sustainability

Article

Enhancing Sustainability in Food Supply Chain: A Blockchain-Based Sustainability Information Management and Reporting System

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Abstract

Global concern over the sustainability impacts of food products has grown considerably in recent years, driven by heightened awareness of environmental issues and the rising demand for sustainably produced foods. In response, industries are increasingly offering sustainable product options and utilizing ecolabels to communicate environmental and social impacts. While product labelling has become one of the most widely adopted tools for conveying sustainability information, existing ecolabeling approaches often face challenges of trust, transparency, and consistency. Current ecolabels are typically issued by supply-chain stakeholders or independent third-party certifiers; however, limitations in accountability and verification hinder consumer confidence. To address these challenges, this study proposes a Blockchain-based Sustainability Information Management and Reporting (BSIMR) model that integrates blockchain technology with sustainability indicators. The framework is designed to provide a standardized, transparent, and reliable approach for managing and verifying sustainability claims across food supply chains. By enhancing traceability, accountability, and consistency in sustainability auditing, the BSIMR model aims to empower consumers with trustworthy information and support industries in meeting sustainability commitments. The feasibility and applicability of the proposed framework are demonstrated through a proof-of-concept case study on sustainability information management in the rice supply chain.

Keywords: blockchain; ecolabels; grain supply chain; supply-chain management; sustainable development; sustainability information management

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1. Introduction

Sustainable development has increasingly become a defining theme across multiple domains of society. Within this context, sustainability assessment has evolved beyond conventional research, emphasizing the integration of scientific evidence with public decision-making. Such assessments are commonly framed through the Triple Bottom Line (TBL): environmental, economic, and social dimensions. The United Nations' 2030 Agenda for Sustainable Development outlines 17 Sustainable Development Goals (SDGs), many of which, including zero hunger, good health and well-being, clean water and sanitation, responsible production and consumption, climate action, life below water, and life on land, are directly linked to the food supply chain (FSC) [1]. Ensuring sustainability in FSC is therefore essential for the achievement of these SDGs.

Food production exerts the most substantial environmental impact within an FSC, primarily attributed to intensive farming practices utilizing machinery and chemical fertilizers to increase productivity [2]. At the same time, food production contributes to economic and social sustainability, particularly in developing countries where large portions of the population are employed directly or indirectly in farming [3]. However, the FSC is inherently complex, involving dynamic interactions between diverse local and global actors. These networks are characterized by shifting partnerships, multifaceted relationships, and evolving consumer expectations. Increasingly, consumers demand transparency regarding environmental, social, and ethical impacts, with sustainability concerns shaping their purchasing preferences [4]. However, assessing and communicating sustainability information across such a fragmented system remains a major challenge.

Various tools have been developed to determine sustainability value, encompassing economic tools such as cost–benefit analysis and life cycle costing, environmental tools, including life cycle analysis (LCA), emergy analysis, material flow analysis, and ecological footprint, indicators and composite indices [5]. Among these, indicators and composite indices are often favoured for their simplicity and practicality [6]. For instance, the Food and Agriculture Organization (FAO) has devised and validated a universal sustainability assessment framework known as the Sustainability Assessment of Food and Agriculture Systems (SAFA), which can be tailored to individual enterprises and expanded to encompass the different supply-chain level [7].

Sustainability in the FSC can be pursued in two primary ways: (i) compelling companies to exclusively offer sustainably produced goods and (ii) raising consumer awareness to encourage the purchase of sustainable products [8]. The latter approach is particularly influential, as consumer demand for eco-friendly goods incentivizes businesses to innovate and reduce their environmental and social footprints [9]. However, for this mechanism to succeed, consumers require accessible, credible, and comparable sustainability information.

Establishing a sustainable food system poses a multifaceted challenge, contingent upon the effective functioning of numerous interconnected elements within FSC management and policies. The bifurcated system of food system governance, comprising predominantly corporate-led private governance and government-led public governance, plays a pivotal role in shaping food systems [10]. Recognizing the contextual agency and understanding the interactions among diverse actors assuming different roles is equally essential [11].

The increasing complexity of global food supply chains has led to the emergence of a new range of risks and concerns regarding food safety. These encompass long-standing issues related to biological and chemical contamination [12]. Moreover, in 2013, adulteration and food fraud resurfaced significant concerns, highlighted by the horsemeat scandal. Extensive media coverage of this scandal unveiled widespread fraud, revealing the previously underestimated intricacies of the UK meat supply chain and the extent of meat imports [13]. Climate change presents yet another array of challenges to the food system, jeopardizing the ability to ensure a safe, sustainable, and equitable food supply amidst widening inequalities and escalating levels of food poverty and food security [14]. Given these myriad challenges, food sustainability must receive heightened policy priority and science and technology based intervention [15].

Food systems fulfil various roles for different stakeholders, each having distinct perceptions of the desirable outcomes of the food system. From a public standpoint, government regulations should establish well-defined and quantifiable social objectives, establish benchmarks for sustainable performance, specify transition periods for achieving standards, and implement universal performance monitoring systems [13,16]. A transparent system is essential for evaluating sustainability across the entire supply chain. It is imperative that the system is secure and tamper-proof, allowing each partner in the supply chain to trust the data and verify sustainability indicators at every stage of the product's life cycle. However, within a supply-chain environment where trading partners are constantly changing, communication model denotes agreements among supply-chain partners. These agreements need to be built upon a fundamental communication layer that extends the chain approach to the entire supply-chain environment.

In recent years, blockchain technology has been recognized as a potential game-changer for food supply chains. Its ability to provide traceability, reliability, and tamper-proof data in a trustless environment offers new opportunities to overcome the challenges of FSC sustainability [17]. Blockchain technology holds the promise of fostering social, environmental, and economic sustainability within the supply chain [18]. The promising attributes of blockchain technology could serve as a remedy for the complexity inherent in the food supply-chain sustainability information system. This study presents a novel blockchain-enabled sustainability information management system that uniquely combines sustainability indicators, streamlined index calculation, and a tamper-proof blockchain database. This system ensures transparency, reliability, accountability, and non-repudiation in sustainability reporting. Its distinct value is further illustrated through a proof-of-concept application, demonstrating both practicality and robustness in real-world contexts.

2. Literature Review

Ecolabelling is designed to inform consumers about a product's environmental performance, and plays two central roles: certifying environmental attributes and enabling consumers to make informed sustainable choices [19]. However, most ecolabels adopt a single-dimensional focus under the Triple Bottom Line (TBL), overlooking the holistic integration of environmental, social, and economic dimensions [20]. Moreover, current ecolabelling systems face challenges as they are often managed either by a central supply-chain partner or third-party auditors, leading to issues of data availability and accountability [21]. This leads to horizontal transparency, limited to single actors, rather than vertical transparency across supply chains.

Blockchain addresses some of these gaps by providing traceable, transparent, and trustworthy data sourcing processes. Tse et al. [22] proposed decentralized authentication models for food safety auditing, while Čapla et al. [23] demonstrated blockchain's role in real-time carbon footprint tracking, thereby enhancing ecolabel accuracy. The primary benefit of blockchain-enabled ecolabelling lies in enhancing consumer trust due to its data immutability features. Stach et al. [24] and Abeyratne and Monfared [25] stressed that verifiable certification improves consumer confidence, while Wu et al. [26] highlighted blockchain's ability to curb greenwashing through immutable ESG reporting. Empirical evidence supports these claims: a study on sustainable denim products found that blockchain-certified eco-labels increase consumer trust and willingness to pay, demonstrating tangible impacts on sustainable consumption patterns [27].

Beyond food and apparel, blockchain also supports life-cycle tracking for recyclability and reuse [28], enables logistics carbon offset accounting [29], and allows the creation of smart ecolabels in the industry [30]. These innovations transform ecolabels from static indicators into dynamic, data-rich sustainability credentials embedded within supply chains.

Despite this progress, most blockchain ecolabelling models remain focused on single sustainability dimensions (e.g., environment [31] or certification [32]). Ecolabelling must adopt vertically integrated, multidimensional frameworks that combine environmental, social, and economic information. Only then can ecolabels serve as effective tools for reducing greenwashing, building consumer trust, and advancing the circular economy.

3. Materials and Methods

The proposed sustainability information system based on blockchain technology consists of three primary stakeholders: supply-chain partners, governing body and regulatory authority (Figure 1). These stakeholders are interconnected to establish a transparent, reliable, adaptable, and trustworthy system for managing sustainability information.

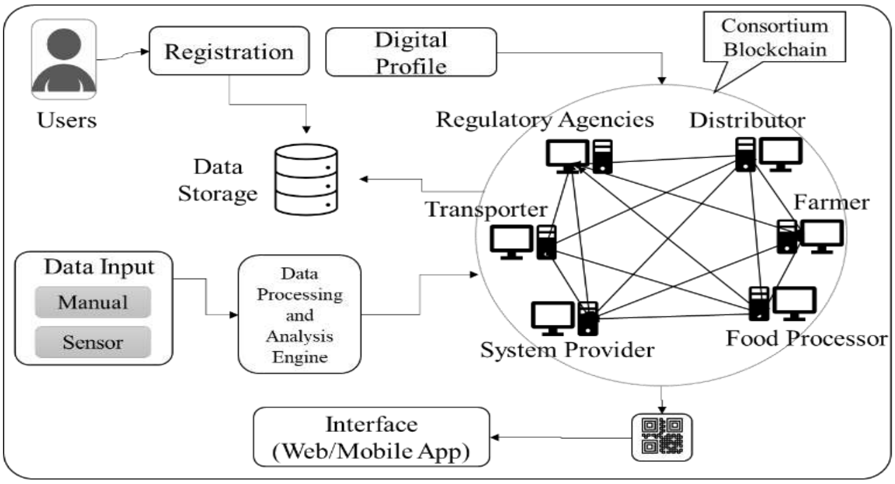

Figure 1. BSIMR architecture.

3.1. Supply-Chain Partner and Technology Provider

The food supply chain encompasses various supply-chain partners, some of whom may be partially or entirely interconnected. In a partially connected supply chain, all stakeholders are linked, but there may be inconsistencies in data flow due to insufficient communication and infrastructure. Consequently, assessing the sustainability score of a product becomes difficult, as it relies on input from all supply-chain partners in providing essential sustainability indicators data. In such partially connected food supply chains, a leading partner typically oversees communication with other stakeholders to collect sustainability indicators data. However, this centralized approach can result in a system that lacks transparency, is perceived as manipulative, and is deemed untrustworthy.

There is a need for transparency in the transmission of supply-chain data and decentralization, achieved by consolidating all supply-chain partners into a consortium where each partner retains responsibility for their data. This approach would facilitate smoother and faster transfer of data along the supply chain. However, supply-chain partners also require assurance that their data is secure and that their privacy is maintained. If all data is shared with every partner in the supply chain, it could pose challenges in terms of maintaining a competitive advantage. Consequently, partners may hesitate to provide the necessary data for sustainability labelling. Hence, technology or service providers must prioritize data privacy while ensuring that the required data is collected from supply-chain partners and feed into the analysis engine to determine the sustainability index.

3.2. Governing Body

The governing body of the proposed system is responsible for developing sustainability scoring criteria, selecting indicators, and assigning responsibilities to supply-chain stakeholders. It will also oversee granting network access based on read and write permissions. There are two categories of stakeholders: direct stakeholders with full read and write access, responsible for providing essential indicators data to determine product sustainability, and indirect stakeholders with read-only access for auditing, data validation and sharing data to third parties via application programming interface (API).

The governing body is responsible for formulating, discussing, and agreeing on smart contract algorithms before implementation, and resolving any disputes if they arise. Therefore, the constitution and functional definition of the governing body are critical in designing a sustainability management system. Additionally, the governing body will be responsible for the management of the entire system and implementing future amendments as needed.

3.3. Regulatory Authority and Consumer

Government and regulatory authorities supervise auditing of the supply chain and issuance of certificates to ensure compliance with country-specific regulations. This plays an important role in the sustainability benchmark, which varies across countries. For example, regulations governing fertilizer usage and other farming inputs differ across regions, posing challenges in standardizing sustainability assessment. National regulatory authorities and international agencies offer certifications, like ISO certification, for various sustainability parameters in the food supply chain. Therefore, these certification and audit reports can be utilized to analyze and evaluate the sustainability index.

Contrary to regulations that directly involve sustainability labelling, consumers indirectly play a vital role in advancing the labelling initiative. Their demand for sustainable products drives the industry to adopt sustainability labelling. Consumers access sustainability data through product labels, underscoring the importance of ensuring that these labels are easily understandable and consistently designed to provide uniform sustainability information. To bring trust in sustainability labelling, consumers require tamper-proof data and sufficient information. Therefore, it is crucial for the system to enhance reliability in delivering trusted source data to consumers.

4. System Design

The sustainability information management system proposed in this study consists of four layers (Figure 2). The first layer involves data collection and filtration, followed by the application layer. The third layer encompasses blockchain and smart contracts, cloud storage services. Finally, the fourth layer is the interface layer, which consists of a mobile app, web app, blockchain explorer and REST API to easily access the data. The blockchain serves as an underlying framework for sharing information across the supply chain. Each actor of the supply chain functions as a node within the blockchain network.

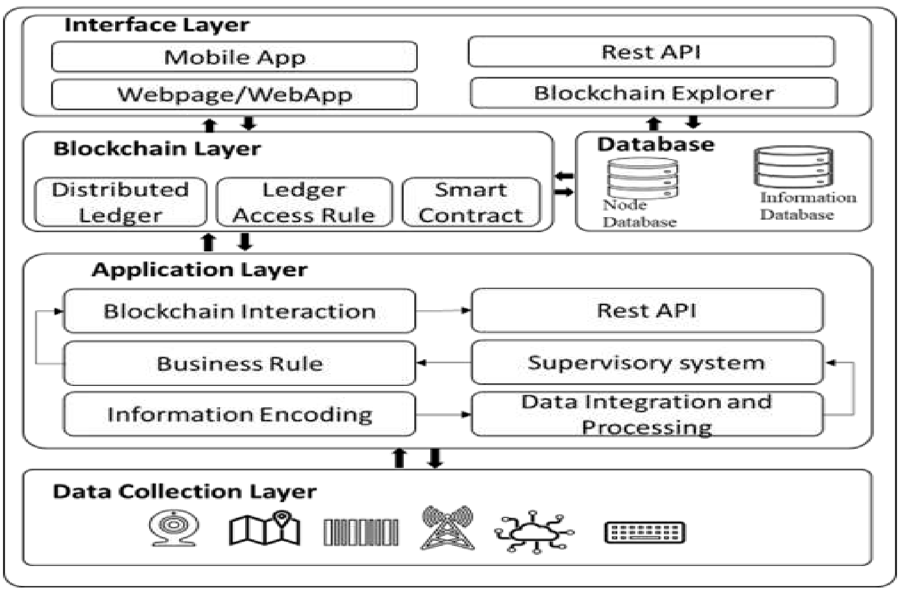

Figure 2. System design.

4.1. Product Coding Design

Products are sourced from different producers and get mixed during the processing, packaging, and transportation processes. prompting the need for coding to differentiate between products originating from different sources. Product coding is crucial for precisely identifying each product at every stage of the supply chain. Additionally, it streamlines the computation of the sustainability index at each stage, contributing to the determination of the final product's comprehensive sustainability index. This study adopts a unique code generation methodology for each batch of data entered into the blockchain.

This identifier will be applied throughout the product's entire life cycle. Creating this unique identification is essential to maintain the product's distinct identity throughout the supply chain, simplifying the computation of its sustainability index. The product ID is linked to the item from its inception through its production phases, and this identifier is logged onto the blockchain. This integration allows for easy monitoring of the product's sustainability score.

4.2. Storage Mechanism

The blockchain system presents a solution to challenges regarding data privacy and management through its utilization of distributed data storage; however, this same feature also introduces concerns related to data redundancy and optimal database usage. The blockchain functions as a decentralized ledger, storing data across all participating network nodes. However, as transaction volumes grow, so does data-storage demand, leading to inefficiencies in data management. To tackle this challenge, this study presents a hybrid storage approach. Important data concerning sustainability indices will be stored within the blockchain in this hybrid setup, while other required data will be exclusively kept on nodes' external databases. To ensure data integrity and minimize potential tampering, a hash of the data stored on nodes will be logged onto the blockchain if required. The critical data retained on the blockchain will cover sustainability indices calculated at various stages, culminating in a comprehensive, integrated sustainability score.

The node database will serve as off-chain data storage for supply-chain partners. The combination of the blockchain and node databases establishes a multi-mode storage mechanism, enhancing data security and management. The blockchain guarantees traceability and immutability of information, while the node database addresses storage capacity limitations inherent in the blockchain. A cloud database could be used for the node, offering benefits such as reduced local resource usage and enabling swift deployment and remote backup of the data.

4.3. Smart Contract

The integration of smart contracts into blockchain technology enhances its practical application by automating business rules through digital contracts. Smart contracts, composed of computer code, reside on the decentralized blockchain network, conducting self-checks and executing transactions autonomously. The main role of smart contracts is to execute different types of transactions within the blockchain.

The proposed system requires a customized coding framework to effectively evaluate the sustainability index of products throughout their journey—from origin to end consumer. This coding scheme enables efficient calculation of the sustainability index by incorporating relevant indicator values at each stage of the supply chain. To ensure seamless integration, smart contracts are employed to automate blockchain transactions, eliminating the need for specialized training among supply-chain partners. These contracts govern three key transaction types: generation of batch IDs, processing of sustainability indicator data, and computation of the overall sustainability index.

Smart contracts embedding the sustainability index calculation algorithm are stored and executed directly on the blockchain and can be deployed across all peer nodes. These contracts not only handle transaction execution but also serve as the backbone of the system by coordinating information flow and enabling real-time calculation of sustainability scores as products move through the supply chain. By automating these calculations according to predefined algorithms, smart contracts provide stakeholders with an objective assessment of the environmental, social, and economic impacts of products, thereby supporting more informed decisions on procurement and distribution.

4.4. Sustainability Indexing

Sustainability indexing begins with the producer and extends up to the retailer (Figure 3). Data from each partner in the supply chain is provided to the smart contract, where analysis is conducted to calculate the necessary sustainability index. The process of generating sustainability data begins at the production site, where data entry occurs through an interactive web application interface. Each supply-chain partner must register on the blockchain platform and create a unique userID and password to create a wallet on the blockchain (Algorithm 1).

Algorithm 1 User Registration. Algorithm at API server side for registration

User Registration:
Input: *User ID, User Role in Supply chain (Farmer(i), Transporter(i + 1), Processor(i + 2), Distributor(i + 3) and retailer (i + 4)), Node Type (User Role in blockchain), organization details.*

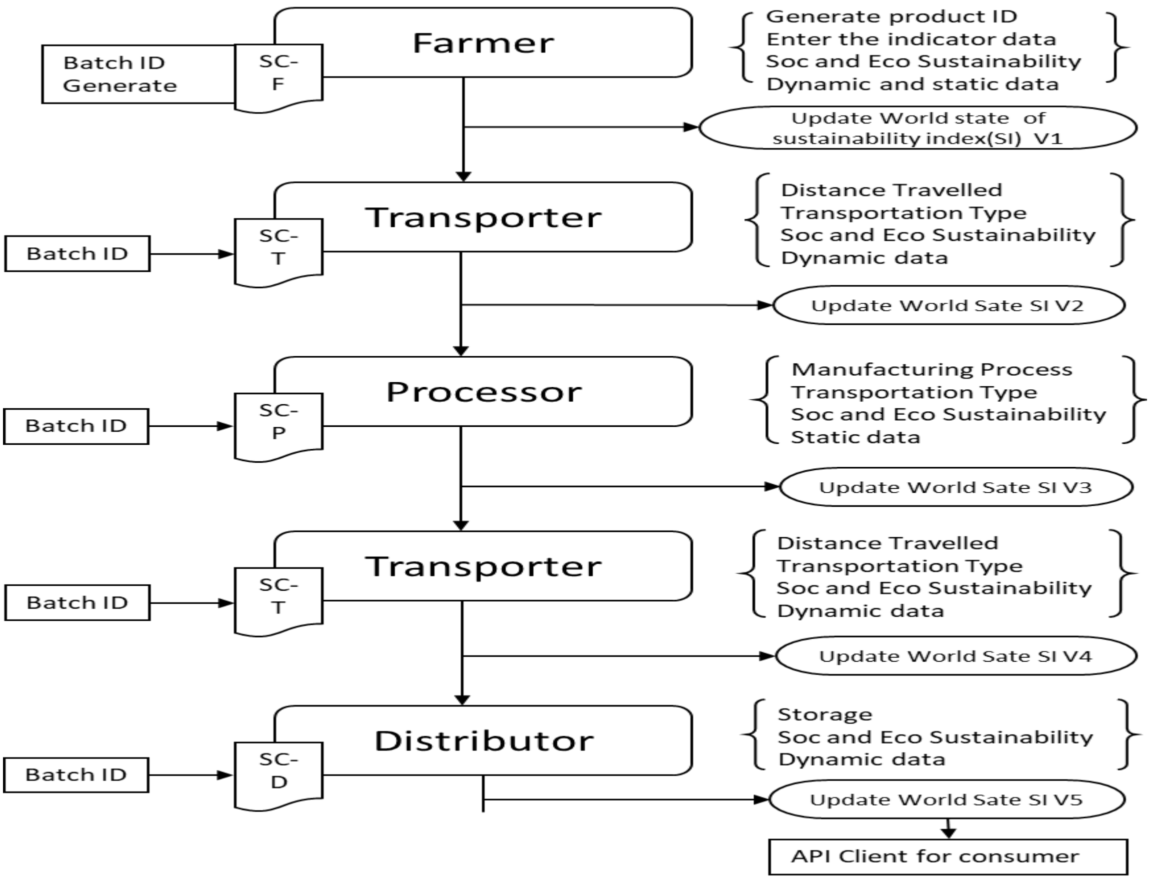

Figure 3. Sustainability indicator indexing process.

A web application acts as the interface for information exchange, enabling data management across the supply chain. Web-based applications and APIs are employed to access the blockchain to facilitate registration process. Supply-chain partners will use the same web application to input and manage their information directly on the blockchain. The product's sustainability indexing commences at the farming or production site, serving as the initial stage for indicator data input. Here, a unique product code, referred to as a batchID, is assigned, which remains consistent throughout the product's life cycle for identification purposes. The product code must be appropriately tagged for tracking.

A transaction is initiated via a smart contract to record the information. The smart contract will autonomously assign and execute transactions to store sustainability information within the blockchain platform. This ensures a streamlined flow of information from the producer to the end-user, facilitated by secure web-based APIs accessible through web applications, thereby enhancing transaction efficiency and speed.

The information is initiated by the producer, who conducts a transaction using the smart contract information upload template to initiate a product sustainability indexing journey into the system. This resulted in the assignment of a unique batchID. Subsequently, as the product progresses to the next stage, it undergoes scanning. If the scanned batchID matches the existing batchID and its last recorded location, the blockchain network is instantiated for the next sustainability indicators data entry.

Figure 3 illustrates the transaction process. After registration in the system, supply-chain partner gets integrated into the blockchain network, with each node having a distinct private key. For uploading the data, the node accesses the system using the registered account details and undergoes verification of the user's rights, i.e., read and write. Following successful verification, the user has the right to write the data, will get permission to upload data. The data is then processed in a standardized format by the data processing module.

The smart contract validates whether the data fulfils the stipulated criteria. Once verified, the data is uploaded to the blockchain network and stored in the blockchain ledger. In the event of a discrepancy during smart contract verification, a block will still be generated; however, a warning will be issued, and the monitoring system will notify relevant enterprises and regulatory authorities for real-time resolution.

5. Proof-of-Concept Design

A proof-of-concept (PoC) sustainability information management and reporting system has been developed for the rice supply chain using the sustainability indicators derived from our previous study [33] to validate the proposed model. The PoC system was built using the Hyperledger Fabric ecosystem, known for its consortium-type blockchain. Leveraging the Hyperledger Fabric software development kit (SDK) v2.2, which includes built-in API features, facilitated seamless integration with external databases and user interfaces (Figure 4). The proposed system adopts a browser/server architecture, with web applications serving as the browser and blockchain-based information management as the server. MongoDB, a NoSQL database, was utilized to store user credentials and non-essential information on the cloud. Development languages employed in the PoC included Typescript, JavaScript, HTML, and CSS, with Node.js facilitating data transmission in JSON format. React frameworks were used to design the web application interface. An integrated web application served as a user interface, interacting with the blockchain via API to provide users with streamlined access to information. This interface allowed user queries using batch IDs and offered a user-friendly platform for information upload and retrieval (Figure 5). The system incorporated sustainability indexing utilizing predefined indicators that were designed as templates on a webpage, aiming to simplify and standardize the sustainability index calculation process (Figure 6).

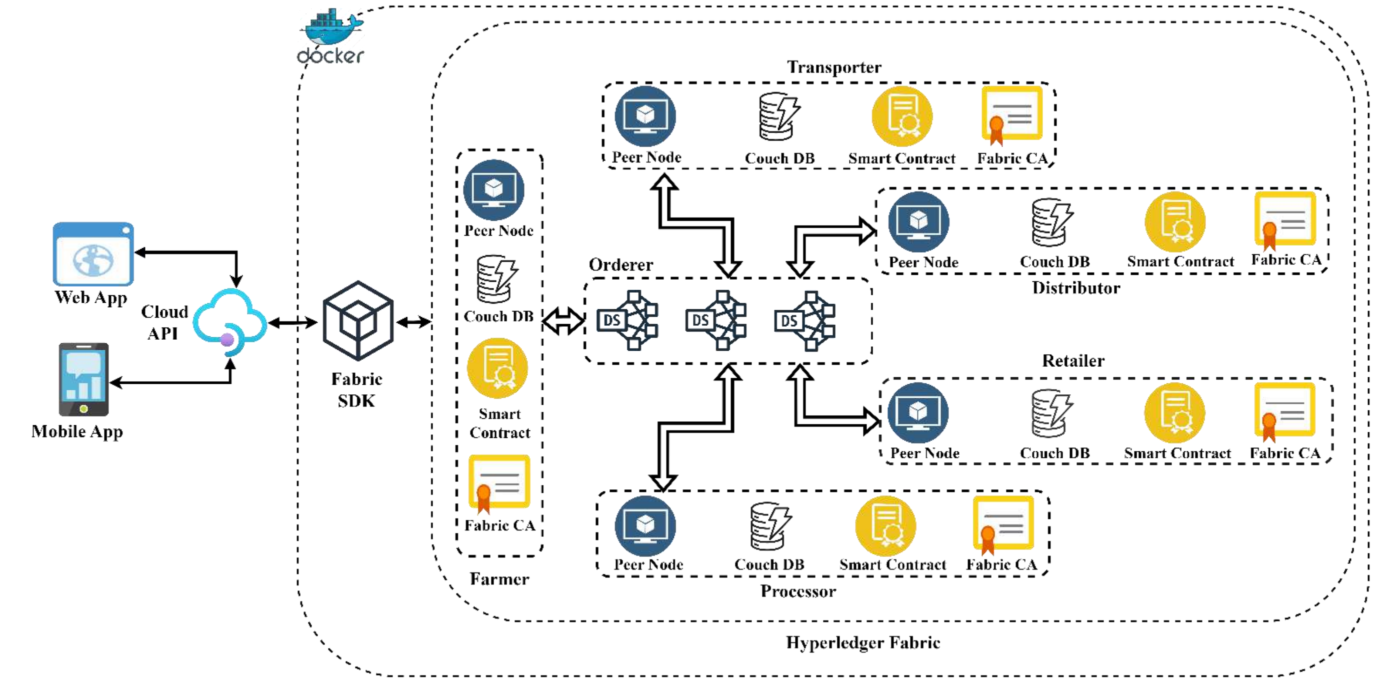

Figure 4. PoC system configuration.

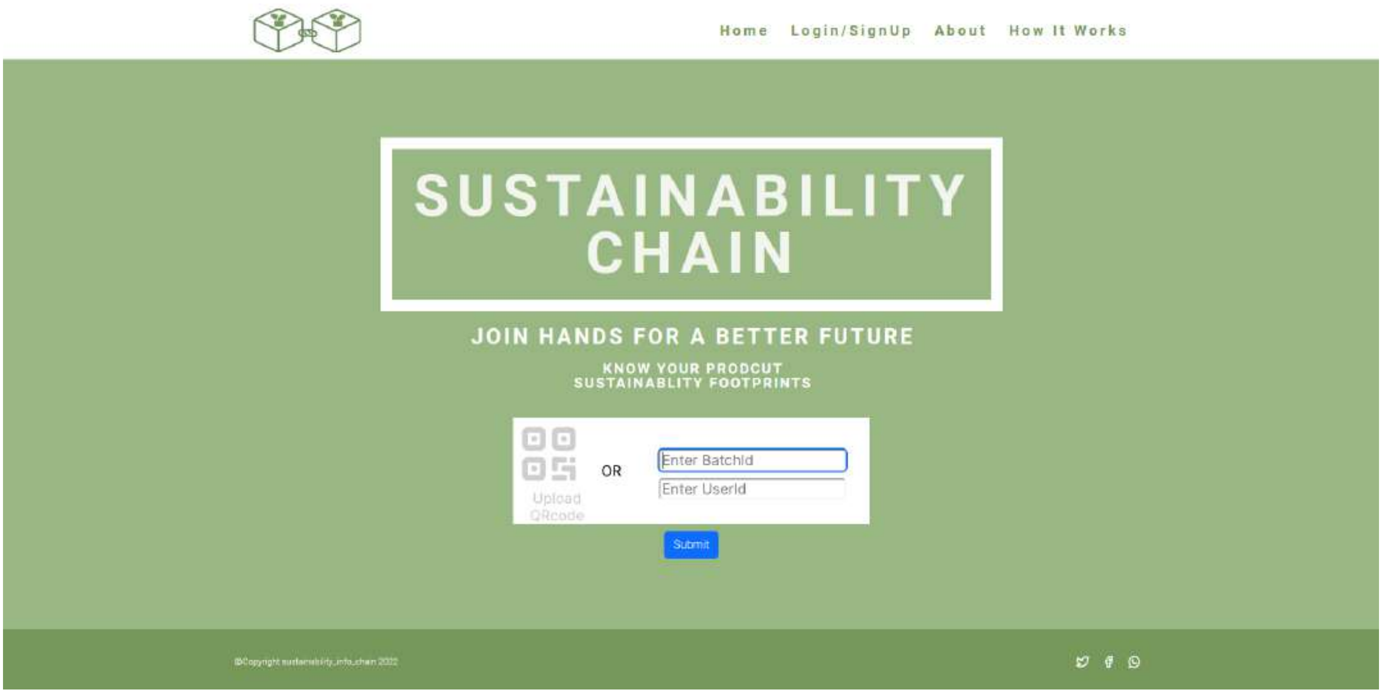

Figure 5. User registration and Login Interface.

The prototype model employed the Hyperledger Fabric blockchain, incorporating five peer nodes and three orderer nodes. Deployment was facilitated through DigitalOcean.com's online cloud platform, with virtual machines (droplets) created to establish the blockchain infrastructure. Docker containers on virtual machines were used to establish the prototype system with five nodes configured on the cloud, each with a CouchDB database and three ordering services to validate the transaction and append the transaction to the blockchain network. These nodes represented distinct entities within the rice supply chain, including farmers, transporters, processors, distributors, and retailers

(Figure 4). Additionally, a MongoDB database was instantiated to store login credentials and signup data.

Figure 6. Sustainability indicators data entry interface.

The explore, an inbuilt feature of the Fabric SDK, provided details of each transaction. Hyperledger Fabric Explorer was initiated to explore sustainability data and block info on the blockchain, facilitating the analysis of blockchain transactions. However, a user-friendly web page was also designed to search for sustainability information from the blockchain using batchId details. Sustainability data for each specific supply-chain partner can also be verified using batchId and userID. The interfaces segment depicted a software as a service (SaaS) stack capable of interfacing with web, tablet, and phone devices, as well as a SaaS API stack with corresponding API and blockchain explorer blocks.

Supply-chain actors are required to register on the blockchain to become members of the sustainability chain and participate in the information management system. All supply-chain actors utilized an interactive webpage interface to update the sustainability data. Figure 6 illustrates the user interface for uploading data into the blockchain to perform the transaction. Smart contracts containing the sustainability index calculation algorithm were deployed and operated on every node within the system. Across all five peer nodes, these smart contracts were hosted, serving as pivotal tools for executing various transactions within the blockchain network. The algorithms for this smart contract are detailed in (Algorithms 2 and 3). This setup ensured decentralized and distributed execution of sustainability information-related transactions, promoting transparency and accountability and reliability. By hosting these contracts on multiple peer nodes, redundancy and fault tolerance were enhanced, ensuring the integrity and availability of sustainability data information management on the blockchain.

Algorithm 2 Smart Contract for information upload and batchID generation. Algorithm for smart contract information upload and batchId generation

```
//Call batch id function to create a batchID
Validate user login

Function batchID {
if User Role in supply chain == 'farmer',
        then
            Create batchID
        else,
              Enter existing batchID
      end,
Return (batchID)
}
//sustainability Scoring smart contract
Function (sustainability score Contract): {
Input: batchId, amount of produce(kg), user role in supply chain

If (! batchID), then
      find last data entered by supply-chain stakeholder (i)
        enter the amount of produce and user role
                     upload sustainability data under environment,
        social and economic
                  update indicators value (i + 1)
                    calculate average index value
                    return indicators value
            else
return this batchID does not exist, create a batchID to initialize the scoring
end
}
```

Algorithm 3 Sustainability information query. Algorithm to query Sustainability Index

```
//Call Query Function
input batchID, local_sustainability_index, user-role [Farmer, Transporter,
processor, Distributor, Retailer]
if (? batchID), then
         // return average sustainability index
          return sustainability index, blocknumber, block hash, data hash
         // return supply-chain-partner-specific sustainability index
        if (local_sustainability_index == userRole[i]) then
        return sustainability index for supply-chain stakeholder
        else
          return no user found
else
          return batchID not found
end
```

The sustainability information management process was initiated by the producer through a transaction executed using the smart contract template (Algorithm 2). After this transaction, the product was assigned a unique product ID, known as batchID, derived using a universally unique identifier (UUID) algorithm. This batchID was utilized throughout the product's life cycle, facilitating successive sustainability score calculations and simplifying traceability and sustainability score queries (Algorithm 2). After batchId generation, the product moved to the sustainability information stage, where each actor of the supply-chain updates sustainability information relevant to their role in the product's life cycle.

Subsequently, the product transitioned to the scanning stage. If the scanned product ID matched the batchID and the last location of the product, the next supply-chain partner entered the respective stage's sustainability indicators data, which were then added to the previous stage's indicator values. For example, the farmer uploaded all required sustainability indicators data and invoked the supply-chain sustainability smart contract (Algorithm 2). An example of sample data entered by Farmer_Alex, an entry in the PoC is presented in Figure 6. Upon data submission, a transaction was completed, followed by block creation reflecting this transaction value. A successful transaction was notified with transactionID, block number, and timestamp (Figure 7). By clicking on transaction details, as depicted in Figure 7, users could access specifics within the block, including sustainability data stored on the blockchain network. The description of the transaction details can be viewed on the Explorer as well (Figure 8). Similarly, five additional transactions updated the sustainability value for each actor involved in the rice supply chain. Following each transaction, except for the batchID creation, the smart contract calculates the arithmetic average of the sustainability indicators data to represent an overall sustainability index of the product. This systematic approach ensured continuous tracking and updating of sustainability-related data, enabling stakeholders to make informed decisions and drive improvements in sustainability practices throughout the product's life cycle. The uploaded data could be accessed externally via an API with the required permission, enabling analysis to improve sustainability performance. Furthermore, the sustainability data could be reported directly to the government for monitoring and regulation purposes.

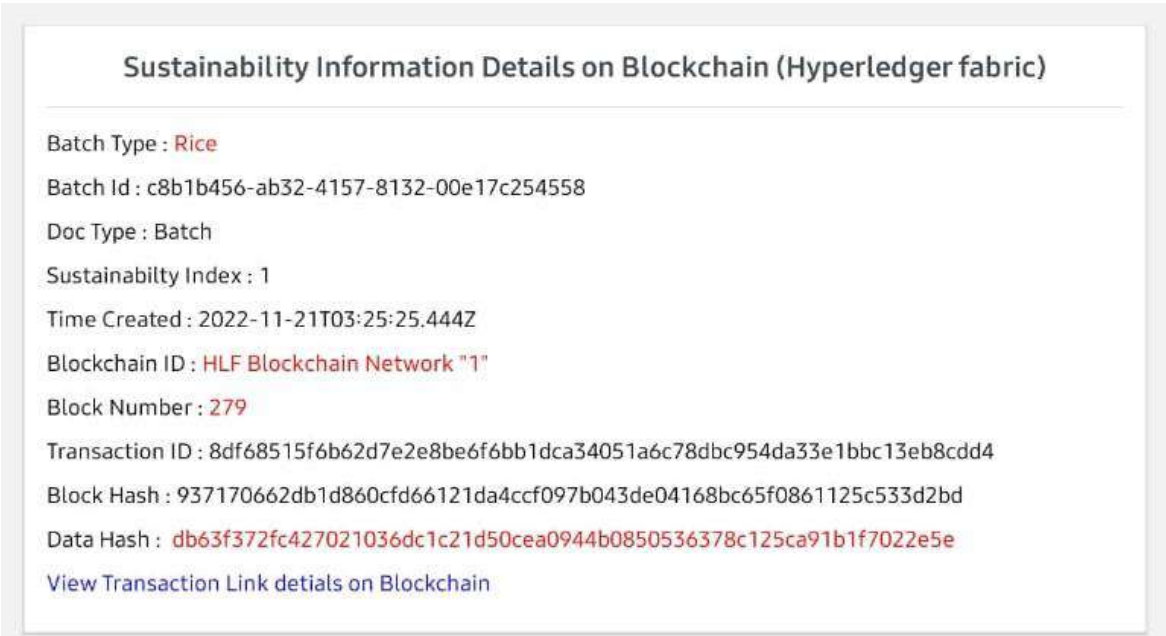

Figure 7. Transaction detail.

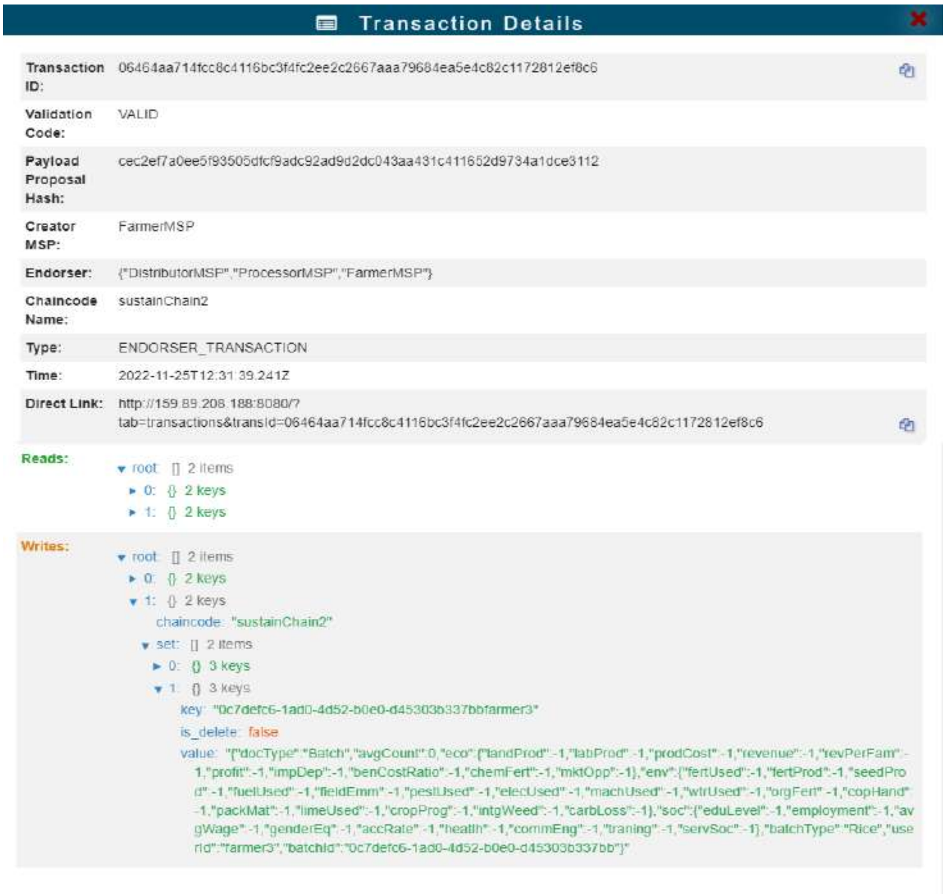

Figure 8. Block details on hyperledger explorer.

Benefits

The proposed system has several advantages compared to traditional ecolabeling systems. The proposed system leverages the inherent strengths of blockchain technology, circumventing the reliance on core enterprises for data collection. This approach fosters greater openness and transparency in exchange of information across all supply-chain partners while enhancing information oversight. By leveraging blockchain's immutable nature, concerns regarding the authenticity of information can be mitigated, thereby preventing data tampering. Additionally, blockchain's consensus mechanism resolves the trust issue prevalent in traditional food supply chains, as all nodes operate within the same network, possessing comprehensive information about the supply chain. This arrangement effectively safeguards against data tampering and loss. All links within the food supply chain are coordinated within a single system through blockchain and smart contract integration, ensuring standardized data formatting, facilitating rapid data exchange and averting "information silo" in the supply chain. Such an approach promotes collaboration and validation among stakeholders in the supply chain, enabling efficient resource integration and maximizing overall benefits.

Transparency facilitated by blockchain technology will foster consumer trust in the system. With the ability to query sustainability indicators and index values, users will have greater confidence in the ecolabels. This enhanced transparency is likely to increase consumer attraction to the system as individuals place more value on access to trusted data from every stage of the supply chain. The traceability and transparency provided by blockchain technology thus become key factors in attracting consumers to the platform.

6. Discussion, Limitations and Future Scope

The proposed sustainability information management system aimed at offering transparent and trustworthy sustainability information to consumers. The modular conceptual framework presented here is adaptable and can be tailored for application in other supply chains with minimal adjustments. By engaging all stakeholders in information management and data collection, the framework promotes comprehensive sustainability reporting. The system, built on a software-as-a-service platform, boasts several advantages, including its scalability for enhanced functionality.

Although this system presents various advantages, it also faces limitations. One significant constraint is ensuring the trustworthiness of data collected within the supply chain. Overcoming the issue of verifying information sources represents a potential area for future investigation. Subsequent efforts could delve into incorporating Internet of Things technology with blockchain to bolster the credibility of data collection [34]; however, it will put an extra financial burden on supply-chain partners, specifically farmers.

This study is constrained by its exclusive focus on the PoC for the rice supply chain, limiting its generalizability to other food sectors. However, the proposed framework is adaptable to other supply chains as well. In such cases, it will be necessary to determine the optimal set of indicators that can be used to derive a sustainability index.

Blockchain, as an evolving technology, has technical and non-technical challenges that impact its deployment, such as data interoperability, scalability, latency, and governance [35]. This study focused on a single blockchain network, presuming the integration of all supply-chain partners onto this network. However, real-world supply-chain setups are varied and intricate, typically involving numerous partners. Hence, there is a necessity for interoperability mechanisms to adequately implement supply-chain sustainability across different blockchain networks [31]. To expand the current understanding of sustainability information management, future research can be conducted, such as data interoperability among two blockchains where the supply-chain partner operates on two different blockchains.

Future studies can focus on identifying potential similarities or dissimilarities among additional indicators and criteria. One of the important aspects for future research areas is index calculation and benchmarking the indicator's value to normalize the sustainability index across varieties of produce and different regions. Future studies could assess the proposed model from both consumer and supply-chain perspectives to validate the system's effectiveness and applicability in real-world scenarios. This can be achieved through consumer surveys or by developing a prototype product for market testing and collecting user feedback.

7. Conclusions

The decentralized and tamper-resistant features of blockchain technology align with the need for a reliable sustainability information management and reporting system for food supply chains. This study conceptualizes and develops a proof-of-concept prototype for sustainability information management across economic, environmental, and social dimensions within the food supply chain.

This study delves into the real-world implementation of blockchain technology in rice supply-chain sustainability information management, offering potential benefits such as enhanced transparency and openness in sustainability indicators data management. Exploring blockchain-driven supply-chain sustainability information management can yield a comprehensive and trustworthy data source, enabling further research into improving the sustainability of the food supply chain.

This study identified system requirements and proposed the system design architecture. A multi-mode storage mechanism was devised to enhance efficiency in blockchain storage. Additionally, custom smart contracts were designed to facilitate indicator data exchange within the supply chain and user-friendly transaction mechanisms with a simplified user interface. A prototype system was implemented using Hyperledger Fabric.

The proposed system was verified through a rice supply-chain case to assess its functionality. It demonstrated the ability to facilitate information sharing throughout the supply chain, ensuring the safety and integrity of data storage and sustainability index calculation while preventing information islanding and tampering. Moreover, it offers reliable sources of supply-chain sustainability information for stakeholders, consumers, and regulatory bodies, along with capabilities for further assessment.

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Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
SaaS	Software as a service
BSMIR	Blockchain-based Sustainability Management and Reporting
SDK	Software Development Kit
UUID	Universally Unique Identifier
SDG	Sustainable Development Goals
LCA	Life-Cycle Assessment
FSC	Food Supply Chain
TBL	Triple Bottom Line

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