Decentralized Materials Data Management using Blockchain, Non-Fungible Tokens, and Interplanetary File System in Web3

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Abstract

In materials science, utilizing globally distributed data is essential for advancing materials design through technologies such as materials informatics. Achieving this requires secure, transparent, and efficient methods for managing and sharing materials data. This study explores the potential of blockchain, smart contracts, Non-Fungible Tokens (NFTs), and the InterPlanetary File System (IPFS) within the Web3 framework for managing and sharing materials data. We developed and tested a prototype data management system using a thermophysical properties dataset. This system facilitates NFT minting, data storage on IPFS, and secure, traceable ownership transfer of NFTs, enhancing traceability, transparency, and security in data sharing. Additionally, decentralized systems employing blockchain technology, smart contracts, NFTs, and IPFS effectively address vulnerabilities associated with single points of failure common in traditional centralized systems. This study offers valuable insights for future materials design, demonstrating the efficacy of blockchain and related technologies in managing and sharing materials data.

Keywords: Blockchain Interplanetary File System, Materials Data, Non-Fungible Token, Smart Contract, Web3

1. Introduction

Blockchain technology has significantly influenced various sectors, especially data management [1]. As a prominent form of distributed ledger technology (DLT), blockchain offers an innovative approach to data handling [2]. It secures information within interconnected blocks, employing cryptographic principles for protection. Through blockchain, transactions can be securely recorded across a distributed network, eliminating the necessity for a central authority. This decentralized architecture enhances system resilience and security. DLT, as exemplified by blockchain, provides an immutable and transparent ledger system that decentralizes record-keeping, thereby fostering trust and cooperation among participants [3].

This study focuses on data sharing in materials science and manufacturing, where data on the physical properties of materials are indispensable across all manufacturing sectors. As products become increasingly complex, so too do their constituent materials. Materials data are dispersed globally and housed in various databases of differing scales. Some of these databases include those of the National Institute of Advanced Industrial Science and Technology (AIST) [4], the National Institute for Materials Science (NIMS) [5], and the National Institute of Standards and Technology (NIST) [6]. Existing systems for managing and sharing materials data, such as web-based database systems, face significant challenges related to security, transparency, and traceability. Centralized systems are susceptible to security breaches, hindering efficient data verification. Moreover, the lack of traceability in these systems undermines accountability, hampering optimal decision-making and compromising overall data integrity and operational efficiency [7]. The effective utilization of globally distributed materials data is crucial for advancing materials design through technologies like materials informatics [8]. Ensuring excellent traceability and tamper-proof functionality is critical for consolidating

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materials data as needed. DLT, such as blockchain technology, offers a solution by capturing comprehensive data histories and mitigating discrepancies among supply chain stakeholders. The growing demand for transparent, secure, and traceable data management infrastructures underscores the relevance of blockchain technology [9]. Blockchain inherently promotes transparency by recording each transaction in a ledger accessible to all participants, thereby facilitating network-wide verification. Its decentralized architecture bolsters security by distributing data across multiple nodes, significantly raising the difficulty in conducting cyberattacks targeting centralized systems. Furthermore, blockchain's immutable nature strengthens traceability by permanently recording all changes and transactions, enhancing trust and accountability in data management processes. In addition, integrating non-fungible tokens (NFTs) as unique identifiers further supports data authenticity and provenance [3]. NFTs provide unique and non-interchangeable benefits for materials data management, including enhanced tracking, security, sharing, and traceability. They can help streamline data-sharing processes, resulting in more reliable and efficient procedures [10], [11], [12], [13], [14], [15], [16], [17]. This technology promises to interconnect materials data globally in an unalterable, and traceable network, offering robust solutions for secure and transparent data management in materials science and manufacturing.

Materials data management involves handling diverse information, encompassing physical and chemical properties. This research specifically addresses the security, traceability, reliability, and trustworthiness of thermophysical property data of materials by developing a distributed storage and utilization system. By leveraging blockchain technology, this system fosters the management and sharing of materials data, aiding researchers and engineers in designing and developing new materials.

A notable innovation in blockchain technology is the emergence of NFTs, which serve as unique digital authentications to verify and transfer the ownership of individual assets [18]. NFTs feature distinct digital identifiers recorded on the blockchain and managed through smart contracts, which can enhance data privacy in materials data management. Specifically, smart contracts can be programmed to incorporate the logic required for creating, managing, and transferring NFTs, as well as implementing zero-knowledge proof mechanism. This mechanism enables the verification of material data sheet record authenticity without disclosing the data contained within the record [19], [20]. Additionally, NFTs improve auditability and transparency by recording access logs on a permissioned blockchain, establishing an accountability trail while maintaining privacy and security [18], [21]. When integrated with decentralized identity management systems, NFTs empower users to control their digital identities, thus mitigating data-exposure risks [22], [23]. As self-executing agreements coded into a blockchain [24], smart contracts automate actions based on predetermined conditions. This automation streamlines processes such as payment and data verification, minimizes reliance on intermediaries, and promotes trust in decentralized systems [8], [25], [26].

This study focuses on developing a materials data management system by integrating NFTs, the InterPlanetary File System (IPFS), Web3, and crypto wallet technologies. IPFS operates as a peer-to-peer protocol linking computing devices to a unified file system, offering secure data identification (ID) and robust storage capabilities [27], [28]. Web3, an evolving concept of the World Wide Web, incorporates technologies such as decentralization, user ownership of data, and cryptocurrency [24]. By employing blockchain technology, Web3 aims to establish a more user-centric and decentralized internet, affording individuals greater control over their data compared to Web1 (the read-only web) and Web2 (the read-write web). This user-centric approach facilitates autonomous decision-making processes. Web3 enhances user control, security, and privacy while integrating with NFTs and other blockchain technologies to strengthen data management and protection [29], [30]. Web3 libraries enable seamless interactions between blockchain nodes managed by data providers and users [31], [32]. Crypto wallets play a pivotal role in our system, serving as secure identity management tools, overseeing user identities and facilitating blockchain transactions [33]. These wallets securely store user data, empowering individuals to maintain control over their digital identities and access global markets through blockchain technology. By implementing encryption mechanisms, crypto wallets enhance security and help mitigate the risks associated with identity theft [34], [35], [36]. Our integrated approach of combining these aforementioned technologies creates a resilient and efficient materials data management system that prioritizes data ownership and user empowerment.

Materials data encompass various attributes, including price, shape, and specific properties such as density, tensile strength (a mechanical property), electrical conductivity (an electrical property), and thermal diffusivity (a thermophysical property). Even for identical materials (e.g., graphitic carbon), diverse datasets are available globally due to variations in shape, synthesis methods, and other factors. These datasets are crucial in numerous fields requiring precise predictions of material behavior, such as materials science, mechanical engineering, aerospace, automotive, and electronics [37]. For instance, thermophysical property data focuses on materials' response to temperature changes, encompassing thermal conductivity, thermal diffusivity, heat capacity, and thermal expansion coefficient. Such data are vital for engineering systems exposed to temperature variations, including heat exchangers, engines, and thermal insulators [38]. Any discrepancies or inaccuracies in these datasets can lead to severe consequences, including material failures and, in extreme cases, operational catastrophes in machinery, vehicles, and other critical systems [39], [40], [41], [42].

Our proposed system leverages blockchain technology (specifically Ethereum) and NFTs on Web3, which are well-regarded for their high traceability and security [43], [44]. To develop decentralized applications, the system employed Polygon, a blockchain platform designed to create a multi-chain system compatible with Ethereum [29]. Ethereum offers a robust platform supported by a large developer community and powerful smart contract capabilities, making it highly suitable for complex applications. Polygon functions as a scaling solution, enhancing Ethereum's scalability by utilizing sidechains and various technologies, facilitating faster and more cost-effective transactions while maintaining security and compatibility with the Ethereum network [45], [46]. Scalability is a critical factor for the efficiency, reliability and viability of decentralized systems, allowing them to handle increasing workloads and user demands without compromising performance. By optimizing network architecture, consensus protocols, data management strategies, interoperability frameworks, and user interface (UI) design, decentralized systems can proactively enhance scalability, meeting user requirements and fostering long-term sustainability [47], [48], [49], [50].

These technologies play a pivotal role in ensuring the reliability and trustworthiness of the system. The primary objective was to establish a robust, secure, and transparent framework by integrating DLT, smart contracts, NFTs, IPFS, and Web3 for the comprehensive management of materials data storage, access, sharing, and transactions. This initiative aims to foster collaboration among various institutions in materials science.

2. Methods

Figure 1 illustrates the primary components of the proposed system and their interactions, depicting the system architecture across three primary layers: user interaction, blockchain, and IPFS. The workflow delineates the sequence of actions, from data upload to NFT minting and data retrieval, simplifying the understanding of materials data management within the system. Users initially access the system via a Web3 browser, which supports decentralized applications [29]. They utilize MetaMask, a software crypto wallet, to securely interact with the Ethereum blockchain for managing ID and signing transactions [51]. Upon verifying their user ID, users upload materials data, including descriptions and comma-separated values (CSV) files, through the UI. These data are stored in IPFS using Infura [52]. Following successful uploading, a content identifier (CID) is generated as a unique code referencing the CSV file. The CID serves as a persistent address for data retrieval. To retrieve a file, users require its CID, a unique address that identifies the data within the IPFS network. IPFS employs the Distributed Hash Table (DHT) to locate nodes containing the requested data. The DHT comprises information regarding the distribution of data across the entire IPFS network. The system employs the JavaScript Object Notation (JSON) remote procedure call (JSON-RPC) protocol to facilitate communication between the UI and the Ethereum Virtual Machine (EVM) via Chainstack. This process involves executing NFT smart contracts on the Polygon network, adhering to the ERC-721 standard [53] and written in Solidity [54]. The smart contract encompasses three main functions: 1) Creating (issuing/mining) NFTs for materials data (referred to as "material NFTs"); 2) Transferring ownership of material NFTs; and 3) Listing material NFTs on the marketplace.

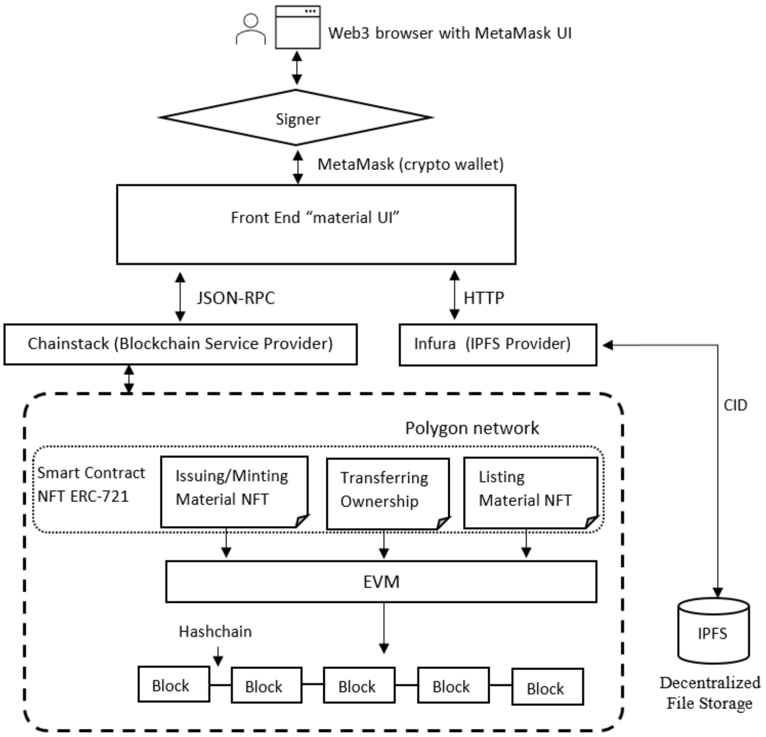

Figure 1. Architecture of the proposed materials data management system leveraging Web3, NFT, and blockchain technology.

In our system, all transactions related to material NFTs are securely recorded on the blockchain, capturing key information such as transaction IDs and timestamps. This transparency ensures that each transaction remains verifiable for future reference, which is crucial for maintaining system credibility. Concurrently, detailed materials data in CSV format are stored in IPFS, utilizing its distributed network for robust data storage. Each CSV file, identified by its CID, is linked to a specific material NFT on the blockchain, also identified by its CID. This linkage guarantees that while material data resides off-chain, they remain securely accessible and verifiable through their associated NFTs. This approach facilitates secure and transparent tracking of NFT ownership and transfers, while also providing efficient access to extensive material datasets.

Table 1 categorizes key aspects of the proposed blockchain-based materials data management system into four areas: security, reliability, traceability, and trustworthiness. Each category outlines specific objectives and features of the prototype, highlighting the corresponding blockchain elements and their functionalities.

Table 1. Functional overview of prototypes developed using blockchain technology and smart contracts.

No.	Categories	Objectives	Features in Prototype
1	Security	Reducing data storage vulnerabilities.	IPFS, decentralized storage, ensures that data is not stored in a single location, minimizing vulnerabilities.
		Ensuring data uniqueness and provenance.	Unique data tokenization using ERC-721 standard NFTs and an immutable ledger
		Strengthening security and confidentiality.	Crypto wallet in Web3 for user authentication and secure identity.
2	Reliability	Enabling reliable and persistent data access.	Access control, decentralized ledger, and IPFS for distributed redundant storage
3	Traceability	Increasing transparency & accountability.	Secure and traceable NFT ownership within the prototype

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4	Trustworthiness	Facilitating decision-making through trustworthy data.	Web3 and crypto wallet enable comparison of trusted materials data, verified by smart contracts.

2.1. Case Study: Application for Thermophysical Property Data

The case study focuses on developing a Web3 application prototype that implements the outlined technological stack, specifically designed to manage, share, and track materials data. In this study, thermophysical property data of thin-film materials and other materials were used as real-world examples. Consequently, the system was evaluated by uploading materials data, creating NFTs, transferring ownership, retrieving data, and comparing data. Thin films play a critical role in various industries, such as integrated circuits and photovoltaic technology. Utilizing thermophysical property data for each constituent thin film can ensure stable device thermal design and facilitate technological advancements [55]. These material properties encompass thermal conductivity, thermal diffusivity, specific heat capacity, density, and coefficient of thermal expansion. Based on Yamashita's study [56], realistic application scenarios were simulated using samples of thermophysical property data.

3. Results and Discussion

Figure 2 displays the UI for adding new materials data. Through this UI, users can initiate the creation of a new NFT and input data properties such as material name (e.g., silicon), file name, material description, and specific material properties (e.g., thermal diffusivity). Users can upload materials data in CSV format, which is subsequently stored in IPFS and represented as an NFT on the blockchain. Additional, users have the option to access all materials data by clicking the "Show all data" button.

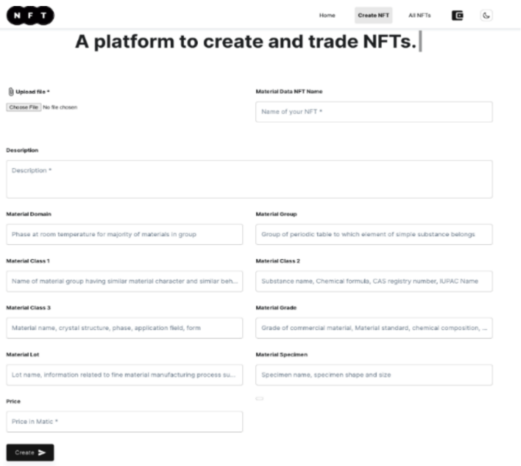
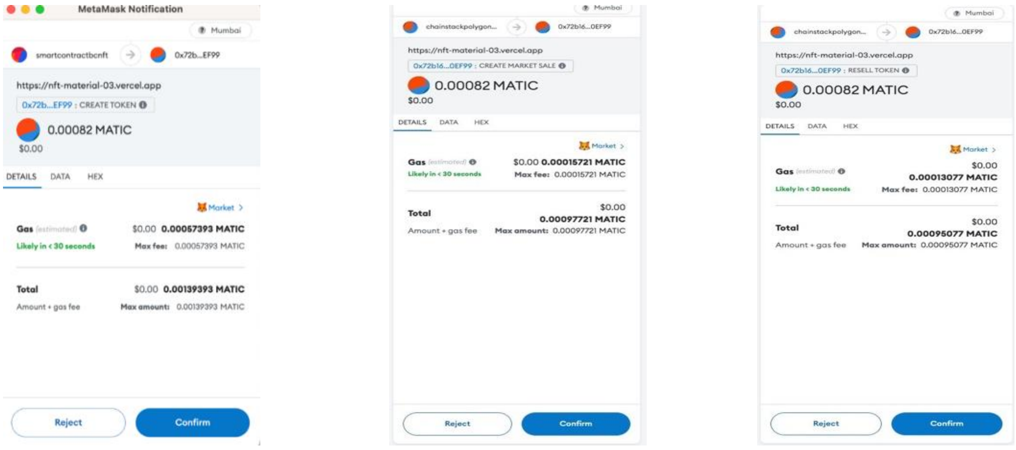


Figure 2. UI for adding new materials data and displaying all data.

3.1. Security

Decentralized storage on IPFS enhances security by distributing data across multiple nodes, thereby reducing vulnerability to single points of failure and minimizing risks from targeted attacks or data loss. By utilizing the ERC-721 standard for NFTs, data tokenization effectively secures identities and transactions, ensuring each piece of data is uniquely mapped to individual tokens for immutability.

The prototype system employs crypto wallets to ensure robust security, with each transaction securely signed using cryptographic techniques to safeguard user identities and prevent unauthorized access. Cryptographic authentication plays a crucial role in maintaining user privacy and security. Figure 3 illustrates the information window for the secure transaction signing process during NFT creation for uploading materials data, as well as for buying or selling materials data. Users authenticate via cryptographic methods to ensure robust security, with the system managing transaction signing and key management. The MetaMask UI displays wallet information and transaction details, including gas fees (transaction fees), enabling users to review and approve this information before confirming transactions. These steps ensure that transactions proceed with user consent, with all activities recorded on an immutable and traceable blockchain.



(a) (b) (c)

Figure 3. Secure transaction signature process using MetaMask to ensure confidentiality of users who (a) Create an NFT, (b) Purchase materials data, or (c) Sell the materials data.

Our proposed system utilizes ERC-721 NFTs, crypto wallets, and IPFS for data tokenization, cryptographic authentication, and decentralized storage, ensuring secure transactions and maintaining privacy. These technologies, along with their security and scalability aspects, have been extensively investigated in [57], [58], and others. In this study, these technologies were integrated and implemented for sharing materials data.

3.2.Traceability

Our prototype demonstrated comprehensive data traceability through the inherent capabilities of blockchain technology. Every transaction and ownership change were meticulously recorded, facilitating easy tracking of data history and enhancing traceability. Figure 4 depicts the detailed history of each data record within the prototype. Users can access the complete immutable history by referencing the transaction hash through a public blockchain explorer (Polygonscan).

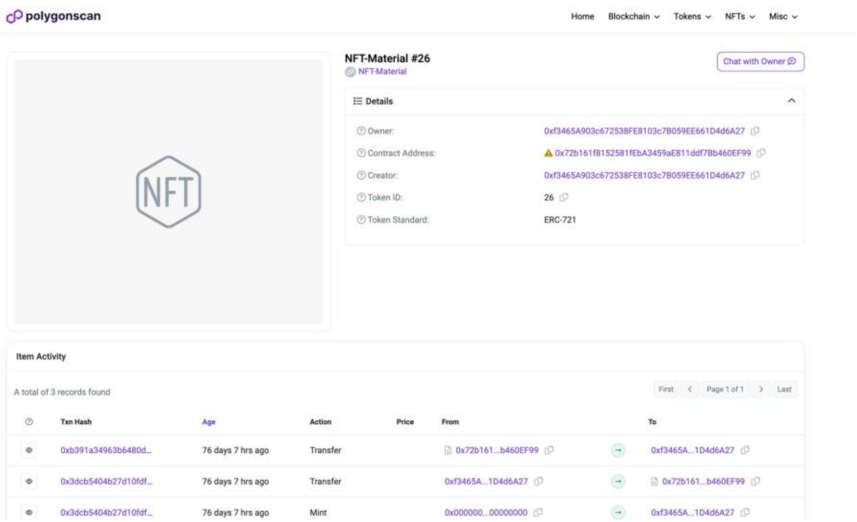


Figure 4. Results of retrieving the traceability of materials data from the blockchain explorer (Polygonscan).

3.3. Reliability

IPFS provides robust storage and reliable access to data, ensuring continuous availability without loss or corruption, as confirmed during our tests of NFT creation, transferring ownership, and data retrieval (i.e., retrieving a token and extracting materials data from IPFS). This underscores the strength and resilience of the proposed system. Figure 5 illustrates the web interface of our prototype, demonstrating how data was retrieved from IPFS. The successful retrieval using a specific IPFS hash emphasizes the system's capability to reliably access and fetch data as required. This dependable data access feature is a key advantage of IPFS. The IPFS hash, serving as a unique data identifier, is integrated and stored within the material NFT, further enhancing the system's reliability.

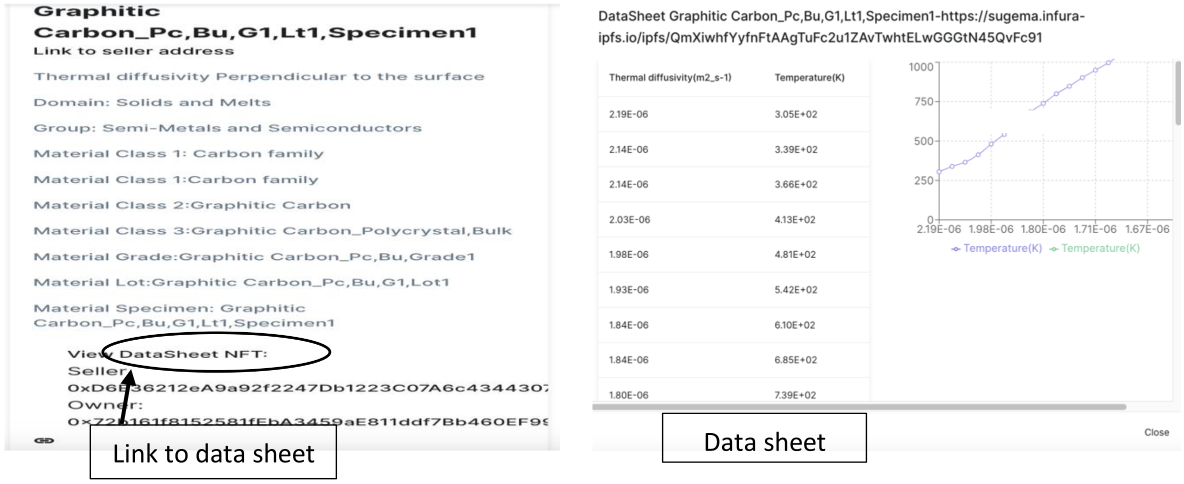


Figure 5. Example of materials data extracted from IPFS and its corresponding graphical output.

By distributing data across multiple nodes, a blockchain significantly reduces the risks of data tampering or loss. Our study assessed the speed and reliability of our system on the Polygon network, focusing on NFT operations such as token creation, ownership transfer, and data comparison. Transaction times on the blockchain are detailed in table 2. Using Google developer tools, we observed an average transaction time of less than 6 s, indicating that the prototype is suitable for materials data management in this case study.

Table 2. Average transaction times (over three attempts) for NFT creation, transfer, retrieval, and comparison.

Functions	Results
Creating a token	New NFTs were successfully minted on Polygon's network, demonstrating the system's reliability. The average minting time was 5.9 s.
Transferring ownership	Successful transfer of ownership on Polygon's network showcased the system's trustworthiness. The average time was 6.0 s.
Retrieving a token and extracting materials data from IPFS	Materials data were successfully extracted consistently from the blockchain and IPFS, indicating the system's reliability. The average time was 3.2 s.

3.4. Trustworthiness

Figure 6 illustrates the functionality of the data comparison tool within the UI data visualization feature. This tool enables users to visually compare differences between various materials data. Our prototype facilitated materials data comparison through smart contracts and integrated data visualization in the Web3 UI. This system streamlines the process for users to locate, compare, and analyze data through graphical representations. Such an approach empowers users to identify trustworthy data based on clear and visually understandable information, facilitating informed decision-making.

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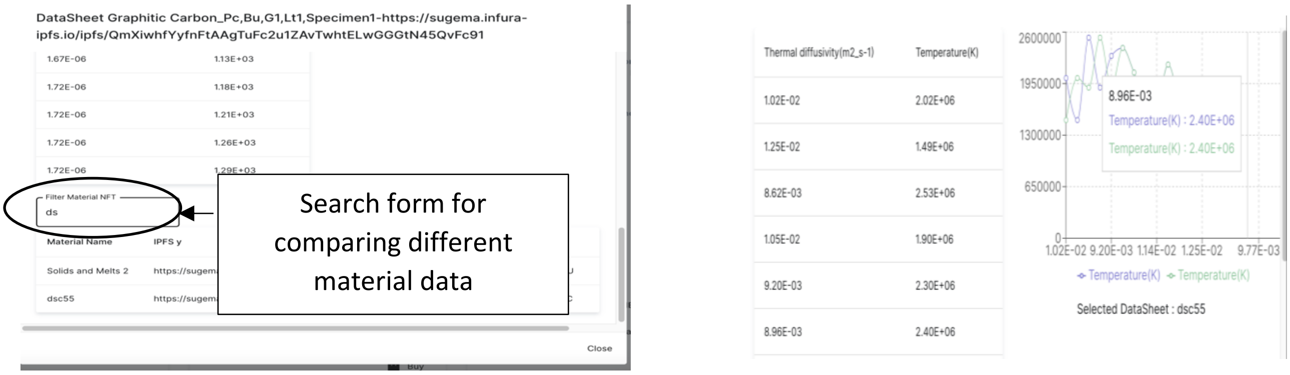

Figure 6. Data comparison tool for different materials data

4. Conclusion

This study implemented a combination of blockchain technology, NFTs, and IPFS on Web3 for achieving the proposed materials data management system to enhance security, reliability, traceability, and trustworthiness through decentralization. The Polygon blockchain network facilitated efficient transaction processing and rapid materials data comparison, primarily due to its scalability and compatibility with the Ethereum ecosystem. We emphasized the importance of NFTs in uniquely representing materials data, ensuring authenticity, and preventing counterfeiting. Web3 was leveraged to improve the website's UI by embracing decentralization, user data ownership, and cryptocurrency integration, thereby enabling a more transparent and user-centric platform for materials data management. IPFS served as the decentralized data storage solution, bolstering data availability and resilience. Crypto wallets were employed to manage user identities, strengthen security, and ensure accountability, providing a robust mechanism for access control and data ownership. NFTs on the blockchain and data on IPFS collaborated to record transaction histories, enhancing traceability and transparency in data sharing. Storing materials data on IPFS ensured timely and reliable data access and retrieval, contributing to system reliability and operational efficiency. Furthermore, introducing the capability to compare different materials datasets via Web3 empowered materials scientists and researchers to make informed decisions based on reliable data. The results of this study demonstrate the adaptability of blockchain-based solutions to materials science and related fields, potentially ushering in a new era of secure, transparent, and efficient materials data management. Future investigations will explore the legal and ethical implications of utilizing blockchain technology and NFTs for materials data management and enhance the UI to provide an increasingly efficient and user-friendly experience.

5. Declarations

5.1. Author Contributions

Conceptualization: I.G.A.K.W., Y.Y., and N.O.; Methodology: Y.Y., and N.O.; Software: I.G.A.K.W.; Validation: I.G.A.K.W., Y.Y., and N.O.; Formal Analysis: I.G.A.K.W., Y.Y., and N.O.; Investigation: I.G.A.K.W.; Resources: Y.Y.; Data Curation: Y.Y., and N.O.; Writing Original Draft Preparation: I.G.A.K.W., Y.Y., and N.O.; Writing Review and Editing: Y.Y., I.G.A.K.W., and N.O.; Visualization: I.G.A.K.W. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Institutional Review Board Statement

Not applicable.

5.5. Informed Consent Statement

Not applicable.

5.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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