International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 6, 2025
https://theaspd.com/index.php

Design Framework for Food Supply Chain Industry with IoT using Blockchain

Ankita Tiwari
LJ University, Seema Mahajan, Indus University

Abstract— *Integrating blockchain technology with the Internet of Things (IoT) in the food supply chain offers a transformative approach to enhancing transparency, traceability, and operational efficiency. This paper presents a comprehensive implementation framework that unifies these advanced technologies into a seamless system, addressing critical challenges in food safety and quality management. The framework comprises five essential processes: IoT device deployment, secure data transmission, blockchain-based data storage, user-friendly frontend development, and system deployment. Firstly, IoT devices, including sensors and RFID tags, are to be strategically deployed across the supply chain to gather real-time data on vital parameters such as temperature, humidity, and location. The data should be transmitted securely using advanced wireless communication protocols to ensure data integrity and prevent tampering. Subsequently, this data is stored on a blockchain platform, leveraging its immutable and transparent nature to create a secure and tamper-proof record of all transactions. A user-centric frontend interface is developed to provide stakeholders with real-time access to blockchain data, facilitating effective tracking of food products from farm to table. The final deployment phase ensures the integration of IoT devices, secure data transmission, blockchain storage, and the frontend interface into a cohesive and operational framework. This integrated framework not only enhances the accuracy and reliability of data collection but also ensures the integrity and traceability of the food supply chain. This paper aims to offer a detailed blueprint for researchers and practitioners interested in implementing blockchain and IoT technologies in the food supply chain, highlighting the potential benefits and associated challenges of this innovative approach.*
Index Terms— *Blockchain, Internet of Things (IoT), Food Supply Chain, Traceability, Transparency, Secure Data Transmission, Food Safety, Implementation Framework..*

I. INTRODUCTION

The integration of blockchain and Internet of Things (IoT) technologies in the food supply chain offers a transformative approach to address longstanding challenges in transparency, traceability, and efficiency. As global food supply chains become increasingly complex and decentralized, ensuring the authenticity and safety of food products has become a critical concern. Traditional systems often struggle with inefficiencies, fraud, and a lack of real-time data visibility, making it difficult to track the journey of food items from farm to table. Blockchain technology, known for its decentralized, immutable, and transparent ledger system, presents a robust solution to these challenges. By recording transactions and data points across various stages of the supply chain on a blockchain, all stakeholders can access a single source of truth that cannot be altered without consensus. This enhances trust among producers, distributors, retailers, and consumers, and enables efficient verification of the origin, handling, and condition of food products.

The implementation of IoT devices further complements the blockchain by providing real-time data collection and monitoring capabilities. IoT sensors can be deployed at various points in the supply chain to capture critical data such as temperature, humidity, and location. This data is then securely transmitted to the blockchain, ensuring accurate and timely updates about the state of the products.

This paper explores the comprehensive framework for implementing blockchain and IoT in the food supply chain, detailing each component's role and the integration process. The framework consists of five main processes: IoT device setup, data transmission, blockchain storage, frontend development, and deployment. Each process is critical in creating a seamless and efficient system that enhances data integrity, reduces operational risks, and provides actionable insights for decision-makers. his research investigates the transformative potential of integrating blockchain and IoT technologies into the food supply chain to improve its overall efficiency, transparency, and reliability. Blockchain provides a decentralized, tamper-proof ledger for recording every transaction and activity within the supply chain, while IoT devices enable real-time data collection, such as environmental conditions, location tracking, and product status. Together, these technologies create an end-to-end system that enhances traceability, combats food fraud, and ensures product safety and quality from farm to fork.

The study further examines the role of smart contracts in automating processes, reducing manual interventions, and fostering trust among stakeholders. It highlights the benefits of these technologies, such as reducing waste, improving accountability, and enabling informed decision-making for consumers and businesses. However, the research also delves into critical limitations, including scalability issues, high energy consumption, data privacy concerns, and challenges related to adoption and regulatory compliance.

By addressing these challenges and proposing practical solutions, the research aims to provide a roadmap for implementing blockchain and IoT technologies effectively in the food supply chain. This innovative approach has the

TABLE I: Comparative Analysis of Blockchain and Traditional Methods

potential to drive sustainability, improve public health outcomes by ensuring food safety, and contribute to building a more resilient global food system.

II. **MATERIALS AND METHODS**

2.1. Comparative Analysis of Blockchain and Traditional Methods in Food Supply Chain

The efficiency and reliability of the food supply chain are critical to ensuring food safety and quality. This comparative analysis explores the differences between blockchain technology and traditional methods in managing the food supply chain, focusing on key features such as accuracy, traceability, scalability, cost, and speed.

2.1.1. Methodology

Data for this analysis were compiled and compared based on existing literature and practical implementations in the food supply chain industry. The features examined include accuracy, traceability, scalability, cost, and speed.

Feature	**Blockchain in Food Supply Chain**	**Traditional Method in Food Supply Chain**
Accuracy	1) Transaction times can be slower due to the need for validation across the network, but data retrieval is quick and efficient. **(Tian, 2017; Muhammad,2023)**	1) Faster transaction recording but slower data retrieval and processing, especially in complex supply chains. **(Galvez et al., 2018)**
Traceability	1) High transparency, as all participants have access to the same data, which is immutable and timestamped. **(Saurabh,2022; Salah,2019; Muhammad,2023)**	1) Limited transparency, as data is often siloed and controlled by individual stakeholders. **(Galvez et al., 2018)**
Scalability	1) Highly secure due to cryptographic techniques and decentralized nature, reducing the risk of data breaches. **(Arena,2019; Oriekhoe,2024)**	1) Lower security, with a higher risk of data breaches and tampering due to centralized databases and paper records. **(Galvez et al., 2018)**
Cost	1) Enhanced trust among stakeholders due to the transparency and immutability of records. **(Zhao et al., 2019, Tsoukas,2022)**	1) Generally lower initial costs, but ongoing operational costs can be high due to inefficiencies and the need for manual oversight. **(Galvez et al., 2018)**
Speed	1) Transaction times can be slower due to the need for validation across the network, but data retrieval is quick and efficient. **(Tian, 2017; Muhammad,2023)**	1) Faster transaction recording but slower data retrieval and processing, especially in complex supply chains. **(Galvez et al., 2018)**

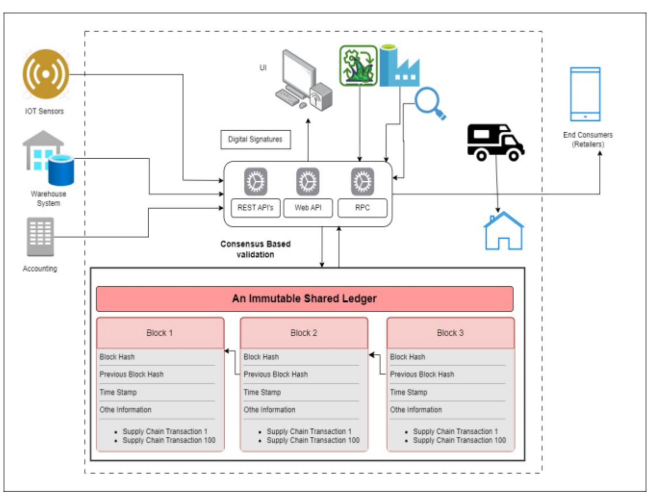
International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 6, 2025
https://theaspd.com/index.php

Transparency	1) High transparency, as all participants have access to the same data, which is immutable and timestamped. **(Saurabh,2021; Salah,2019; Muhammad ,2023)**	1) Limited transparency, as data is often siloed and controlled by individual stakeholders. **(Galvez et al., 2018)**
Data Security	1) Highly secure due to cryptographic techniques and decentralized nature, reducing the risk of data breaches. **(Arena,2019; Rubee,2023)**	1) Lower security, with a higher risk of data breaches and tampering due to centralized databases and paper records. **(Galvez et al., 2018)**
Stakeholder Trust	1) Enhanced trust among stakeholders due to the transparency and immutability of records. **(Zhao etal.,2019, Tsoukas,2022)**	1) Variable trust, often dependent on established relationships and the perceived reliability of individual stakeholders. **(Galvez et al., 2018)**
Environment Impact	1) Can be significant due to the energy consumption of blockchain networks, though improvements are being made. **(Jiang et al., 2021)**	1) Generally lower energy consumption, but inefficiencies and waste can have a negative environmental impact. **(Galvez et al., 2018)**

2.2. Proposed Model

The implementation aims to overcome the limitations of traditional supply chain systems by leveraging the unique capabilities of blockchain and IoT technologies. This includes improving data accuracy and reliability, ensuring end-to-end visibility, and enhancing consumer trust through greater transparency. Moreover, the system's decentralized nature provides resilience against single points of failure, making it more robust against disruptions. In this context, the paper will delve into the technical aspects of each process, discuss the potential challenges and limitations, and highlight the expected outcomes and benefits of the implementation. Through this exploration, the paper aims to provide a comprehensive understanding of how blockchain and IoT can be effectively integrated to revolutionize the food supply chain, setting a new standard for quality and safety in the industry.

Fig. 1. Proposed Model



This research explores a system architecture that integrates Blockchain and Internet of Things (IoT) technologies to revolutionize the food supply chain by enhancing transparency, traceability, and operational efficiency. The proposed architecture leverages real-time data acquisition through IoT sensors and ensures the integrity and trustworthiness of the data via a blockchain-based immutable shared ledger. This approach addresses critical challenges in the food supply chain, such as food safety, fraud prevention, and inefficiencies in monitoring and managing supply chain operations. By implementing these technologies, the system provides end-to-end visibility and accountability for stakeholders, ensuring that food products meet quality and safety standards from production to consumption.

The architecture comprises three primary components. IoT sensors monitor critical parameters like temperature, humidity, and location in real-time, collecting data at various points in the supply chain, including warehouses, transportation, and production facilities. This data is then transmitted to the blockchain, where it is validated through consensus protocols and recorded immutably. The blockchain ledger links blocks using cryptographic hashes, ensuring that data cannot be tampered with or altered. Additionally, an integration layer utilizing REST APIs, Web APIs, and Remote Procedure Calls (RPC) facilitates seamless communication between IoT devices, blockchain nodes, and user interfaces. Stakeholders use digital signatures for authentication and can access the system through secure user interfaces and APIs to view and verify data.

This integrated system offers numerous benefits. It enhances transparency by enabling all stakeholders to access and verify real-time data, improving accountability and trust across the supply chain. Traceability is significantly improved, allowing products to be tracked back to their origins, which is crucial for addressing recalls or quality issues. Furthermore, the blockchain's immutable nature ensures data security and protects against unauthorized modifications or fraud. Despite these advantages, the system faces challenges such as high implementation and operational costs, scalability issues, and connectivity problems in remote areas that can affect IoT performance. Addressing these challenges is vital to achieving widespread adoption and maximizing the potential of this technology.

In conclusion, this research presents a robust framework for integrating blockchain and IoT in the food supply chain, demonstrating its potential to transform how food products are monitored, managed, and delivered. While challenges like cost and scalability remain, the system provides a foundation for building a more transparent, secure, and efficient supply chain. Future research will focus on overcoming these limitations and exploring energy-efficient alternatives to enhance the system's scalability and environmental sustainability.

2.3. Data-Set

Database Searched	Database(area)	Productions(Area)	Productions(Units)	Average-Productions(Units)	Year	Type of Food	Location(state)	Websites
Data collection	Farming	213.27	617.87		2018-19	Total Wheat	Kachchh	https://www.nass.usda.gov/
Data collection	Farming	324.37	948.23	722.51	2019-20	Total Wheat	Kachchh	https://www.nass.usda.gov/
Data collection	Farming	357.49	1039.79		2020-21	Total Wheat	Kachchh	https://www.nass.usda.gov/
Data collection	Farming	52.44	205.39		2018-19	Total Wheat	Rajkot	https://www.nass.usda.gov/
Data collection	Farming	1393.32	4947.71	3226.29	2019-20	Total Wheat	Rajkot	https://www.nass.usda.gov/
Data collection	Farming	1195.12	4526.07		2020-21	Total Wheat	Rajkot	https://www.nass.usda.gov/
Data collection	Farming	48.6	122.07		2018-19	Total Wheat	Surat	https://www.nass.usda.gov/
Data collection	Farming	36.59	94.25	123.11	2019-20	Total Wheat	Surat	https://www.nass.usda.gov/
Data collection	Farming	57.67	153.02		2020-21	Total Wheat	Surat	https://www.nass.usda.gov/
Data collection	Farming	1087.03	2790.1		2018-19	Total Wheat	Ahmedabad	https://www.nass.usda.gov/
Data collection	Farming	1563.79	4206.09	3691.76	2019-20	Total Wheat	Ahmedabad	https://www.nass.usda.gov/
Data collection	Farming	1564.62	4079.09		2020-21	Total Wheat	Ahmedabad	https://www.nass.usda.gov/
Data collection	Farming	258.61	903.28		2018-19	Total Wheat	Gandinagar	https://www.nass.usda.gov/
Data collection	Farming	290.21	1025.17	979.65	2019-20	Total Wheat	Gandinagar	https://www.nass.usda.gov/
Data collection	Farming	288.43	1010.51		2020-21	Total Wheat	Gandinagar	https://www.nass.usda.gov/

Fig. 2. Dataset for product(wheat)

The provided dataset appears to focus on agricultural data collection, specifically concerning the production of total wheat across different regions and years. Here is a detailed breakdown of the dataset:

2.3.1. Columns and Attributes:

1.Database Searched: Indicates the source or activity from which the data was collected, labeled as "Data collection."

2.Database (Area): Specifies the domain or sector within which the data falls, in this case, "Farming."

3.Productions (Area): Represents the area of production measured in unspecified units, likely hectares or acres.

4.Productions (Units): Refers to the quantity of production, presumably measured in metric tons or similar units.

5.Average Productions (Units): Provides the average production units, offering a central value that summarizes the data.
6.Year: Denotes the year during which the data was collected or pertains to, ranging from 2018-2019 to 2020-2021.
7.Type of Food: Specifies the type of agricultural product, which is "Total Wheat" in this dataset.
8.Location (State): Indicates the geographical location, specifically the state where the data was collected. The states listed include Kachchh, Rajkot, Surat, Ahmedabad, and Gandhinagar.
9.Websites: Provides URLs for accessing the source of the data or related information. The URL given is for the USDA's National Agricultural Statistics Service (https://www.nass.usda.gov/), which likely contains detailed reports and statistics related to the dataset.
Similar to Ahmedabad, this region shows a steady increase in both production area and units over the years, though the values are slightly lower than in Ahmedabad. This dataset is useful for agricultural analysis, policy-making, and economic studies related to food security and regional agricultural development.

2.4. Practical Implementation

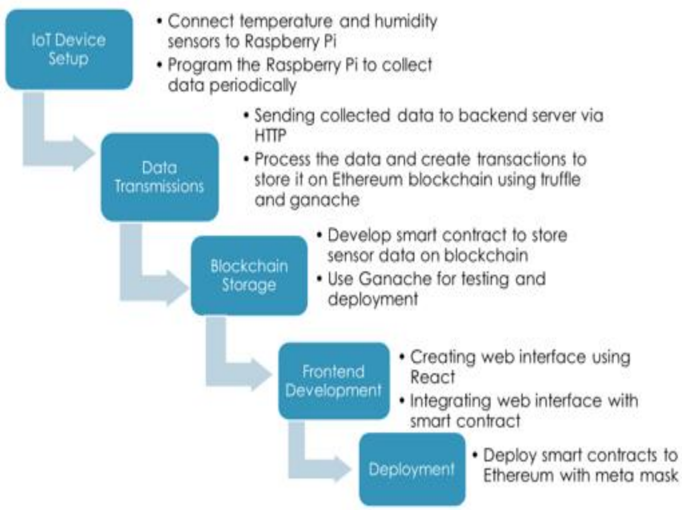


Fig. 3. Steps to Integrate Proposed Model

The integration of blockchain technology with the Internet of Things (IoT) in the food supply chain can significantly enhance transparency, traceability, and efficiency. This section details an implementation framework for incorporating blockchain technology into the food supply chain, as illustrated in the provided diagram.
Process 1: IoT Device Setup
The first step involves setting up IoT devices throughout the supply chain. These devices include various sensors and RFID tags placed at strategic points such as farms, processing facilities, and distribution centers. The IoT devices collect real-time data on critical parameters like temperature, humidity, and location.
Process 2: Data Transmission
The data collected by the IoT devices are transmitted securely to a centralized storage system. This transmission uses secure wireless communication protocols to ensure data integrity and prevent tampering during the transfer process.
Process 3: Blockchain Storage
Once transmitted, the data is stored on the blockchain. Blockchain technology ensures that the data is immutable and transparent, providing a tamper-proof record of all transactions within the food supply chain. This step is crucial for maintaining the integrity and traceability of the data.
Process 4: Frontend Development
A user-friendly frontend interface is developed to allow stakeholders across the supply chain to interact with the blockchain data. This interface provides real-time access to data, enabling stakeholders to track the status and history of food products from farm to table.
Process 5: Deployment
The final step is deploying the entire system, integrating IoT devices, data transmission protocols, blockchain storage,

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 6, 2025
https://theaspd.com/index.php

and the frontend interface into a cohesive and functional framework. This deployment ensures that the system operates smoothly and meets the requirements of all stakeholders.

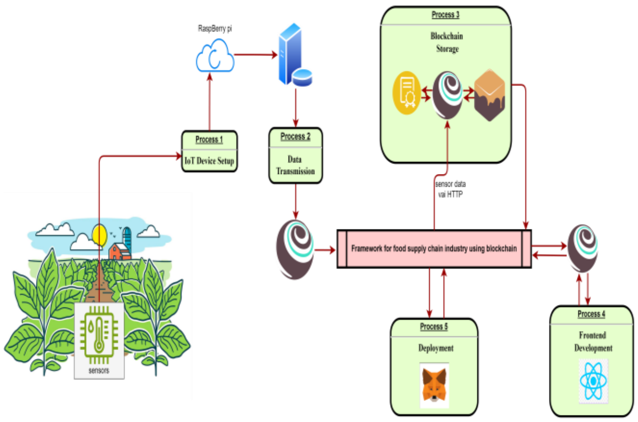


Fig. 4. Practical implementation of proposed model

The process begins with IoT Device Setup, where IoT sensors are installed in agricultural environments, such as farms. These sensors monitor various environmental factors such as temperature, humidity, soil moisture, and crop conditions. This data collection is crucial for ensuring optimal conditions for farming and product quality. The next step, Data Transmission, involves securely transmitting the collected data from the IoT sensors to a central cloud-based system. The data is sent via wireless communication channels such as Wi-Fi, LoRaWAN, or cellular networks, ensuring that the information is transferred in real-time and can be accessed remotely by the stakeholders.

Once the data is received, it moves into the Blockchain Storage phase. Here, the data is stored in a decentralized, immutable blockchain ledger. The use of blockchain ensures that the information cannot be altered or tampered with after being recorded, which provides transparency, security, and traceability in the food supply chain. This is particularly beneficial for consumers and businesses that rely on accurate product information and trustworthy supply chain data.

After the data is securely stored, the Frontend Development process comes into play. In this stage, a user-friendly interface is developed to allow stakeholders such as farmers, distributors, retailers, and consumers to access and interact with the data. This frontend interface, built using frameworks like React, makes it easy to view real-time information on the condition and movement of products throughout the supply chain, from farm to table.

Finally, the system undergoes Deployment, where the smart contracts and blockchain-based functionalities are made operational. Smart contracts are deployed using platforms like Ethereum to automate key aspects of the supply chain, such as product tracking, payment processing, and verification of transactions. This integration ensures that all operations are carried out seamlessly, with trust and transparency maintained at every stage.

Through this integrated flow, the system provides a secure, transparent, and efficient way to track food products, manage logistics, and enhance consumer trust, ultimately improving the overall food supply chain process.

2.5. Implementation Code

2.5.1. Functions for Smart Contract

1) Farmer creates a product and lists it to be purchased by Distributor
2) Farmer ships the product
3) Distributor receives the product, process it, package it and put it on sale
4) Retailer buys the product from Distributor
5) Distributor ships the product to Retailer
6) Retailer receives the product and put it on sale
7) Consumer purchase the product

2.5.2. Steps in Supply-Chain Smart contract
1) Allows farmer to create product
2) Allows farmer to sell product
3) Allows distributor to purchase product
4) Allows farmer to ship product purchased by distributor
5) Allows distributor to receive product
6) Allows distributor to process product
7) Allows distributor to package product
8) Allows distributor to sell product
9) Allows retailer to purchase product
10) Allows Distributor to ship product
11) Allows Retailer to receive product
12) Allows Retailer to sell product
13) Allows Customer to buy product

The Supply-Chain Smart Contract is designed to systematically manage and monitor the various stages of a product's journey, ensuring transparency, traceability, and accountability. The process begins by allowing the farmer to create a product and record its initial details on the blockchain. The smart contract then facilitates the farmer to offer the product for sale, making it available to potential buyers. When a distributor purchases the product, the transaction is securely recorded, and the farmer is authorized to ship the product to the distributor. Upon receipt, the smart contract enables the distributor to confirm delivery, ensuring that both parties are aligned on the handover.

Following this, the distributor can process the product, such as by sorting or refining it, and then package it for the next stages in the supply chain. Once ready, the distributor is able to sell the product, typically to a retailer. The retailer purchases the product, and the smart contract ensures that the distributor ships the product to the retailer. Once the retailer receives the product, it is prepared for sale. The smart contract enables the retailer to sell the product, marking the final availability for consumers. The journey concludes when the customer buys the product, completing the lifecycle recorded and managed by the smart contract.

This step-by-step process ensures that every transaction and action in the supply chain is securely logged and verified, fostering trust and accountability among all stakeholders involved. It also provides real-time visibility into the supply chain, which can improve operational efficiency and reduce potential fraud or delays.

2.5.3. Events

```
event ProduceByFarmer(uint productCode);             //1
event ForSaleByFarmer(uint productCode);             //2
event PurchasedByDistributor(uint productCode);      //3
event ShippedByFarmer(uint productCode);             //4
event ReceivedByDistributor(uint productCode);       //5
event ProcessedByDistributor(uint productCode);      //6
event PackagedByDistributor(uint productCode);       //7
event ForSaleByDistributor(uint productCode);        //8
event PurchasedByRetailer(uint productCode);         //9
event ShippedByDistributor(uint productCode);        //10
event ReceivedByRetailer(uint productCode);          //11
event ForSaleByRetailer(uint productCode);           //12
event PurchasedByConsumer(uint productCode);         //13
```

These events collectively represent key milestones in a blockchain-enabled supply chain system for tracking the journey of a product from its origin to the consumer. The process begins with the ProduceByFarmer event, which signifies the creation or harvesting of the product by the farmer. Following this, the ForSaleByFarmer event indicates that the farmer has made the product available for purchase. When a distributor acquires the product, the transaction is recorded through the PurchasedByDistributor event, marking a change in ownership. The ShippedByFarmer and ReceivedByDistributor events ensure transparency in the logistics, confirming that the product has been shipped by the

farmer and received by the distributor, respectively.
The distributor's subsequent actions are tracked through events such as ProcessedByDistributor, which logs activities like sorting or processing the product, and PackagedByDistributor, which documents the packaging stage. Once the product is ready for sale, the ForSaleByDistributor event is triggered. Further stages, such as purchase by a retailer (PurchasedByRetailer), shipping by the distributor (ShippedByDistributor), and receipt by the retailer (ReceivedByRetailer), ensure detailed traceability. The final stages involve the retailer offering the product for sale (ForSaleByRetailer) and the consumer purchasing it (PurchasedByConsumer). Together, these events enhance accountability, improve traceability, and foster trust among all stakeholders in the supply chain ecosystem.
2.5.4. Step-by-Step Implementation
1. Setting Up the IoT Device
1) The hardware setup with an Arduino/Raspberry Pi and sensors (e.g., temperature and humidity sensors).
2) Explaining the connection of sensors to the device.
3) Writing and upload the code to the Arduino/Raspberry Pi to collect data.
2. Programming the IoT Device
Displaying the code used to read sensor data and send it to a server. Example code snippet for an Arduino:

```
void setup() {
  Serial.begin(115200);
  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("WiFi connected");
  dht.begin();
}

void loop() {
  float temp = dht.readTemperature();
  float hum = dht.readHumidity();

  if (WiFi.status() == WL_CONNECTED) {
    HTTPClient http;
    http.begin(serverName);
    http.addHeader("Content-Type", "application/json");
    String postData = "{\"temperature\":" + String(temp) +
     ",\"humidity\":" + String(hum) + "}";
    int httpResponseCode = http.POST(postData);
    http.end();
  }
  delay(60000); // Send data every minute
}
```

Fig. 5. Code to Deploy Sensor data to Server

This code is a key component for the integration of IoT technology in a food supply chain system, as described earlier. The IoT device here is used to gather critical environmental data, such as temperature and humidity, which are vital factors in monitoring food quality and ensuring optimal conditions during transportation and storage.
The process begins with the setup of the Wi-Fi connection, ensuring the device can transmit data to the cloud or a server. In this specific scenario, the device is likely placed in a warehouse, transportation vehicle, or farm (as shown in previous research diagrams) to monitor conditions in real-time. For instance, temperature and humidity are crucial in food storage and transportation because improper conditions can affect food quality, spoilage rates, and overall safety.
Once the IoT device connects to the Wi-Fi, it retrieves the temperature and humidity data from the sensor. This data is then formatted into a JSON object and transmitted via an HTTP POST request to a server or a blockchain-based ledger (as mentioned in the research). Blockchain technology ensures that the data is securely stored in an immutable ledger, providing transparency, traceability, and real-time access to stakeholders in the food supply chain, such as farmers, distributors, retailers, and consumers. The use of blockchain guarantees that once the environmental data is recorded, it cannot be tampered with, offering all parties a high level of trust and accountability.

In the supply chain framework, this environmental data is essential for maintaining the quality of food products as they move through different stages, such as from the farm to the distributor and eventually to the consumer. IoT sensors enable real-time monitoring of these conditions, allowing stakeholders to take corrective actions if needed, like adjusting the temperature in storage areas or transportation vehicles. As part of the overall system, this integration of IoT and blockchain improves the efficiency, security, and reliability of the food supply chain, ultimately enhancing consumer safety and reducing waste caused by improper storage or transportation conditions.

3. Setting Up the Blockchain Environment

Install Truffle and Ganache, and showing the setup process.

npm install -g truffle
npm install -g ganache-cli
ganache-cli

4. Developing the Smart Contract

```
pragma solidity ^0.8.0;
contract FoodSupplyChain {
  struct SensorData {
    uint256 timestamp;
    uint256 temperature;
    uint256 humidity;
  }

  SensorData[] public data;

  function addData(uint256 _temperature, uint256 _humidity) public {
    data.push(SensorData(block.timestamp, _temperature, _humidity));
  }

  function getData(uint256 index) public view returns (uint256, uint256, uint256)
  {
    SensorData memory record = data[index];
    return (record.timestamp, record.temperature, record.humidity);
  }
}
```

Fig. 6. Smart Contract Development to store IoT data

this code represents the interaction of an IoT device integrated into a smart food supply chain system. The device's primary function is to monitor environmental factors such as temperature and humidity, crucial parameters for maintaining the quality and safety of food products throughout the supply chain.

The process begins by establishing a Wi-Fi connection, ensuring that the IoT device is connected to a server or cloud platform. Once connected, the device continuously reads temperature and humidity data from sensors (as indicated in the code) at regular intervals. These readings are essential for tracking the conditions under which food is stored, transported, and handled. In the context of the food supply chain, monitoring these factors helps prevent spoilage, contamination, or quality degradation of products.

Next,the code formats this data into a JSON object, which is then transmitted via an HTTP POST request to a central server or a blockchain network. The data sent to the blockchain serves as an immutable record, ensuring that temperature and humidity data are securely stored, and that it cannot be altered or tampered with. This use of blockchain aligns with the research's goal of providing transparency and traceability within the food supply chain.

Blockchain ensures that all stakeholders, such as farmers, distributors, retailers, and consumers, have access to accurate and trustworthy data. By utilizing blockchain's decentralized and secure nature, the system mitigates risks of data manipulation and enhances trust among all participants in the supply chain. Moreover, this real-time data can be used to make timely interventions, such as adjusting storage conditions or rerouting shipments if temperature or humidity levels fall outside optimal ranges.

In essece, this IoT device and its data transmission mechanism play a critical role in the food supply chain framework, integrating both IoT technology and blockchain to ensure the safe, efficient, and transparent movement of food from farm to table. By providing real-time, verifiable environmental data, the system supports the goal of maintaining food quality and safety while also improving supply chain efficiency and accountability.

5. Deploying the Smart Contract

Using Truffle to compile and deploy the smart contract.

```
truffle compile
truffle migrate ~network development
```

6. Integrating IoT Data with the Blockchain

Writing a Node.js script to receive data from the IoT device and send it to the blockchain.

```
const Web3 = require('web3');
const contract = require('@truffle/contract');
const express = require('express');
const bodyParser = require('body-parser');
const app = express();
app.use(bodyParser.json());

const web3 = new Web3('http://localhost:8545');
const FoodSupplyChainArtifact = require('./build/contracts/FoodSupplyChain.json');
const FoodSupplyChain = contract(FoodSupplyChainArtifact);
FoodSupplyChain.setProvider(web3.currentProvider);

let foodSupplyChainInstance;
FoodSupplyChain.deployed().then(instance => {
  foodSupplyChainInstance = instance;
});

app.post('/data', async (req, res) => {
  const { temperature, humidity } = req.body;
  await foodSupplyChainInstance.addData(temperature,humidity,{from: web3.eth.accounts[0]});
  res.send('Data recorded on blockchain');
});app.listen(3000, () => {console.log('Server listening on port 3000');});
```

Fig. 7. Code to Integrate IoT data With Blockchain

2.6. **Limitations**

Implementing blockchain and IoT technologies in the food supply chain brings numerous advantages but also presents several limitations and challenges that require careful consideration. Scalability issues arise as the volume of transactions and data increases, leading to longer transaction processing times and potential network congestion, which could result in delays in data verification and higher operational costs. Data privacy and security concerns are significant, as the initial data collection and transmission processes involving IoT devices are vulnerable to cyber-attacks and data breaches, necessitating robust security measures to maintain data integrity and stakeholder trust. The high implementation and operational costs, including substantial setup costs for IoT devices, blockchain infrastructure, and ongoing expenses like energy consumption and maintenance, pose a significant barrier, especially for small and medium-sized enterprises (SMEs). Energy consumption is another critical challenge, particularly for blockchain networks using proof-of-work consensus mechanisms, which consume large amounts of energy and raise environmental sustainability and cost-efficiency concerns. Additionally, the evolving regulatory landscape for blockchain and IoT technologies varies by region, making compliance complex and potentially costly. User adoption and training are also crucial, as successful implementation requires stakeholders to be adequately trained and willing to adopt the new system; resistance to change and lack of technical knowledge can hinder adoption. Finally, network latency and connectivity issues, especially for IoT devices in remote or rural areas, can affect real-time monitoring and data accuracy, reducing the system's reliability and responsiveness. Addressing these limitations through strategic planning, technological innovation, and stakeholder engagement is essential for the successful deployment and integration of blockchain and IoT technologies in the food supply chain.

III. RESULTS

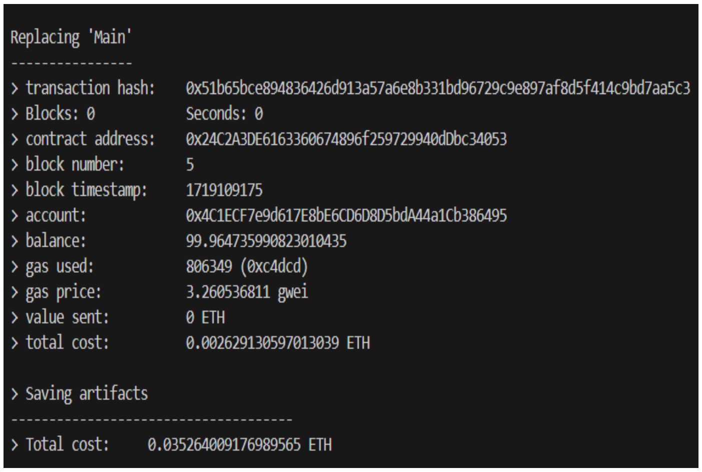


Fig. 8. Result of Smart Contract Deployment of Supply chain Using Truffle

The deployment of the smart contract on the blockchain network was successfully completed. The transaction associated with this deployment is identified by the unique hash x51b65bce894836426d913a57a6e8b331bd96729c9e897af8d5f414c9bd7aa5c3, which can be used to verify and view details on a blockchain explorer. This transaction was included in block number 5, and the exact timestamp when the block was mined is 1719109175. The smart contract was assigned the address 0x24C2A3DE6163360674896f259729940dDbc34053, which will be used for future interactions with the contract.
The deployment transaction was initiated by the account 0x4C1ECF7e9d617E8bE6CD6D8D5bdA44a1Cb386495. After the deployment, the account had a remaining balance of 99.964735990823010435 Ether (ETH). The deployment utilized 806,349 units of gas, with the gas price set at 3.260536811 gwei. No Ether was sent with this transaction, and the total cost for deploying the smart contract amounted to 0.002629130597013039 ETH, calculated by multiplying the gas used with the gas price. Additionally, there appears to be a cumulative or total cost mentioned as 0.035264009176989565 ETH, although it is unclear why this amount differs from the immediate transaction cost. This might include other associated costs or cumulative costs over multiple transactions. The deployment artifacts, including metadata and the ABI (Application Binary Interface), were saved for future use, ensuring the deployed contract can be interacted with and managed effectively.

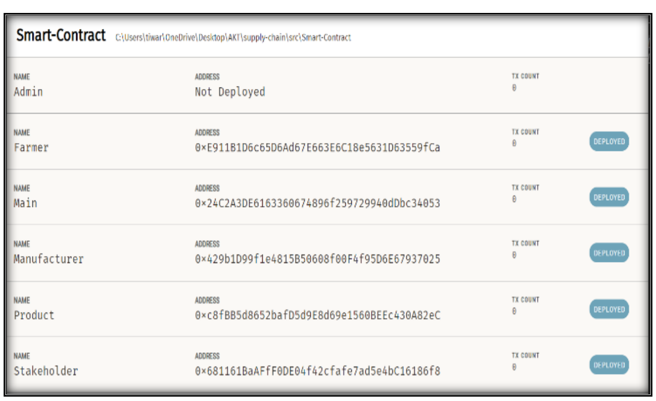


Fig. 9. Result of Smart Contract Deployment in Ganache

The displayed screen captures the status of various smart contracts within a blockchain-based supply chain system. Each contract is listed with its name, address, and deployment status. The “Admin” contract is noted as “Not Deployed,” indicating it has not yet been deployed to the blockchain. The other contracts – “Farmer,” “Main,” “Manufacturer,” “Product,” and “Stakeholder” – have all been successfully deployed. Each of these contracts is assigned a unique address, signifying their distinct locations on the blockchain.
The addresses are as follows:

1) Farmer: 0xE911B1D6c65D6Ad67E663E6C18e5631D63559fCa
2) Main: 0x24C2A3DE6163360674896f259729940dDbc34053
3) Manufacturer: 0x429b1D99f1e4815B50608f00F4f95D6E67937025
4) Product: 0xc8fBB5d8652bafD5d9E8d69e1560BEeC430A82eC
5) Stakeholder: 0x681161BaAFfF0DE04f42cfafe7ad5e4bC16186f8

Each deployed contract currently shows a transaction count (TX Count) of zero, implying that no transactions have been performed with these contracts since their deployment. The presence of a "DEPLOYED" status for these contracts confirms that they are active and ready for interaction within the blockchain network. This setup demonstrates a multi-tiered approach to managing different roles and responsibilities within the supply chain, ensuring transparency and traceability through blockchain technology.

IV. CONCLUSIONS

The implementation of a blockchain-based framework for the food supply chain industry, augmented with IoT devices for data collection, heralds a transformative shift towards enhanced transparency, traceability, and security. By integrating real-time data from IoT sensors with the immutable and decentralized nature of blockchain technology, this framework ensures that every step of the supply chain is meticulously recorded and verifiable. This implementation significantly mitigates issues related to food safety, quality control, and fraud, providing stakeholders with a robust mechanism to trace the origin and journey of food products from farm to table. Key to this implementation are smart contracts, which automate and secure transactions among various stakeholders, including farmers, manufacturers, and distributors. These contracts, once deployed, ensure that all actions are transparent and tamper-proof, fostering trust and efficiency across the supply chain. The deployment records indicate successful interactions and readiness for practical application, showcasing the system's potential to revolutionize the industry.

IV. CHALLENGES

However, despite its promising advantages, this implementation is not without challenges. The dependence on IoT devices necessitates a robust and uninterrupted internet connection, which may be difficult to achieve in remote or underdeveloped areas. Additionally, the initial investment required for setting up IoT devices and integrating blockchain technology can be substantial, potentially posing a barrier for small-scale farmers and producers. Scalability issues and the high energy consumption associated with blockchain networks are also significant concerns that need to be addressed to ensure sustainable and widespread adoption. In conclusion, this blockchain-based framework represents a significant leap forward in modernizing the food supply chain industry. It offers unparalleled transparency, traceability, and security, contributing to better food safety and quality management. Nevertheless, overcoming the associated limitations is crucial for realizing its full potential and ensuring broad accessibility and adoption. Continued innovation and investment in this area will be essential to address these challenges and unlock the full benefits of this transformative technology for the food supply chain industry.

REFERENCES

[1] Yong, Binbin, Jun Shen, Xin Liu, Fucun Li, Huaming Chen, and Qingguo Zhou. "An intelligent blockchain-based system for safe vaccine supply and supervision." International Journal of Information Management 52 (2020): 102024. https://doi.org/10.1016/j.ijinfomgt.2019.10.009.

[2] Rana, Roberto Leonardo, Caterina Tricase, and Luigi De Cesare. "Blockchain technology for a sustainable agri-food supply chain." British Food Journal 123, no. 11 (2021): 3471-3485. https://doi.org/10.1155/2021/5580179

[3] Ehsan, Ibtisam, Muhammad Irfan Khalid, Laura Ricci, Jawaid Iqbal, Amerah Alabrah, Syed Sajid Ullah, and Taha M. Alfakih. "A Conceptual Model for Blockchain-Based Agriculture Food Supply Chain System." Scientific Programming 2022, no. 1 (2022): 7358354. https://doi.org/10.1155/2022/7358354

[4] Behnke, Kay, and M. F. W. H. A. Janssen. "Boundary conditions for traceability in food supply chains using blockchain technology." International Journal of Information Management 52 (2020): 101969. https://doi.org/10.1016/j.ijinfomgt.2019.05.025
[5] Pandey, Vivekanand, Millie Pant, and Vaclav Snasel. "Blockchain technology in food supply chains: Review and bibliometric analysis." Technology in Society 69 (2022): 101954. https://doi.org/10.1016/j.techsoc.2022.101954
[6] Rejeb, Abderahman, John G. Keogh, and Horst Treiblmaier. "Leveraging the internet of things and blockchain technology in supply chain management." Future Internet 11, no. 7 (2019): 161. https://doi.org/10.3390/fi11070161
[7] Bosona, Techane, and Girma Gebresenbet. "The role of blockchain technology in promoting traceability systems in agri-food production and supply chains." Sensors 23, no. 11 (2023): 5342. https://doi.org/10.3390/s23115342
[8] Saurabh, Samant, and Kushankur Dey. "Blockchain technology adoption, architecture, and sustainable agri-food supply chains." Journal of Cleaner Production 284 (2021): 124731. https://doi.org/10.1016/j.jclepro.2020.124731
[9] Singh, Rubee, Shahbaz Khan, Jacinta Dsilva, and Piera Centobelli. "Blockchain integrated IOT for Food Supply Chain: A grey based Delphi-DEMATEL approach." Applied Sciences 13, no. 2 (2023): 1079. https://doi.org/10.3390/app13021079
[10] Ray, Papri, Hari Om Harsh, Anu Daniel, and Aishwarya Ray. "Incorporating block chain technology in food supply chain." International Journal of Management Studies 6, no. 1 (2019): 5. http://dx.doi.org/10.18843/ijms/v6i1(5)/13
[11] Tse, Daniel, Bowen Zhang, Yuchen Yang, Chenli Cheng, and Haoran Mu. "Blockchain application in food supply information security." In 2017 IEEE international conference on industrial engineering and engineering management (IEEM), pp. 1357-1361. IEEE, 2017. https://doi.org/10.1109/IEEM.2017.8290114
[12] Zhao, Guoqing, Shaofeng Liu, Carmen Lopez, Haiyan Lu, Sebastian Elgueta, Huilan Chen, and Biljana Mileva Boshkoska. "Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions." Computers in industry 109 (2019): 83-99. https://doi.org/10.1016/j.compind.2019.04.002
[13] Casino, Fran, Venetis Kanakaris, Thomas K. Dasaklis, Socrates Moschuris, and Nikolaos P. Rachaniotis. "Modeling food supply chain traceability based on blockchain technology." Ifac-Papersonline 52, no. 13 (2019): 2728-2733. https://doi.org/10.1016/j.ifacol.2019.11.620
[14] Bumblauskas, Daniel, Arti Mann, Brett Dugan, and Jacy Rittmer. "A blockchain use case in food distribution: Do you know where your food has been?." International Journal of Information Management 52 (2020): 102008. https://doi.org/10.1016/j.ijinfomgt.2019.09.004
[15] Yadav, Vinay Surendra, Amit Raj Singh, Rakesh D. Raut, and Usharani Hareesh Govindarajan. "Blockchain technology adoption barriers in the Indian agricultural supply chain: an integrated approach." Resources, conservation and recycling 161 (2020): 104877. https://doi.org/10.1016/j.resconrec.2020.104877
[16] Chang, Yanling, Eleftherios Iakovou, and Weidong Shi. "Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities." International Journal of Production Research 58, no. 7 (2020): 2082-2099. https://doi.org/10.1080/00207543.2019.1651946
[17] Casino, Fran, Venetis Kanakaris, Thomas K. Dasaklis, Socrates Moschuris, Spiros Stachtiaris, Maria Pagoni, and Nikolaos P. Rachaniotis. "Blockchain-based food supply chain traceability: a case study in the dairy sector." International journal of production research 59, no. 19 (2021): 5758-5770. https://doi.org/10.1080/00207543.2020.1789238
[18] Kayikci, Yaşanur, Nachiappan Subramanian, Manoj Dora, and Manjot Singh Bhatia. "Food supply chain in the era of Industry 4.0: Blockchain technology implementation opportunities and impediments from the perspective of people, process, performance, and technology." Production planning & control 33, no. 2-3 (2022): 301-321. https://doi.org/10.1080/09537287.2020.1810757
[19] Tsang, Yung Po, King Lun Choy, Chun Ho Wu, George To Sum Ho, and Hoi Yan Lam. "Blockchain-driven IoT for food traceability with an integrated consensus mechanism." IEEE access 7 (2019): 129000-129017. https://doi.org/10.1109/ACCESS.2019.2940227
[20] Lin, Weijun, Xinghong Huang, Hui Fang, Victoria Wang, Yining Hua, Jingjie Wang, Haining Yin, Dewei Yi, and Laihung Yau. "Blockchain technology in current agricultural systems: from techniques to applications." Ieee Access 8 (2020): 143920-143937. https://doi.org/10.1109/ACCESS.2020.3014522
[21] Kumar, Shashank, Rakesh D. Raut, Nishant Agrawal, Naoufel Cheikhrouhou, Mahak Sharma, and Tugrul Daim. "Integrated blockchain and internet of things in the food supply chain: Adoption barriers." Technovation 118 (2022): 102589. https://doi.org/10.1016/j.technovation.2022.102589
[22] Mondal, Saikat, Kanishka P. Wijewardena, Saranraj Karuppuswami, Nitya Kriti, Deepak Kumar, and Premjeet Chahal. "Blockchain inspired RFID-based information architecture for food supply chain." IEEE Internet of Things Journal 6, no. 3 (2019): 5803-5813. https://doi.org/10.1109/JIOT.2019.2907658
[23] Shingh, Shuvam, V. Kamalvanshi, Sarthak Ghimire, and Sudarshan Basyal. "Dairy supply chain system based on blockchain technology." Asian Journal of Economics, Business and Accounting 14, no. 2 (2020): 13-19. https://doi.org/10.9734/ajeba/2020/v14i230189
[24] Rizwan, Ali, Dimitrios A. Karras, Jitendra Kumar, Manuel Sánchez-Chero, Marlon Martín Mogollón Taboada, and Gilder Cieza Altamirano. "An internet of things (IoT) based block chain technology to enhance the quality of supply chain management (SCM)." Mathematical Problems in Engineering 2022, no. 1 (2022): 9679050. https://doi.org/10.1155/2022/9679050
[25] Bhat, Showkat Ahmad, Nen-Fu Huang, Ishfaq Bashir Sofi, and Muhammad Sultan. "Agriculture-food supply chain management based on blockchain and IoT: a narrative on enterprise blockchain interoperability." Agriculture 12, no. 1 (2021): 40. https://doi.org/10.3390/agriculture12010040
[26] Kumar, Mukesh, Vikas Kumar Choubey, Rakesh D. Raut, and Sandeep Jagtap. "Enablers to achieve zero hunger through IoT and blockchain technology and transform the green food supply chain systems." Journal of Cleaner Production 405 (2023): 136894. https://doi.org/10.1016/j.jclepro.2023.136894
[27] Chandan, Anulipt, Michele John, and Vidyasagar Potdar. "Achieving UN SDGs in food supply chain using blockchain technology." Sustainability 15, no. 3 (2023): 2109. https://doi.org/10.3390/su15032109

[28] Duan, Jiang, Chen Zhang, Yu Gong, Steve Brown, and Zhi Li. "A content-analysis based literature review in blockchain adoption within food supply chain." International journal of environmental research and public health 17, no. 5 (2020): 1784. https://doi.org/10.3390/ijerph17051784

[29] Jagtap, Sandeep, Linh Duong, Hana Trollman, Farah Bader, Guillermo Garcia-Garcia, George Skouteris, Jie Li et al. "IoT technologies in the food supply chain." In Food technology disruptions, pp. 175-211. Academic Press, 2021. https://doi.org/10.1016/B978-0-12-821470-1.00009-4

[30] Ronaghi, Mohammad Hossein. "A blockchain maturity model in agricultural supply chain." Information Processing in Agriculture 8, no. 3 (2021): 398-408. https://doi.org/10.1016/j.inpa.2020.10.004

[31] Tsoukas, Vasileios, Anargyros Gkogkidis, Aikaterini Kampa, Georgios Spathoulas, and Athanasios Kakarountas. "Enhancing food supply chain security through the use of blockchain and TinyML." Information 13, no. 5 (2022): 213. https://doi.org/10.3390/info13050213

[32] Kaijun, Leng, Bi Ya, Jing Linbo, Fu Han-Chi, and Inneke Van Nieuwenhuyse. "Research on agricultural supply chain system with double chain architecture based on blockchain technology." Future Generation Computer Systems 86, no. 641-649 (2018). https://doi.org/10.1016/j.future.2018.04.061

[33] Tribis, Y., El Bouchti, A., Bouayad, H.: Supply chain management based on blockchain: a systematic mapping study. In: International Workshop on Transportation and Supply Chain Engineering. https://doi.org/10.1051/matecconf/201820000020

[34] Madumidha, S., P. Siva Ranjani, S. Sree Varsinee, and P. S. Sundari. "Transparency and traceability: In food supply chain system using blockchain technology with internet of things." In 2019 3rd international conference on trends in electronics and informatics (ICOEI), pp. 983-987. IEEE, 2019. https://doi.org/10.1109/ICOEI.2019.8862726

[35] Ray, Papri, Hari Om Harsh, Anu Daniel, and Aishwarya Ray. "Incorporating block chain technology in food supply chain." International Journal of Management Studies 6, no. 1 (2019): 5. http://dx.doi.org/10.18843/ijms/v6i1(5)/13

[36] Park, Arim, and Huan Li. "The effect of blockchain technology on supply chain sustainability performances." Sustainability 13, no. 4 (2021): 1726. https://doi.org/10.3390/su13041726

[37] Yakubu, Bello Musa, Rabia Latif, Aisha Yakubu, Majid Iqbal Khan, and Auwal Ibrahim Magashi. "RiceChain: Secure and traceable rice supply chain framework using blockchain technology." PeerJ Computer Science 8 (2022): e801. https://doi.org/10.7717/peerj-cs.801

[38] Salah, Khaled, Nishara Nizamuddin, Raja Jayaraman, and Mohammad Omar. "Blockchain-based soybean traceability in agricultural supply chain." Ieee Access 7 (2019): 73295-73305. https://doi.org/10.1109/ACCESS.2019.2918000

[39] Arena, Antonio, Alessio Bianchini, Pericle Perazzo, Carlo Vallati, and Gianluca Dini. "BRUSCHETTA: An IoT blockchain-based framework for certifying extra virgin olive oil supply chain." In 2019 IEEE international conference on smart computing (SMARTCOMP), pp. 173-179. IEEE, 2019. https://doi.org/10.1109/SMARTCOMP.2019.00049

[40] Jiang, Nan, Xing Liu, and Ming Xu. "Evaluating blockchain technology and related policies in China and the USA." Science and Public Policy 48, no. 4 (2021): 562-575. https://doi.org/10.1093/scipol/scab032

[41] Kaur, Amanpreet, Gurpreet Singh, Vinay Kukreja, Sparsh Sharma, Saurabh Singh, and Byungun Yoon. "Adaptation of IoT with blockchain in Food Supply Chain Management: An analysis-based review in development, benefits and potential applications." Sensors 22, no. 21 (2022): 8174. https://doi.org/10.3390/s22218174

[42] Dey, Somdip, Suman Saha, Amit Kumar Singh, and Klaus McDonald-Maier. "FoodSQRBlock: Digitizing food production and the supply chain with blockchain and QR code in the cloud." Sustainability 13, no. 6 (2021): 3486. https://doi.org/10.3390/su13063486

[43] Damoska Sekuloska, Jovanka, and Aleksandar Erceg. "Blockchain technology toward creating a smart local food supply chain." Computers 11, no. 6 (2022): 95. https://doi.org/10.3390/computers11060095

[44] Oriekhoe, Osato Itohan, Bamidele Segun Ilugbusi, and Olawale Adisa. "Ensuring global food safety: integrating blockchain technology into food supply chains." Engineering Science & Technology Journal 5, no. 3 (2024): 811-820. https://doi.org/10.51594/estj.v5i3.905

[45] Galvez, Juan F., Juan C. Mejuto, and Jesus Simal-Gandara. "Future challenges on the use of blockchain for food traceability analysis." TrAC Trends in Analytical Chemistry 107 (2018): 222-232. https://doi.org/10.1016/j.trac.2018.08.011