, blockchain architecture analysis, and integration of smart contracts and IPFS. Aditiya Hermawan contributed to formal analysis, manuscript review and editing, and visualization of system models. Kevin contributed to software implementation, debugging, and practical deployment aspects. All authors reviewed and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no known financial or non-financial competing interests that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The datasets generated and analyzed during the current study, including transaction logs, performance measurements, and usability evaluation results, are available from the corresponding author upon reasonable request. The source code, smart contract implementations, and supporting resources developed for this research are publicly accessible at the following repository: https://github.com/QuertyCube/NFTFactory. This repository contains all scripts, configuration files, and documentation necessary to reproduce the experimental procedures and system deployment described in the manuscript.

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