

## **CARB-CHAIN: BLOCKCHAIN-BASED CARBON NFT FOR PLANTATION ASSETS**

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### **Abstract**

This research endeavours to construct a blockchain-based carbon record-keeping system wherein non-fungible tokens (NFTs) are employed as digital assets to elevate transparency and accountability in carbon emissions documentation within the palm oil plantation industry. Leveraging the Solana blockchain, the framework converts carbon datasets into immutable NFTs, thereby preserving the authenticity and provenance of the information. Methodological procedures comprise a comprehensive literature survey, rigorous system analysis, detailed design, iterative implementation, and a multi-layered testing regimen encompassing black box, application programming interface (API), and token validation assessments. Outcomes indicate the framework's proficiency in reliably logging carbon metrics, facilitating the NFT minting procedure, anchoring carbon datasets to both the blockchain and the interplanetary file system (IPFS), and interoperating effortlessly with the Phantom Wallet and analogous digital wallets. Furthermore, the architecture maintains efficient component intercommunication and ensures the cryptographic integrity of the recorded carbon information. Collectively, the proposed system is anticipated to substantially streamline the logging and auditing of carbon emissions within the plantation sector, while concurrently equipping stakeholders to navigate the evolving carbon trading regulatory landscape in Indonesia.

Keywords: Blockchain, Carbon data, NFT, Palm oil plantation, Solana.

## 1. Introduction

The global warming, caused by greenhouse gas emissions, represents a serious threat to global ecosystems, characterized by rising temperatures, ocean acidification, and extreme weather. Over the last century, the Earth's average surface temperature has increased significantly. The emissions, which are largely from the combustion of fossil fuels and deforestation, require urgent and effective mitigation strategies [1]. Governments and green businesses are actively working to minimize their carbon footprints through replanting in several places, including Indonesia, and there is a growing trend toward digital carbon trading methods [2].

Carbon emissions frequently rise in line with economic expansion, especially in developing countries like Indonesia, emphasizing the commitment to global greenhouse gas reduction targets [3]. However, present carbon emission documentation frequently relies on third parties, posing hazards of data inaccuracy and lack of transparency. Such mistakes not only inhibit good environmental management, but they may additionally decrease a company's sustainability value [4]. A significant concern is the carbon emission logging accuracy, fairness, integrity, and security, as the use of middlemen can result in the misuse of data and breaches of information [5]. Therefore, there is a need for automated and reliable systems to enhance the integrity and trustworthiness of carbon emission recording.

The use of blockchain technology offers a significant opportunity to reduce the risks of data manipulation in information systems. Its use of a decentralized architecture where data is encrypted reduces the risk of extrinsic interference, as only authorized users can alter transaction records [6, 7]. At the same time, the application of consensus algorithms as a prerequisite for transaction inscription ensures that the network validates each transaction, thus creating a timeless, unchangeable, and universally accessible chain of blocks that can be tested for authenticity [8, 9].

Within this context, smart contracts function as algorithms that automatically implement delegated actions, thus removing the need for agents and improving the efficiency of the transactions while protecting compliance with the terms of the contracts through automated logic [10]. Therefore, merging advanced blockchain technology with well-designed legal policies is essential for enhanced long-enabled carbon footprint registers that are protected against double counting and other fraud, thus improving data integrity and increasing the reliance of the stakeholders [11]. The development of blockchain services in the fields of finance, digital assets, and trading forms the basis for the development of blockchain systems used in the distributed, secure, and reliable management of digital assets [12, 13].

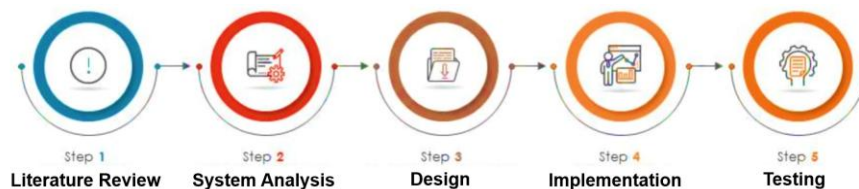
NFTs mark an evolution in digital commerce by shifting the paradigms of ownership and provenance associated with digital assets. Unlike traditional cryptocurrencies, the uniqueness of each NFT means it cannot be condensed, recirculated, or fractionally subdivided [14]. This has created space for widespread adoption, with major companies offering proprietary digital content in NFT format. Thus, it has acquired greater functional autonomy—attaining the ability to accommodate a wider range of tokenized objects, including digital artworks [15], audio files [16], and game assets [17], while providing verifiable and tamper-proof indices of ownership. Recent research suggests that the expanding NFT segment not only acts as a catalyst for inventive activity in artistic and financial fields but also extends feasible peripheral digital applications [18].

The combined use of distributed-ledger technology and NFTs potentially offers an advanced structure for a carbon-trading marketplace that seeks improved transparency, streamlined operations, and dependable counterparty trust [19, 20]. As a distributed ledger protocol, Solana shows promise for the pilot use of digital emissions certificates due to its high transaction speed and low cost per transaction [21]. Existing digital objects, including cryptocurrencies and NFTs, have cumulatively simplified the modern financial system and facilitated the measurement and transfer of value. Moreover, these digital objects ensure the immutability and transparency of transaction records which solves the responsibility and ownership validation problems of the conventional systems [22, 23].

This research aims to design a carbon trading system based on blockchain technology for carbon stock assets derived from tree plantation projects with the assets represented digitally as NFTs. The system seeks to improve transparency and accountability by embedding the carbon emission tracks to a verifiable and immutable ledger, overcoming the pervasive information asymmetries.

## 2. Method

This research focused on the development of a carbon trading system on the blockchain that integrates NFTs with plantation assets. The work proceeded with a comprehensive literature review, system analysis, design, an implementation, and a complete testing suite. Figure 1 illustrates the research process.



**Fig. 1. Research methodology.**

**Literature Review:** In this phase, I examined the existing literature pertaining to blockchain technology, NFTs, carbon trading systems, and their applications within the environmental and agricultural sectors. This was aimed at understanding new trends, identifying gaps within the existing plantation carbon emission recording systems, and acquiring valuable information for system design.

**System Analysis:** The literature review was accompanied by an analysis of the issues, user requirements, and the existing procedures for recording carbon emissions. During this phase, the proposal for the system based on blockchain technology, including the functional and non-functional requirements, data flow, users, and the system interfaces, was mostly outlined.

**Design:** The system architecture was developed during this phase. It comprised design on smart contracts for the mint, management and transfer of NFTs, representing carbon credits, and the database schema for the pertinent carbon data. Also, the interfacing blockchain: Solana, wallets like Phantom Wallet, and APIs for intersystem interactions were substantial.

Implementation: Based on the detailed design, the system was developed. This involved coding the frontend interface, backend logic, and deploying the smart contracts on the Solana blockchain. Specific attention was given to ensuring that the carbon data could be accurately recorded and subsequently tokenized into NFTs.

Testing: The system underwent thorough testing to validate its integrity, performance, and security, and to confirm that all functions are working properly and aligned with requirements. This testing phase is divided into 4 categories:

- (i) Black Box Testing: No prior examination of the code structure is needed as the tester draws up an assessment based on interactions with the system.
- (ii) API Testing: Implemented to confirm all system components are communicating and exchanging data properly, including the frontend, backend, and blockchain components.
- (iii) Token Testing: Focuses on the whole NFT minting life cycle, ensuring the conversion and creation processes as well as the subsequent management of carbon NFTs on the blockchain are functioning as intended.

### 3. Results and Discussion

Based on the main objective of this research to improve transparency and accountability in carbon emission recording in the palm oil plantation sector through the use of blockchain and NFTs as digital assets, an integrated system architecture has been designed. This proposed architecture systematically describes the interactions between various key components and workflows that enable secure and transparent carbon data recording, tokenization, and management. To provide a clear visual understanding of the structure and functions of this system, the architecture details are presented in Fig. 2 Blockchain-based carbon recording system architecture utilizing NFTs.

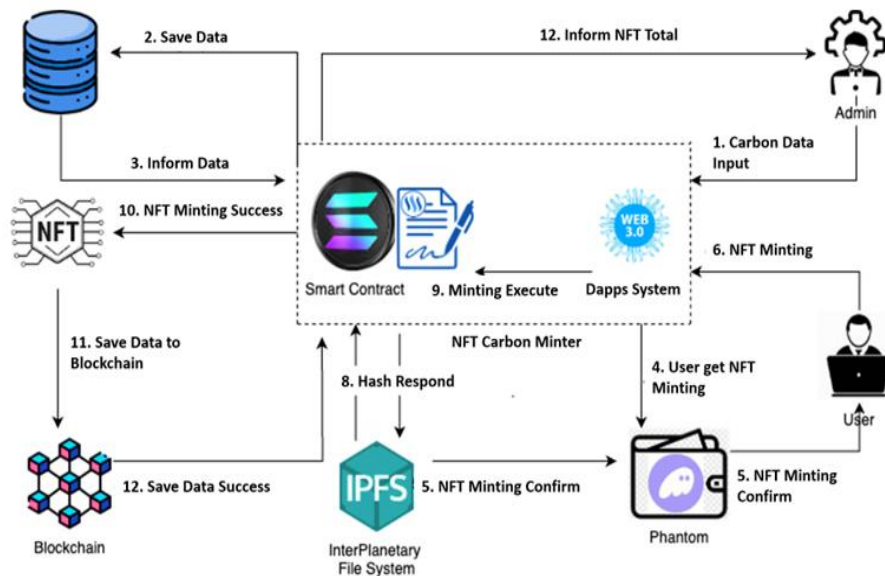


Fig. 2. System design of blockchain-based carbon recording system.

### 3.1. Palm oil carbon stock formulation

In order to have accurate estimations, plant biomass, soil carbon reserves, and emissions associated with production and processing activities need to be carefully tracked. In a carbon management context, the recording and the representation of carbon data on blockchain technology in the form of NFTs enhances transparency and trust [24]. The evaluation of stored carbon and CO<sub>2</sub> offset on oil palm plantations, as well as plant and understory biomass measurements, are the primary methods to quantify carbon [25]. The following are the equations related to palm oil carbon stock calculation:

#### 3.1.1. Biomass measurement

The Eq. (1) is used to measure the above-ground biomass ( $B_{ap}$ ) of oil palm plants:

$$B_{ap} = 0.0706 + 0.0976H \quad (1)$$

Where:

- (i)  $B_{ap}$  = Above-ground biomass (Ton/Tree)
- (ii)  $H$  = Oil palm plant height (meters)

#### 3.1.2. Calculating undergrowth biomass

The total dry weight of undergrowth is calculated using the Eq. (2):

$$\text{Total DW} = \frac{DW_{\text{subsample}}}{WW_{\text{subsample}}} \times \text{Total WW} \quad (2)$$

Where:

- (i) Total DW = Total Dry Weight of undergrowth
- (ii)  $DW_{\text{subsample}}$  = Dry weight of the subsample (grams)
- (iii)  $WW_{\text{subsample}}$  = Wet weight of the subsample (grams)
- (iv) Total WW = Total wet weight of undergrowth per hectare (grams)

#### 3.1.3. Calculation of potential stored carbon

The carbon reserve ( $C$ ) is calculated by multiplying the total biomass by a conversion factor of 46% (0.46) in Eq. (3):

$$C = (B_{ap} + B_{tb}) \times 0.46 \quad (3)$$

Where:

- (i)  $C$  = Potential stored carbon (Ton C/Ha)
- (ii)  $B_{ap}$  = Oil palm plant biomass (Ton/Ha)
- (iii)  $B_{tb}$  = Undergrowth biomass (Ton/Ha)

#### 3.1.4. Calculation of CO<sub>2</sub> absorption

CO<sub>2</sub> absorption is calculated by converting the potential stored carbon ( $C$ ) using a conversion ratio of 3.67 like in Eq. (4):

$$CO_2 = C \times 3.67 \quad (4)$$

Where:

- (i) CO<sub>2</sub> = Carbon dioxide absorption (Ton CO<sub>2</sub>/Ha/Year)
- (ii)  $C$  = Potential stored carbon (Ton C/Ha)
- (iii) 3.67 = Conversion ratio from carbon (C) to carbon dioxide (CO<sub>2</sub>)

### 3.2. NFT design

NFT is a unique digital asset verified using blockchain technology. Unlike cryptocurrencies such as Bitcoin or Ethereum, which are fungible (can be exchanged for the same value), NFTs have unique characteristics that cannot be directly exchanged. Each NFT has specific metadata and ownership information recorded on the blockchain, making it an unalterable proof of digital ownership [26].

Figure 3 shows that the minting process on Solana is a process that combines several technologies to convert data into unique digital assets on the blockchain. This process begins with data preparation, where digital assets, such as images, are uploaded to a decentralized storage system like IPFS to ensure the data cannot be altered. After that, metadata is created that describes the NFT, including its name, description, and connection to the digital item.

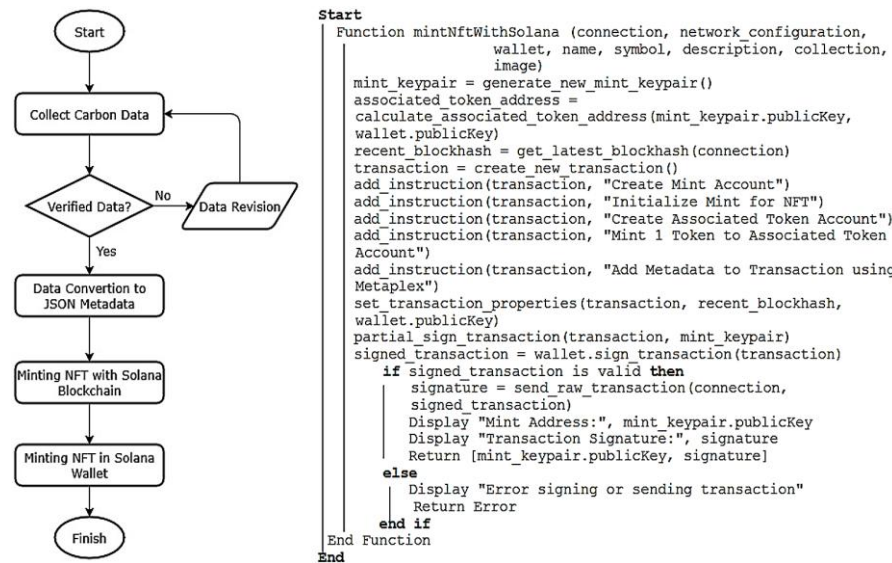


Fig. 3. Carbon NFT minting process on Solana blockchain.

### 3.3. Smart contract design

Smart contracts are digital agreements which can execute transactions automatically [27]. Efficient allocation of resources, cost minimization, enhanced security, independence, and trust optimization among entities are the core objectives of a smart contract [28].

Smart contracts on Solana are called programs and have been created with the capability to operate autonomously within the Solana blockchain. They must adhere to particular logic for certain conditions. Solana programs respond to particular events, which include transactions or user commands. In the developed system, there are two phases of smart contracts, as depicted in Fig. 4, which are intended to automatically validate, capture, and encode carbon data into distinct NFTs. The process begins when carbon data input by the admin is verified to ensure its validity. Once the data is validated, the smart contract uploads it to the IPFS, a distributed storage system, to ensure that the data cannot be altered.

```

Algorithm 1: Smart contract logic
Start
Function Input_Carbon_Data()
if Data_Input == Valid then
    Store_File_in_IPFS()
else
    Return "Input data is not valid"
end
end
Function Store_File_in_IPFS()
if File_Stored == True then
    Execute_Blockchain_Transaction()
else
    Return "File storage failed"
end
end
Function Execute_Blockchain_Transaction()
if User_Confirms_Transaction
== True then if
Transaction_Confirmed ==
True then
    Return "Data successfully stored in blockchain"
else
    Return "Transaction failed to confirm"
end
else
    Return "Transaction not confirmed by user"
end
end
end

Algorithm 2: Smart contract validated Carbon NFT
Start
Function Input_Carbon_Data()
Input_Carbon_Data
End Function
Function Validate(Carbon_Data)
if Carbon_Data is valid then
    Return True
else
    Return False
end if
if Validate(Carbon_Data) == True then
    Function SaveFile_IPFS(Carbon_Data)
    Save_Carbon_Data to IPFS
End Function
if SuccessfullySaved_IPFS() == True then
    Function SaveData_NFT(Carbon_Data)
    Save_Carbon_Data as NFT using Smart Contract
End Function
else
    Display "Failed to save file to IPFS"
end if
else if
    Display "Carbon data is not valid"
end if
end
end
    
```

Fig. 4. Smart contract design of blockchain-based carbon recording system.

### 3.4. Data management design

This system utilizes a hybrid data management design that integrates off-chain and on-chain storage to optimize performance, transparency, and security. Table 1 shows that data in the developed system is stored in two storage mechanisms, namely off-chain storage and on-chain storage. Off-chain storage is used to store data outside the blockchain network [29]. Every piece of data uploaded to IPFS generates a unique content identifier (CID) that can be embedded in NFT metadata. On-chain storage, on the other hand, is storage within the blockchain network, making data a permanent, transparent, and traceable collection of blocks/ledgers [30-32]. Data stored on-chain includes carbon data and NFTs, which are in the form of hashes (CIDs).

Table 1. Data management of blockchain-based carbon recording system.

Data	Attribute	Storage
Actor/User	Admin, Farmer (Plantation Business Operator)	Off-Chain
Carbon Recording	Palm oil height, above-ground biomass, wet weight, dry weight, total wet weight of undergrowth, potential stored carbon	Off-Chain
Non-Fungible Token (NFT)	Unique NFT ID, Owner, Ownership History	On-Chain
Blockchain Solana	Publickey, owner, signature, mint address, blockhash, data	On-Chain
Interplanetary file system (IPFS)	Name, size, CID, created	Off-Chain

### 3.5. Implementation and testing

Initial testing was conducted to functionally test the modules within the developed system. Functional testing used the black-box method to test the functionality of the system software and ensure that it operated according to the expected specifications, detected errors, and provided a good user experience [33] (see Table 2). The second test is API testing (Table 3), which has the main function of ensuring that the API works according to its specifications and objectives [34]. The third test is to ensure storage in the blockchain environment, token creation, and NFT storage. The process begins with palm oil farmers minting NFTs through a special interface which automatically stores the relevant data on the Solana blockchain

network. This storage is crucial because it guarantees the security, decentralization, and transparency of carbon data. Once the data is stored, users can verify it in real-time using Solscan to view transaction information and data status (see Fig. 5).

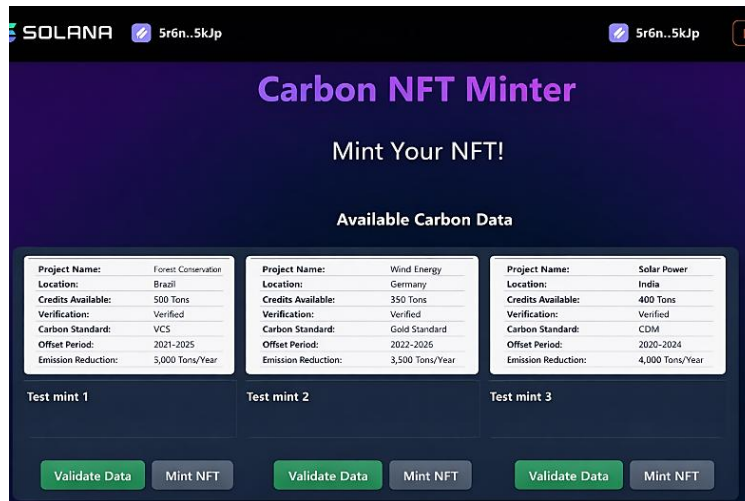
**Table 2. Blackbox testing of blockchain-based carbon recording system.**

Test Component	Test Point	Test Result
Carbon Data Management	Carbon data successfully managed (add, edit, delete)	Accepted
Blockchain Wallet Connection	Blockchain wallet successfully connected	Accepted
Carbon Data Page	Carbon data page successfully displayed	Accepted
NFT Minting	NFT successfully minted and appears in the wallet	Accepted
Upload Carbon Recording Report	Carbon data successfully uploaded to IPFS and recorded on the Blockchain	Accepted

**Table 3. API's testing of blockchain-based carbon recording system.**

Test Scenario	Expected Result
The API should create carbon data	Status: 201 Create
The API should retrieve the carbon data view page	Status: 200 OK
The API should delete carbon data	Status: 200 OK
The API should update carbon data	Status: 200 OK
The API should connect to the wallet and mint the NFT	Status: 200 OK

This analysis involves examining token details such as supply and ownership, as well as transaction analysis to detect potential errors, ensuring that each transfer is properly recorded and the token can be fully verified on the network. Once the token has been properly verified through the smart contract (see Fig. 6), it is converted into an NFT and stored in the user's wallet account as a digital asset they own (see Fig. 7).



**Fig. 5. Data validation and NFT minting on blockchain-based carbon recording system.**

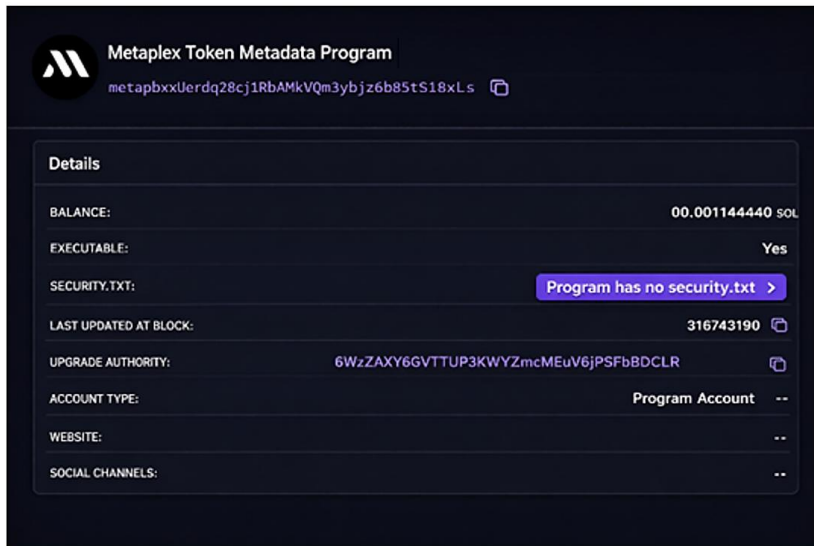


Fig. 6. Token testing.

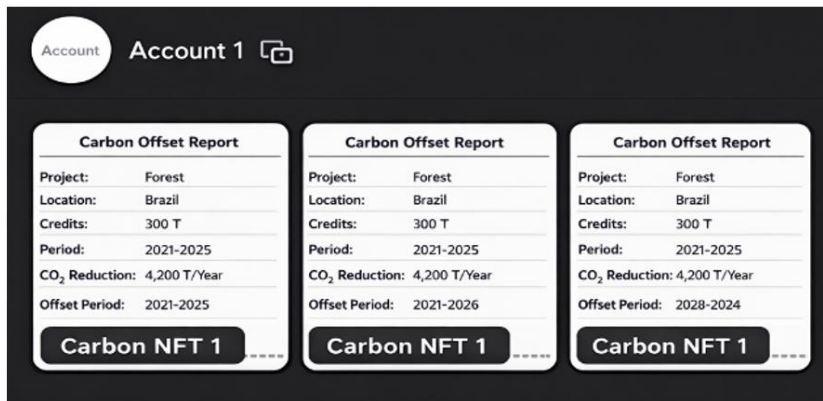


Fig. 7. NFTs store in user wallets.

This study successfully demonstrates that integrating blockchain and NFTs can drastically enhance transparency and accountability within the palm oil sector. These findings align with global shifts toward utilizing decentralized ledgers to solve the chronic inefficiencies and opacity prevalent in traditional carbon markets [35]. By adopting a hybrid architecture that offloads heavy data to IPFS while retaining core records on Solana, we effectively bypassed the scalability hurdles that typically stymie public blockchain adoption [36]. Furthermore, the implementation confirms that smart contracts can reliably automate the NFT validation and minting process, transforming raw carbon metrics into immutable digital assets a conclusion mirrored by research highlighting verification automation as a driver for market efficiency [37]. While this research provides a vital case study for the agricultural sector (diverging from the usual focus on energy), it also highlights the non-technical barriers specifically cost and technical learning curves that continue to challenge widespread adoption [38].

#### 4. Conclusion

This study successfully demonstrates a blockchain-driven framework for carbon tracking, using NFTs to instill transparency and accountability in the palm oil sector. By anchoring real-time plantation data to the high-speed, low-cost Solana network, the research introduces a scalable architecture capable of overcoming traditional blockchain storage constraints. The integration of custom smart contracts ensures carbon data is not only validated but converted into immutable, tamper-proof digital certificates. Given Indonesia's tightening carbon regulations, this system offers a timely foundation for farmers and enterprises to enter emerging carbon markets. While this research focuses primarily on the minting process rather than a complete trading environment, it paves the way for future modules centred on tokenized carbon exchange and broader agricultural asset tracking.

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