DEVELOPMENT OF AN IOT AND BLOCKCHAIN INTEGRATED VERTICAL FARMING SYSTEM

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M.Sc. Engineering Thesis

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DECLARATION

I hereby declare that the study reported in this thesis entitled as above is my original work and has not been submitted anywhere for any degree or other purposes. Further, I certify that the intellectual content of this thesis is the product of my work and that all the assistance received in preparing this thesis and sources have been acknowledged and/or cited in the reference section.

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ABSTRACT

Development of an IoT and Blockchain Integrated Vertical Farming System

The demand for sustainable and efficient procedures to produce safe food is increasing due to ongoing global challenges like population growth, resource deficiency, climate change, and global warming. Thus vertical farming, a pioneer emerging technology, may play a vital role in addressing such challenges in agriculture. Vertical farming systems need continuous monitoring of the plants and farm environment. There are scopes to improve efficiency, reduce human effort, and ensure proper yield. This research aims to explore the parameters required to monitor a vertical farm and to propose an IoT and blockchain based automated and efficient food production system. The IoT devices allow real-time monitoring and controlling of essential parameters like temperature, moisture, light, nutrient levels, and alike, while the Blockchain technology provides a transparent and immutable ledger of the records regarding crop growth and resource consumption of the farm, enhancing the framework's traceability. A prototypical system of this framework was developed and simulated in the lab environment to evaluate its performance. By generating the required control instructions to maintain the ideal environment, the prototypical system proved to be effective, efficient, and reliable.

সারসংক্ষেপ

Development of an IoT and Blockchain Integrated Vertical Farming System

জনসংখ্যা বৃদ্ধি, সম্পদের ঘাটতি, জলবায়ু পরিবর্তন এবং বৈশ্বিক উষ্ণতা বৃদ্ধির মতো চলমান বৈশ্বিক চ্যালেঞ্জের কারণে নিরাপদ খাদ্য উৎপাদনের জন্য দীর্ঘমেয়াদী এবং কার্যকর পদ্ধতির চাহিদা বাড়ছে। Vertical Farming, যা কিনা একটি নব্য-উন্নতিশীল প্রযুক্তি, খাদ্য উৎপাদনের এই ধরনের চ্যালেঞ্জ মোকাবেলায় গুরুত্বপূর্ণ এবং অগ্রণী ভূমিকা পালন করতে পারে। Vertical Farming পদ্ধতিতে প্রত্যেকটি গাছ এবং farm environment প্রতিনিয়ত পর্যবেক্ষণ প্রয়োজন। একইসাথে, এ পদ্ধতি ব্যবহারে farm এর কর্মদক্ষতা উন্নত করা, কায়িক শ্রম কমানো এবং সঠিক ফলন নিশ্চিত করার সুযোগ রয়েছে। এই গবেষণার লক্ষ্য হল, একটি Vertical Farming পর্যবেক্ষণের জন্য প্রয়োজনীয় parameter গুলো অন্বেষণ করা এবং একটি IoT ও blockchain-ভিত্তিক স্বয়ংক্রিয় এবং কার্যকর খাদ্য উৎপাদন ব্যবস্থা প্রস্তাব করা। Vertical farm এর বিভিন্ন স্থানে IoT device এবং sensor স্থাপন করা হয়েছে যাতে তাপমাত্রা, আর্দ্রতা, আলো, মাটির গুণগত মানসহ কিছু অতিপ্রয়োজনীয় parameter গুলিকে real-time পর্যবেক্ষণ এবং নিয়ন্ত্রণ করা যায়। আবার, blockchain প্রযুক্তি ফসলের উৎপাদন বৃদ্ধি এবং সম্পদের পর্যাপ্ত ব্যবহারের পাশাপাশি সকল রেকর্ডগুলির একটি স্বচ্ছ এবং অপরিবর্তনীয় খতিয়ান প্রদান করে। এই framework এর একটি prototypical system তৈরি করা হয় এবং lab environment-এ এর কার্যকারিতা মূল্যায়ন করা হয়। উক্ত মূল্যায়নের ফলাফল বিশ্লেষণ করে দেখা যায়, আদর্শ farming environment বজায় রাখার জন্য prototypical system স্বয়ংক্রিয়ভাবে প্রয়োজনীয় control instruction তৈরি করে প্রস্তাবিত Vertical Farming মডেলটি কার্যকর, কার্যক্ষম এবং নির্ভরযোগ্য বলে প্রমাণ করে।

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LIST OF ALGORITHMS

LIST OF ABBREVIATIONS

ACM : Association for Computing Machinery

API : Application Programming Interface

CPS : Cyber-Physical Systems

CPU : Central Processing Unit

CRUD : Create, Read, Update, Delete

CSS : Cascading Style Sheets

DB : Database

DoS : Denial of Service

DSR : Design Science Research

EC : Electrical Conductivity

EJS : Embedded Java Script

HTML : HyperText Markup Language

ICT : Information and Communication Technologies

IEEE : Institute of Electrical and Electronics Engineers

IoT : Internet of Things

MIT : Massachute Institute of Technology

NPK : Nitrogen, Phosphorus and Potassium

OS : Operating System

pH : potential of Hydrogen

QR : Quick Response

RAM : Random Access Memory

SDK : Software Development Kit

SMS : Short Message Service

TDS : Total Dissolved Solids

UX : User eXperience

VM : Virtual Machine

CHAPTER 1

INTRODUCTION

This chapter presents a brief discussion on the background of this thesis; next, the motivation and problem statement of this research; then, an overview of the methodology adopted and the scope of the thesis following the organization of the chapters.

1.1 Thesis Background

According to the United Nations, the world population is predicted to reach 9.7 billion in 2050[1]. This increased population will occupy more land than before. So, the amount of arable land per person is decreasing gradually at a constant rate[2] (Figure 1.1). Thus, firstly, the world will need more food production for this increased population. And secondly, this larger amount of food is required to be grown on less arable land. To address the challenge to produce significantly more food using significantly less land, several approaches have been followed like high yield crop production (Tester and Langridge, 2010), usage of more effective herbicides (Gianessi, 2013), applying nano-fertilizer (M. R. Khan and Rizvi, 2017), vertical or 3D farming (Benke and Tomkins, 2017). Among these approaches, vertical farming has a lot of potentials although it is still in its infancy.

Vertical farming, a technique of growing crops in a controlled environment using vertically stacked layers (Birkby, 2016; Suvarna et al., 2020), has gained attention in promoting agricultural sustainability. Vertical farming offers numerous advantages like- *(a)* it provides higher crop yield throughout the year; *(b)* it increases the volume of arable lands vertically; *(c)* it can convert deserted or unused land like rooftop into arable land; *(d)* for being in a controlled environment, it does not need any fertilizers, herbicides, or pesticides and also it reduces pathogens; *(e)* it provides organic food since it does not require any chemicals (Suvarna et al., 2020). Since the rising demand as well as changing consumer preferences

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[1] https://www.un.org/sustainabledevelopment/blog/2019/06/growing-at-a-slower-pace

[2] https://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC?end=2021&locations=1W&start=1961

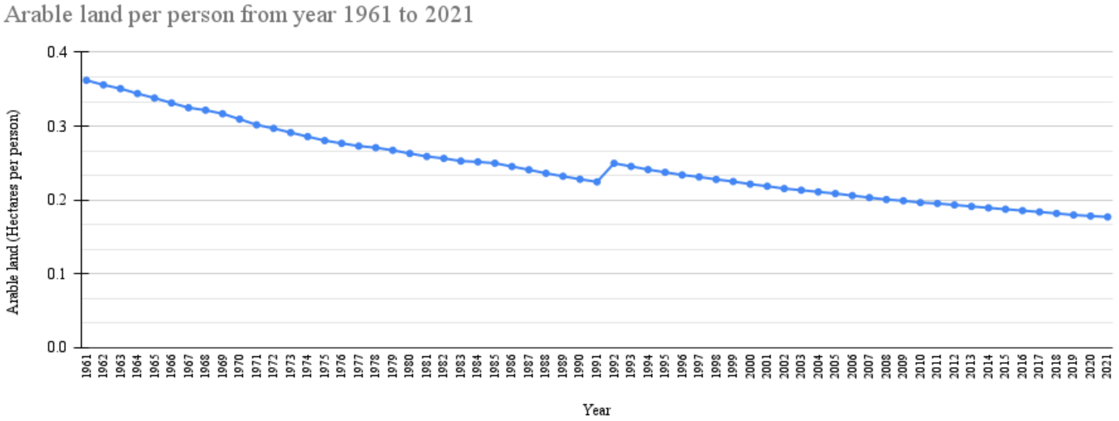


Fig. 1.1. Arable land per person (1961-2021)

for food and other products are increasing pressure on our existing resources (Banerjee and Adenaeuer, 2014), vertical farming can be used to grow more crops for the increased population with less water and arable land.

To ensure proper utilization of the available resources, Information and Communication Technologies (ICT) can be adapted in vertical farming (V. P. Mishra and Chaudhry, 2019; Munim and Islam, 2024). An automated system can reduce the involvement of time, money, and manpower (I. Islam et al., 2019; Munim, Islam, & Islam, 2019; Munim, Islam, Sarker, et al., 2019). Some existing studies focused on integrating ICT with vertical farming like smart service-based farming (Sivamani et al., 2013), automated indoor plant watering system (Hanif bin Ismail and Thamrin, 2017), optimized power consumption and distribution model (Labrador et al., 2018), digital twin for vertical farming to improve the planning, monitoring and, optimization (Monteiro et al., 2018), etc. Similarly, the implementation of the Internet of Things (IoT) in vertical farming is increasing day by day since it promotes smart monitoring of environmental attributes like soil moisture, temperature, light, etc (Kaur et al., 2022; Oh and Lu, 2023; Putri et al., 2023). Implementing a vertical farm is not dependent on soil or direct sunlight. So, it can be placed anywhere including indoor unused spaces providing local, nutritious, and fresh produce (Avgoustaki and Xydis, 2020). Since vertical farming is constructed in a controlled environment, parameters like temperature, airflow, light, nutrients, pH in water, water quality and level, etc. need to be monitored continuously. Thus, vertical farming management automation can help to monitor and make decisions to solve any sudden issue. It can provide ease of handling, reduced human effort, and increased efficiency. To make the system secure, reliable, and verifiable, the crop data can be collected through IoT devices and stored in the blockchain ensuring food safety and tamper-proof historical data. Such kind of security, reliability, and verifiability of systems can be ensured by adopting blockchain technology I. Islam, 2022. Blockchain technology stores the immutable and irreversible historical records of all transactions to ensure transparency (I. Islam et al., 2020). To enhance traceability, ensure food safety, and tamper-proof historical data, blockchain is suitable to integrate into vertical farming food manufacturing and supply chain (Chin and Audah, 2017).

For example, IoT-based modular indoor vertical farming system (Chin and Audah, 2017; Haris et al., 2019), recycling water in vertical hydro farming automatically using IoT and big data analysis (Shrivastava et al., 2021), remote-controlled robot to perform tasks and making decisions for farming (Gondchawar and Kawitkar, 2016), automated control of hydroponic plants using IoT and deep neural network (Mehra et al., 2018), etc. Despite such advancement, the security, reliability, and verifiability issues are required to focus that may arise with this type of remotely controlled system (Huh, 2018).

1.2 Motivation and Problem Statements

The problem statements could be outlined as follows:

a. Several studies have been carried out implementing blockchain, IoT, QR code techniques in food production which mostly focused on smart agriculture.

b. A few existing research addressed some of the farm monitoring attributes and parameters.

c. A few studies indicated data storing strategy or predictive measures for the future.

d. The exploration of integrating IoT and blockchain in vertical farming has been limited. An updated IoT and blockchain based vertical farming system can be designed.

1.3 Thesis Objectives

This research intends to explore the factors of vertical farming and to facilitate the control and monitor vertical farm environment. In a broader perspective, this research covers the fields of *Blockchain* and *Vertical Farming*. In short, the objectives of this research are stated below:

Firstly, to explore the limitations and challenges of existing technological solutions of vertical farming.

Secondly, to propose a blockchain and IoT based framework for automated and reliable vertical farming system.

Thirdly, to evaluate the proposed framework in terms of its reliability, security, and efficiency.

These research objectives will result in two expected outcomes. *Firstly,* finding the research gaps and improvement scopes in making vertical farming system more efficient and reliable.*Secondly,* a prototypical vertical farming system integrating blockchain and IoT ensuring scalable and transparent food production and distribution.

1.4 Methodological Overview

The Design Science Research (DSR) (Peffers et al., 2007) procedure was adopted as the methodology of this study. The methodology was divided into six activities: problem identification and motivation, objectives of a solution, design and development, demonstration, evaluation, and communication.

To identify the problem and motivation, the existing related studies were reviewed to derive the features and required parameters to monitor a vertical farming system. Based on the review findings and state-of-art, the objectives of this research were defined: to outline an IoT and blockchain based vertical farming framework. Next, the architectural design of the framework adopting the emerging technologies was conducted and a prototypical system was also developed. Then, the prototype was simulated and evaluated in lab environment in terms of efficiency, security, reliability, and verifiability. Finally, the study data were synthesized to outline the study findings for reporting.

1.5 Thesis Scope

The scope of this thesis can be described from several perspectives. From an agricultural point of view, the thesis aims to ensure real-time monitoring and control of environmental variables crucial to vertical farming, such as temperature, humidity, and nutrient levels. The difficulties in producing enough food with the increasing rate of population in recent years can be solved by combining emerging technologies. Furthermore, from a technological perspective, this thesis aims to explore the implementation of innovative technologies, specifically blockchain and IoT, in the domain of vertical farming. The scope includes the design and development of a framework integrating these technologies to enhance the efficiency, transparency, and sustainability of vertical farming practices. This study addresses the challenges related to data security and traceability within the agricultural domain.

1.6 Organization of the Chapters

The organization of the thesis for the remaining chapters is as follows:

Chapter 2: This chapter presents the ‘Theoretical Background’ and the ‘Related Work’. In this chapter, the relevant conceptions for this research are discussed. Perceptions include vertical farming, blockchain, and the Internet of Things. Then, the existing related studies are presented. Finally, the research opportunity for this research along with a critical summary of the literature review is outlined.

Chapter 3: This ‘Research Methodology’ chapter depicts the methodology adopted for this research following the DSR approach. The methodology can be divided into six sequential activities: problem identification and motivation, objectives of a solution, design and development, demonstration, evaluation, and communication. The detailed procedures of each of these phases are described.

Chapter 4 This chapter contains the design of the 'Proposed Framework'. The features derived from the findings literature review and considering the features of the architectural design of the framework with four modules are proposed. The data flow among the modules as well as the system workflow is also presented in this chapter.

Chapter 5: This chapter presents the 'Development of the Prototype' based on the architectural design of the framework. The detailed development procedure of a prototype along with the tools/applications used is described in this chapter.

Chapter 6: This chapter describes the 'Simulation and Evaluation of the Prototype'. The prototype was demonstrated in the lab environment and an evaluation study of the developed prototype, as well as the framework, are discussed.

Chapter 7: This chapter contains the 'Discussions and Conclusions' with a summarized discussion of this study's outcomes and implications. Later, the limitations along with the future work of this research have been stated.

CHAPTER 2

THEORETICAL BACKGROUND AND RELATED WORK

This chapter briefly presents the related theoretical discussion for this research background. Next, an overview of the existing works directed to vertical farming in recent years followed by a critical summary of research gaps, is depicted.

2.1 Research Background

This section discusses key concepts like vertical farming, blockchain, and IoT. The application of these emerging technologies in vertical farming is also presented shortly.

2.1.1 Vertical Farming

Vertical farming allows farming as multiple layers of plants horizontally or vertically, focusing on farming upwards rather than outwards (Beacham et al., 2019). This technique requires a very small amount of agricultural land and a soil-free environment. So, vertical farming is more appropriate for urban areas. Figure 2.1 shows a generic structure of the vertical farming system. Vertical farming can be organized generally in three forms- (a) hydroponics, (b) aeroponics, and (c) aquaponics (Birkby, 2016). In hydroponic vertical farming (Figure 2.2 (a)), plants are grown in water only mixed with essential nutrient solutions. In aeroponics (Figure 2.2 (b)), crops are planted in air or mist with very little water. In aquaponics (Figure 2.2 (c)), plants and fish are kept in the same ecosystem producing nutrient-rich waste as plant feed (Birkby, 2016).

2.1.2 Blockchain

Blockchain is a distributed ledger containing blocks with data (messages, proof of work, and hash of the previous block) (I. Islam et al., 2020). The first block is called Genesis block (Zhu et al., 2024). Figure 2.3 shows a typical structure of blocks over the blockchain. Whenever any new data arrives, all the data is hashed, and a link with the previous block is stored and augmented as a new block to the chain. So, the blockchain contains the history of

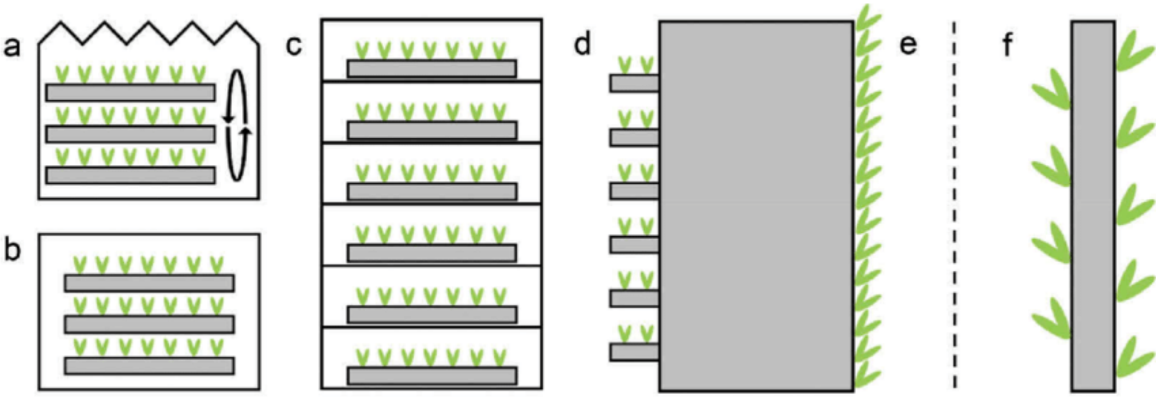
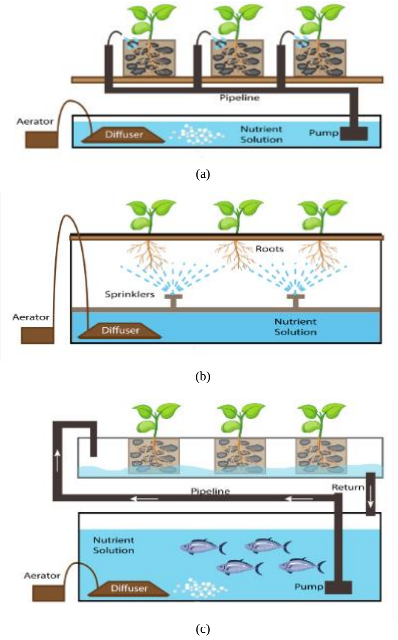


Fig. 2.1. Typical Vertical Farming Structure (Beacham et al., 2019)



(a)

(b)

(c)

Fig. 2.2. (a) Hydroponic vertical farming (b) aeroponic vertical farming (c) aquaponic vertical farming (Velazquez-Gonzalez et al., 2022)

all the transactions from the beginning. Though blockchain was designed to introduce the digital currencies, in recent years blockchain is implemented in various sectors like healthcare (I. Islam and Islam, 2022), financial organizations (Davidson et al., 2016), medicine production and distribution system (I. Islam and Islam, 2023), e-governance (Hou, 2017), agriculture (Sajja et al., 2021), voting (E. Khan et al., 2022), product supply chain (Azzi et al., 2019), etc. Blockchain stores the immutable and irreversible historical records of all transactions to ensure transparency (I. Islam et al., 2020).

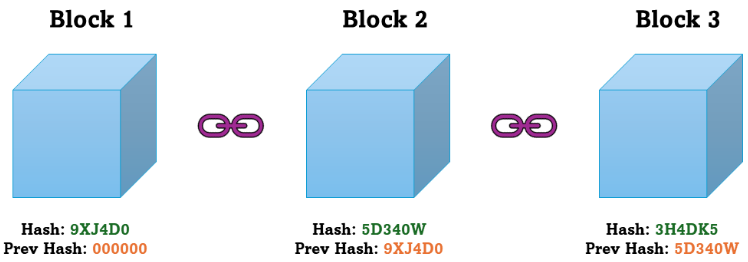


Fig. 2.3. Typical structure of blockchain

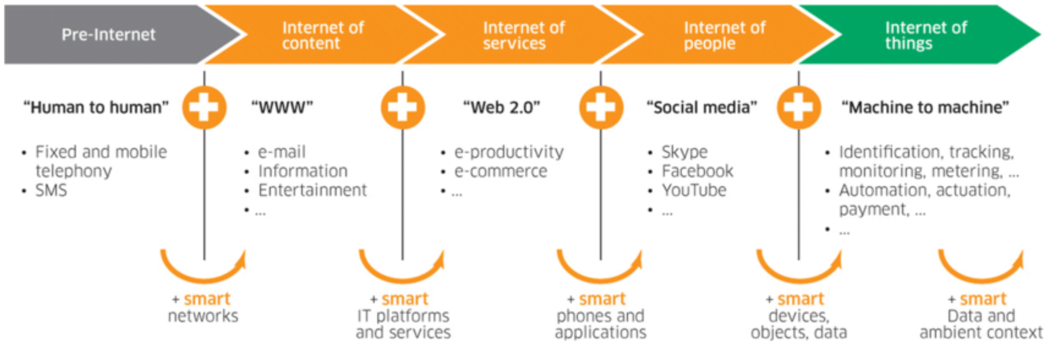


Fig. 2.4. Transition phases from pre-internet to IoT (Khanna and Kaur, 2020)

2.1.3 Internet of Things

The IoT refers to the network of interconnected devices with sensors that can collect data and communicate among them to exchange data (Mouha, 2021). IoT combines existing resources and obtains control over these devices. The concept of IoT was first introduced by Auto-ID Labs of Massachute Institute of Technology (MIT) in the early 1990s (Sinha and Brar, 2021). There are several phases of transition from the pre-internet to IoT (Khanna and Kaur, 2020): (a) in the Pre-Internet phase, two devices could communicate over a fixed telephone line in the form of Short Message Service (SMS). (b) In the second phase named Internet of Content, mobile telephony devices were used for communication enabling larger-sized messages, i.e., e-mail with or without attachments. (c) In the third phase of the Internet of Services, electronic applications like E-productivity, E-commerce, etc. were introduced. (d) Internet of People is the fourth phase which can associate people with each other through social media and other mediums (i.e., Facebook, Skype, YouTube, etc.). (e) The last phase is Inter of Things where the machines can communicate over them automatically. Figure 2.4 shows the phases of the transition to IoT.

2.2 Related Work

This section presents the related studies conducted focusing on vertical farming using IoT and blockchain technology. For the related literature review, the major scholar databases like Google Scholar, Science Direct, Springer Link, IEEE Explorer, ACM Scholar, and Scopus were searched using keywords like *blockchain IoT vertical farming, blockchain vertical farming, IoT vertical farming, food traceability system blockchain IoT,* etc. The related articles are categorized into three subsections- (a) vertical farming using IoT, (b) vertical farming using blockchain, and (c) IoT and blockchain in vertical farming.

2.2.1 Vertical farming using IoT

Some research has been conducted focusing on IoT in vertical farming.

For example, Bhowmick et al. (2019) proposed a conceptual framework for smart vertical farming to analyze the parameters of a plant automatically and report to the users for any abnormality in the reading. A prototype was developed and the sensor data were graphically represented using ThingSpeak and Virtuino. Similarly, Babu et al. (2018) also proposed an IoT-based solution to observe the weather parameters from anywhere especially from the agriculture or vertical farming zone since it is difficult to perform continuous observation through wires and analog devices. In another study, Hidayanti et al. (2020) designed the mockup of an IoT application with solar panels to observe different parameters of hydroponics. The tool was able to regulate the pH conditions and other parameters accurately which resulted in an increased plant growth rate. Again, an automated vertical farming system was developed by Belista et al. (2018) that eliminates the continuous monitoring and involvement of people in residential and commercial areas and controls the light, temperature, humidity, and other nutrients through sensors, while Hanif bin Ismail and Thamrin (2017) also implemented an IoT-based automatic vertical farming system to monitor soil moisture and contents in the water from a web portal. The user could control the water valve through the portal to make necessary changes in the water contents or moisture. In another research, a vertical farm tracking system with a remote controlling facility using a microcontroller and IoT considering the physical conditions of the crops was developed by Chin and Audah (2017) where the system is capable of reporting if any equipment is broken down and all data collected from the crops are also shown in graphical representation for a better understanding of the user. Using Web Ontology Language and IoT, a service-based vertical farm model for smart and intelligent agriculture was designed by Sivamani et al. (2013) where the developed prototype's functionality was evaluated as well as design mistakes were highlighted. In another study, after exploring the required equipment as well as the tools and methods used for an indoor vertical farming system, Haris et al. (2019) implemented a prototypical smart agricultural using Cyber-Physical Systems (CPS)/IoT, while Siregar et al. (2022) conducted Preferred Reporting for Systematic Review and Meta-analysis to derive the potential research gaps in the integration of artificial intelligence (machine learning and IoT) in vertical farming where the studies implemented different approaches (Fuzzy Logic, Neural Networks, Decision Support Systems etc.) with IoT focusing on optimization and automation technologies for high productivity, quality, and profit.

2.2.2 Vertical farming using blockchain

Some studies were found working with blockchain in agriculture. Like, Kamilaris et al. (2019) explored the implications, challenges, and current status of the usage of blockchain in the agriculture and food supply chain. while Awan et al. (2020) introduced an IoT and blockchain-based energy-efficient routing protocol. A simulation and comparative view were conducted to show that the proposed scheme can enhance the network life as well as throughput consuming less energy than the existing IoT-based Architecture. Similarly, N. Mishra et al. (2020) presented the pros and cons of decentralized systems followed by a conceptual framework of a food traceability system using blockchain and QR code technology. The system was able to ensure transparency, efficiency, reliability, and security over the food supply chain. In another research, a blockchain-based smart farming framework using IoT sensors was presented by Sreethi et al. (2022). This system also provided a support system for the farmer.

Table 2.1: Summary of the related articles

Ref	**Objectives/ Primary artifacts**	**Technology**	**Methodology**	**Performance metrics**	**Evaluation findings**
Sivamani et al. (2013)	Vertical farm ontology (VFO)	IoT	–	–	–
Hanif bin Ismail and Thamrin (2017)	Automated Indoor Vertical Farming Watering System	IoT	Simulation	Case study	The system properly displays the farm water data using a web browser with interfacing with the Ethernet shield.
Haris et al. (2019)	CPS/IoT Ecosystem for Indoor Vertical Farming System	IoT	–	–	–
Chin and Audah (2017)	Vertical farming monitoring system	IoT	Simulation	Case study	Increased productivity with less water usage ensuring environmental friendly, and a better farming experience.
Bhowmick et al. (2019)	Vertical farming monitoring system	IoT	Simulation	Case study	Allowing proper monitoring and control of the ambient parameters.
Lin et al. (2018a)	Food Traceability system	Blockchain , IoT	–	–	–
Caro et al. (2018)	Traceability solution for Agri-Food supply chain management	Blockchain , IoT	Comparison between blockchain platforms	Latency, CPU, and Network usage	Hyperledger Sawtooth-based implementation showed better results than the Ethereum one.
Devi et al. (2019)	Smart agriculture architectural framework	Blockchain , IoT	Simulation	Throughput in terms of latency	10 concurrent users were able to use the system
Awan et al. (2020)	A routing scheme for smart agriculture	Blockchain , IoT	Simulation	Network stability period, Energy consumption, Network lifetime, Throughput	The proposed scheme has a longer network life and throughput consuming lower energy than the existing IoT-based Architecture.
Pranto et al. (2021)	A smart architecture model	Blockchain , IoT	Simulation	comparative view of the features; cost of gas	ensuring data availability, security, immutability, and trust among the producers and consumers
Umamaheswari et al. (2019)	Architectural framework for smart agriculture	Blockchain , IoT	–	–	–
N. Mishra et al. (2020)	Food Traceability system	Blockchain , QR code	–	–	–
Belista et al. (2018)	A Smart Aeroponic Tailored for Vertical Agriculture	IoT , mechatronics	Simulation	Case study	The system is able to efficiently monitor the different parameters of crop production.
Babu et al. (2018)	Weather Monitoring System	IoT	–	–	–
Hidayanti et al. (2020)	Hydroponics Plant Monitoring System	IoT	Simulation	Case study	Regulating the pH conditions in the desired range of 6.5 to 7.5 drawing a relationship among the temperature, lighting, pH parameter, and liquid level to monitor the status.

2.2.3 IoT and blockchain in vertical farming

A few studies also aimed to implement both blockchain and IoT in vertical farming. N. Mishra et al. (2020) investigated the characteristics and aspects of blockchain in vertical farming to propose a conceptual model for intelligent farming by combining IoT and blockchain, while Lin et al. (2018b) proposed an IoT and blockchain-based self-organized and secured food traceability system for smart agriculture ecosystem. IoT and blockchain were adopted to automate and improve data recording, data verification, finding anomalies, and effective processing. On the other hand, Caro et al. (2018) introduced a blockchain and IoT-based Agri-Food supply chain management system named “AgriBlockIoT”. After developing a specified use case and deployment in Ethereum and Hyperledger Sawtooth, Caro also evaluated the performance of both deployments in terms of latency, CPU, and network usage. A comparative view between the two deployment approaches was also drawn. Devi et al. (2019) discussed the working principles and features of blockchain technology and proposed an architectural framework for smart agriculture integrating blockchain and IoT. The framework was implemented in the Ethereum private network to validate the enhanced performance of security and data transparency over the system. Pranto et al. (2021) developed a system that uses blockchain to maintain the working principle and IoT to collect data from the plants in pre-harvesting and post-harvesting segments. Pranto et al. (2021) analyzed the gas cost for every blockchain operation as well as extracted the pros of the system like secured, authentic, automated, etc., and cons of the system like blockchain is immutable even in case of unintentional wrong input, very expensive initial setup, highly depended on IoT devices, etc. Umamaheswari et al. (2019) implemented a blockchain and IoT-based system that stores the sensor data and builds smart contracts deployed in the Ethereum private network to support the farmers with various necessary information related to seed, climate, soil, and payment, price in the market, etc, while Praveen et al. (2021) proposed a blockchain and IoT-based agricultural system focusing food supply chain. It could enhance data security as well as track the entire process of product life.

Table 2.1 shows an overview of the related works highlighting the technology used, perfor-

Table 2.2: Parameters required to monitor in vertical farming

Ser.	Parameters	Description	Required Sensor	References
1	Air temperature	These parameters of the farm environment need to be in a favorable range for the plants to ensure proper growth.	Temperature sensor	Jans-Singh et al. (2019), Rao et al. (2020), Suvarna et al. (2020), Chuah et al. (2019)
2	Air humidity		Humidity sensor	
3	Lighting		Light sensor	
4	CO_2 concentration	The adequate concentration of CO_2 must be maintained to help the plants in the photosynthesis process.	CO_2 gas sensor	Jans-Singh et al. (2019), Chuah et al. (2019)
5	Soil moisture	Proper soil moisture is needed for plants to get the nutrients from the water.	Moisture sensor	Suvarna et al. (2020), Chuah et al. (2019), Rao et al. (2020)
6	Water flow	Periodic and proper water flow is needed to ensure the transportation of nutrients along with the water.	Water flow sensor	Suvarna et al. (2020)
7	pH value of water	An appropriate pH level needs to be maintained in the water to keep the plants healthy.	pH sensor	Suvarna et al. (2020), Chuah et al. (2019)
8	Nutrients in water	The plants need suitable nutrients to grow properly.	EC/TDS sensor	Pramono et al. (2020)

mance measuring methodology, performance metrics, and evaluation findings. Moreover, according to the related works, parameters that are required to monitor vertical farming for automated monitoring, generating alerts, controlling the farm, and finally, offering all the crop data to the end-user to ensure the quality of the agri-food is shown in Table 2.2.

2.3 Chapter Summary

The literature survey showed that some research has been conducted using blockchain, IoT, and QR code techniques but most of them explicitly focused on smart agriculture. Moreover, integrating both blockchain and IoT in vertical farming production has not yet been explored. Sensors are to be used to achieve the current status of the parameters. In the existing works, some of these sensors have been used but there was no system containing the features of monitoring all these parameters for vertical farming. Moreover, how the data are stored or if any predictive measure for the future can be drawn from the sensor data was not indicated in any research. Rather, the data were used to monitor the current status and provide an immediate solution or action for the status.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter presents the methodology adapted to conduct this research with a detailed discussion of each phase.

3.1 Key Phases of Research Methodology

From the methodological perspective, the DSR (Peffers et al., 2007) procedure was adopted for this study. DSR is a research paradigm that focuses on the creation (development) and evaluation of innovative artifacts or designs to solve relevant and complex problems (Brocke et al., 2020; Weber, 2010). In traditional scientific research, knowledge is developed for the research purpose whereas DSR highlights the development as well as the application of knowledge in the form of practical solutions. More particularly, this research followed the ’Problem Centered Approach’ since the idea of this research resulted from the observation of the problem. So, the methodology consists of six activities in nominal sequence (Figure 3.1): problem identification and motivation, objectives of a solution, design and development, demonstration, evaluation, and communication.

3.1.1 Problem identification and motivation

In this phase, the existing related studies were reviewed to identify the research problem. The major scholar databases like Google Scholar, ACM digital library, ScienceDirect, SpringerLink, IEEE Xplore, and Wiley Online Library were searched to explore the related studies focusing vertical farming using Iot and Blockchain and to outline a comparative view among the studies yielding to the current research gaps in this field. The keywords used for this search were: vertical farming, IoT, blockchain, internet of things. Boolean operator *AND* was used with the keywords like the following pattern: (“Vertical Farming”) AND (“Blockchain”).

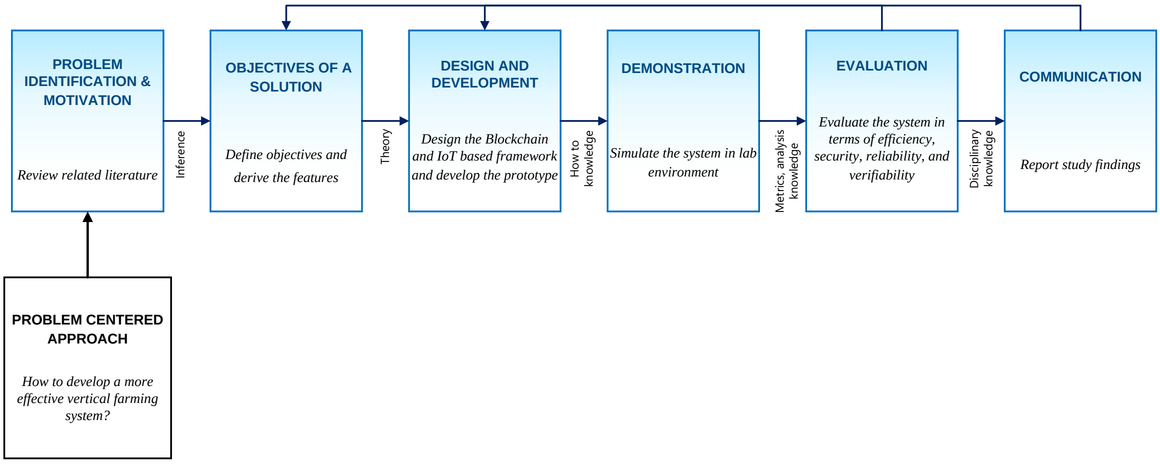


Fig. 3.1. Methodology adopted for this research

3.1.2 Objectives of a solution

The mostly related studies were selected and reviewed to derive the parameters that are required to monitor a vertical farming system as per research objectives. in *Objectives of a solution* phase, the objectives of this research were defined. This study aims to outline an IoT and blockchain-based vertical farming framework providing increased efficiency, security, reliability, and verifiability. The outcome of the literature review was considered to derive the required features of the framework.

3.1.3 Design and development

In the *Design and development* phase, features that are required for controlling and monitoring a vertical farming system were derived. Based on the features, the architectural design of the framework adopts IoT and blockchain to attain the research objectives and required features. The workflow of the model was also designed considering the modules: controller, blockchain, API, and web portal. A prototypical system was also developed based on the proposed framework.

3.1.4 Demonstration

The prototypical system included local blockchain which was simulated in the laboratory environment in the *Demonstration* phase. Conducting lab-based demonstration allowed to control the values of the parameters easily as well as was helpful for isolating how one variable impacts another (Courage and Baxter, 2005).

3.1.5 Evaluation

While simulating the prototype, the system was evaluated through some predefined test cases. For a particular test case, only temperature was considered. Based on this trial case, the prototype was evaluated in terms of effectiveness, security, and reliability during the *Evaluation* phase.

3.1.6 Communication

Data collected from the evaluation was analyzed to generate evaluation feedback and findings. These findings were reported in the *Communication* phase and the prototype was refined according to the results.

CHAPTER 4

PROPOSED FRAMEWORK

This section briefly discusses the system architecture of the proposed framework along with the proposed features.

4.1 System Overview

Food production using the vertical farm or any agri-farm requires producing quality food products following proper guidelines and then packaging and transporting the food to the consumer. In the proposed model, environment data like air temperature, humidity, light, CO_2 concentration; and plant nutrients data like pH of water, EC/TDS of water, moisture in plant roots, etc. are monitored and maintained automatically. These actions will ensure the plants' expected growth and reduce human dependency since the system will automatically address any issue that might arise in those data. So, the system will use IoT sensors to collect those data and store them in the blockchain, and analyzing those data the system will regulate the farm environment and the water, nutrients, etc. of the plants. When the plants are grown enough to be harvested, the farmer will collect the plants and package them. On the packaging there will be QR/bar codes attached and the codes will be mapped to the crop data when the plants were growing. This will enable the consumer to scan the QR/bar codes and get the crop data and thus the system will be able to indicate if the crops were grown following the proper methods and the food is safe to consume.

There are various actors, business models, and stakeholders involved in the process of production and distribution of vertical farming (Caro et al., 2018; Dahlberg and Lindén, 2019). For this research, six actors were considered: suppliers, manufacturers, processors, wholesalers, retailers, and consumers. The suppliers provide necessary growing raw materials like energy, seeds, nutrition, pesticides, chemicals, and to some extent space for farming. Manufacturers, mostly farmers, are responsible for food production and harvesting. While

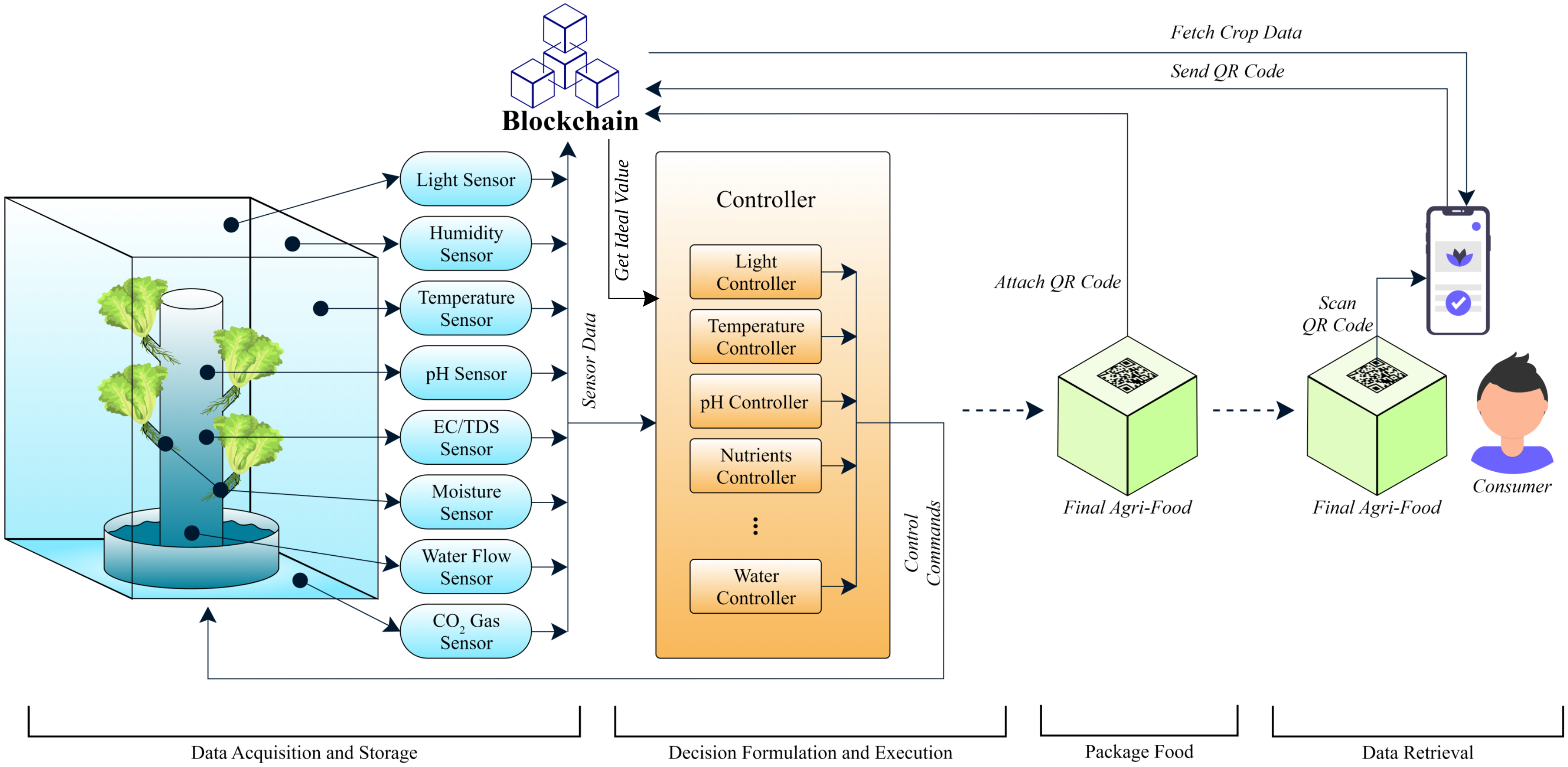


Fig. 4.1. IoT and Blockchain integrated Vertical Farming model

growing the crops, all related data are stored in the blockchain after a time interval. Food processor organizes and store foods in different forms such as baked, iced, canned, etc., and maintains documentation. Besides, complex processes like cooking and combining several ingredients to ensure the highest quality are also done by a food processor. Wholesalers purchase food in large quantities and sell it to retail shops or directly to the end customer. Retailers buy food from wholesalers and sell foods in relatively small quantities for use or consumption only. The final actor in the food production and distribution system is the customer.

All these actors can view the crop-growing data. Transferring the food ownership from one participant to another is considered as a transaction while the previous owner is the sender and the current owner is the receiver.

4.2 Revealed Features

Based on the requirement analysis from the literature review, the following features could be adopted in the proposed IoT and blockchain based framework:

Feature 1. Plant data collection: IoT sensors collect the values of predefined parameters like temperature, humidity, water flow, pH value, and nutrient levels, crop cultivation data for each plant; and keep a record in the blockchain as a secured and immutable ledger.

Feature 2. Real-time and automated farm monitoring: Integrating IoT sensors and devices in vertical farming allows constant monitoring of the parameter values. Real-time collection of data helps to automate decision-making and enhance the efficiency of farming activities.

Feature 3. Efficient supply chain management: The system ensures the management of a product from the manufacturing to sale to the end customer. Any transaction record is stored in the blockchain automatically after verification at each stage.

Feature 4. Verification of food quality standards: The customer can verify the food quality as the shopkeeper states using a QR code, or numerical code. Scanning the code, the system states if the product is authenticated and organic.

Feature 5. Empowerment of consumers with access to detailed product information: Any customer may verify if any food product is authenticated by scanning a QR code from their phone. This allows the customers to access the product information easily in a moment.

4.3 The IoT and blockchain based Framework

From the revealed features listed in Section 4.2, considering Feature 1, 2, 4, and 5 an IoT and blockchain integrated vertical farming model is proposed in this section. Among the three forms of vertical farming (Birkby, 2016), the hydroponics is considered for the proposed framework. The framework consist of four key modules (see Figure 4.1):

4.3.1 Data Acquisition and Storage

The first stage of this system consists of different sensors and IoT devices for data acquisition which is directly connected to the plants. According to the findings of the literature review (shown in Table 2.2) eight sensors are involved in this framework:

1. **Light (environment):** There may be sunlight present in the vertical farming environment or may be not. If there is sunlight in the environment, then the lighting will be changed according to the time schedule as well as the weather changes. Depending on the type of plants, the amount of sunlight, time, and weather the light must be controlled. The plants grow best in red and blue wavelengths only instead of all colors of light (Dahlberg and Lindén, 2019).

2. **Temperature (air):** The temperature of the environment must be moderate for the proper growth of the plants. The temperature of air and water should not be changed frequently with the climate changes. Depending on the plant type, usually, the temperature of the water and the environment should be between 18 to 25°C (Lubna et al., 2022).

3. **Humidity (air):** The air humidity is very closely related to the air temperature. So, it is very important to maintain a balance among these parameters. The humidity of the air must be maintained to a specific range appropriate for the plants. Relatively high humidity causes plants' failure in water balance and transpiration cooling. On the other hand, low humidity increases vapor pressure deficit which in turn results in plant transpiration, causing dehydration, wilting, and necrosis (Rabbi et al., 2019).

4. CO_2 **gas (air):** Since the plants need to use carbon dioxide to build plant tissue, there must be the optimal amount of CO_2 present for plant growth. If the CO_2 concentration drops below 250 parts per million (ppm), plant growth will be stopped (Dahlberg and Lindén, 2019). Therefore, it is required to check CO_2 levels in the environment and if necessary CO_2 supplement must be used. The optimal CO_2 concentration level for plant growth is around 1200 ppm (Dahlberg and Lindén, 2019).

5. **Moisture (root):** The basic need of a plant is water. So, it is very important to keep the roots of the plants moist enough. If the moisture of the root decreases, that means there is a deficiency of water at the root. To keep the root moist, some materials like coco peats are used at the roots. Using a moisture sensor, the amount of moisture present at the plant roots is measured.

6. **Water flow (water):** The moisture of the plant roots and water flow at the roots are quite related. The water flow is required to increase the moisture of the plant roots. In vertical farming (especially hydroponics), water flow at the roots of the plants is ensured by circulating water repeatedly in a closed loop system (Dahlberg and Lindén, 2019).

7. **EC/TDS (water):** In a vertical farm, only mineral nutrients are added which basically naturally exist in soil like Nitrogen, Phosphorus, Potassium (NPK), calcium nitrate, and magnesium sulfate (Epsom salt) (Dahlberg and Lindén, 2019). Other nutrients like oxygen, hydrogen, and carbon are usually obtained from the air and water. Vitamins need not be imposed explicitly since they are produced by the plants themselves. The required nutrient levels depending on the plant type, need to be checked regularly.

If necessary, organic nutrients need to be added in a specific amount.

8. **pH (water/ soil):** The pH of the nutrient solution mixed with the water supplies proper nutrients to the plants. Since there is no soil in vertical farming, it is very important to maintain the pH level of the water to ensure proper absorption of the nutrients in the water. Usually, the water is required to be slightly acidic with an optimal pH value of 5.5 to 6.5 (Lubna et al., 2022).

To ensure the proper regulation of the plant parameters, it is good to use a greenhouse environment. All the sensors as well as IoT devices are placed in suitable places, for example, the pH sensor, EC/TDS sensor, and water flow sensor are kept in the water; the moisture sensor is placed in the roots of the plants for measuring soil moisture; the light sensor, temperature sensor, humidity sensor, and CO_2 gas sensor are placed in the farm environment. The pH sensor senses the pH level in the water, the EC/TDS sensor identifies the electrical conductivity and total dissolved solids in the water, the water flow sensor determines if the water is circulated periodically, the moisture sensor senses if the plants' roots are moist enough, the light sensor, temperature sensor, and the humidity sensor will sense the farm environmental data, the CO_2 gas sensor will sense the CO_2 concentration in the air. For each batch of plants, a unique code (bar code/ QR code/ numeric code) is generated and assigned to each batch. This code must be unique to define this batch only and link to the blockchain for associated data stored over the blockchain. The code is mapped with the crop data that were recorded throughout the entire production time in a specific time interval of that crop. Data are collected after a very small time interval (i.e., 10 ms) but not this large amount of data are stored in the blockchain. After a pre-specified time interval (i.e., 10 min), all sensor values are stored for a plant in the blockchain.

4.3.2 Decision Formulation and Execution

Based on the data collected at a particular time, the system makes control decisions. For each parameter, an accepted range is specified from the beginning in the blockchain. Comparing the current readings retrieved from the blockchain, with the ideal values, the system determines the parameters that need to be adjusted (increase or decrease). So, depending on the control decisions, instructions are generated and executed to regulate the parameter values at an acceptable level. For example, the pH and EC/TDS levels in water are required to be in a certain range for the expected plant growth and crop production. If these levels do not remain in the desired range, the system will generate alerts. On the other hand, to maintain the desired pH level, there are several options like using pH up and pH down products or using automated pH controller. and also, automatically power on the pH and nutrients dispenser to match up the ideal pH and EC/TDS level. Similarly, the system can act on the unfavorable readings of the other sensors like automatically controlling the light and temperature of the farm, increasing the water flow if the plants' roots are not moist enough, and increasing the CO_2 concentration in the air if it falls under the required level. Another example is in day time if the weather is cloudy, then the expected amount of sunlight won't be received although it is daytime. So, the light sensor is used to sense the amount of light, if enough light is not present, the secondary light sources will be automatically switched on.

4.3.3 Package Food

When the crops are mature enough, they are harvested. After necessary processing, the foods are delivered to the consumer. Before delivery, the foods are packaged and the associated QR/bar/ numeric code is given to the package.

4.3.4 Data Retrieval

To know the value of the parameters stored in the blockchain the unique code attached on a food package is used. Scanning the code/ giving the code as an input, the entire crop data are fetched from the blockchain and shown to the user. The crop data can increase the credibility of the food if it was produced following the quintessential process and the food is fresh, safe to consume, and healthy. Since the data is stored in the blockchain, it cannot be altered, thus the consumer will be able to rely on the integrity of the data. This data retrieval can be performed from only verified actors discussed in the following subsection.

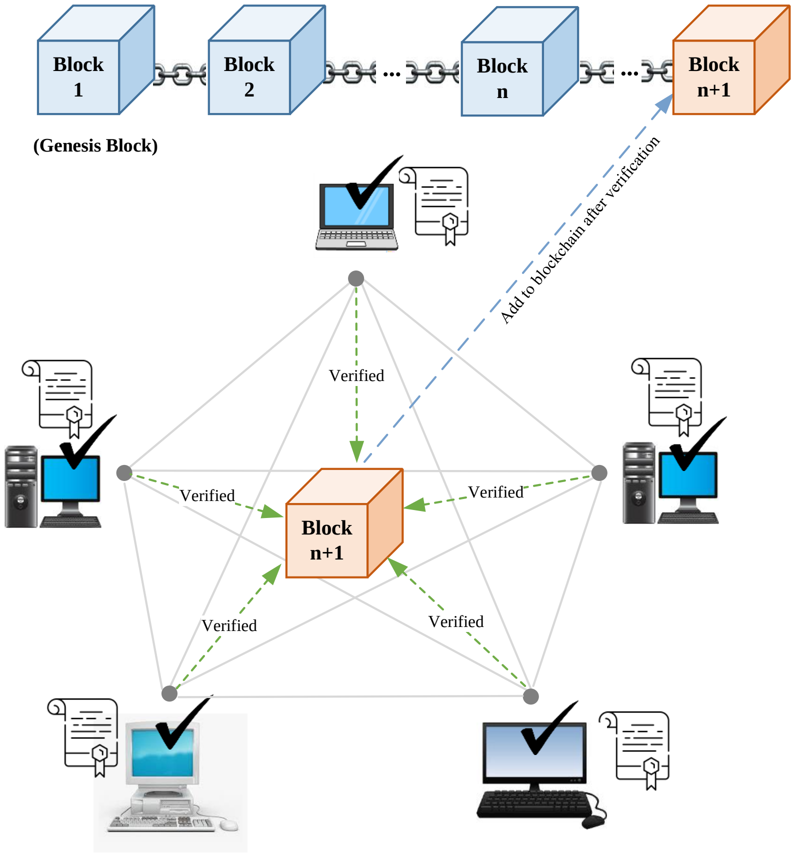


Fig. 4.2. Blockchain structure for proposed framework

4.4 Workflow of the system

The framework supports data storage and retrieval from the blockchain (Figure 4.2). Different nodes under a farm are connected through a common network. The first block of the blockchain is called the genesis block. Other blocks are added to the blockchain by storing the hash value of the previous block (link) with the current block. Whenever the (n+1)th block is ready to add, at first the block is verified by the other nodes and then it is added to the blockchain. Once the new block is added to the blockchain after verification from the other nodes, the data cannot be deleted. And no unauthenticated user can access the data which makes the blockchain secure.

The data flow (Figure 4.3) over the model goes according to the order of four phases: firstly, data acquisition from the plants using several sensors is performed and data are stored. After processing the collected data, some decisions regarding the controlling instruction of the farming environment are determined, generated, and executed automatically. This process is continued till the crops are ready to harvest. When the crops are ready to harvest, they are

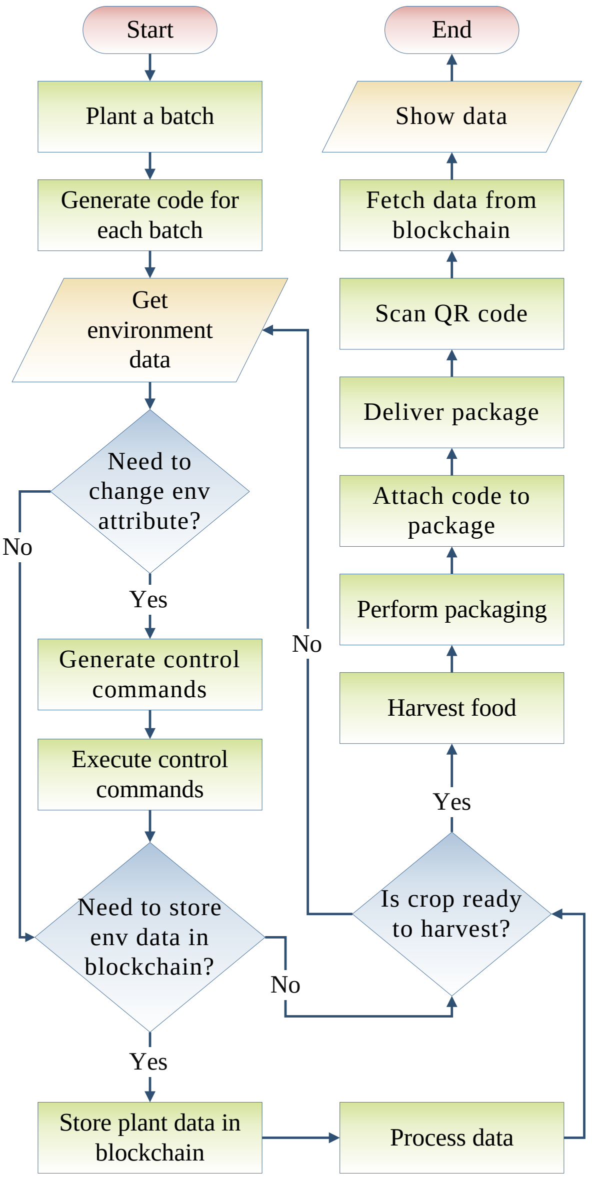


Fig. 4.3. Workflow of the proposed system

collected and packaged for sale. For each package, a unique identifier code (i.e., bar code/ QR code) is generated from the batch code and attached to the package. Then the package is delivered to the next participant. This package may travel to different actors before arriving at the end consumer. At any stage of this journey over the food production and distribution system, all historical data regarding the package as well as growing the crop can be retrieved anytime from any participant.

In this model, IoT enables real-time monitoring and control of essential parameters of a vertical farm. IoT devices (sensors) are deployed throughout the farm to collect data on various factors like temperature, moisture, light, nutrient levels, etc. This data is analyzed to make informed decisions. By continuously monitoring these parameters, IoT ensures that the farm operates within optimal conditions for crop growth and resource utilization. Additionally, IoT devices allow for remote monitoring and control, reducing the need for manual intervention and enabling farmers to respond promptly to changes or issues within the farming environment.

CHAPTER 5

DEVELOPMENT OF THE PROTOTYPE

This chapter discusses the development of the prototype considering the architectural design of the framework.

5.1 System Overview

The proposed blockchain and IoT-based vertical farming system can be divided into four components. Figure 5.1 depicts the tools used for each of the components and the way the components are connected as a system. The components are listed below.

(a) IoT and Environment Controllers

(b) Blockchain

(c) API Server

(d) Web Application

The *IoT and Environment Controllers* component contains sensors, microcontroller, and controllers. Sensors collect the farm environment data and send them to the microcontroller. The microcontroller gets the ideal farm environment values from the blockchain using the APIs and then it compares the sensor data with the ideal value and makes decisions on whether the farm environment needs to be regulated or not. If it's needed, the controllers get the control commands from the microcontroller and regulate the farm environment as per instruction. The microcontroller also sends the sensor data using the APIs so that it can be saved in the blockchain. So here the *API Server* component can communicate with the *Blockchain* component meaning it can get data from and store data in the blockchain. The *Web Application* component also uses the APIs to get data from and send data to the blockchain.

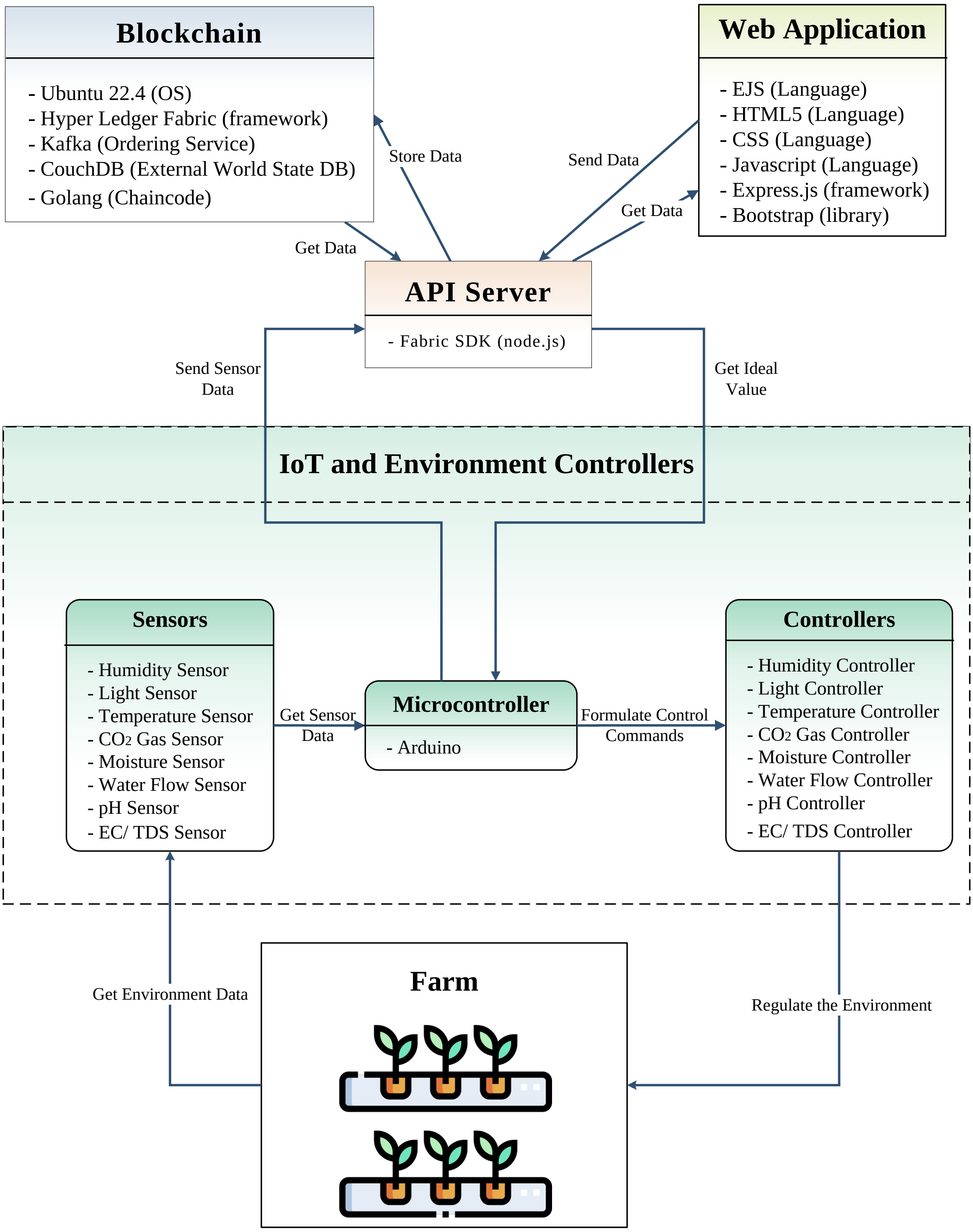


Fig. 5.1. Tools used to develop different modules

5.2 System Development

This section describes the details of the components from the development and technical point of view.

(a) **IoT devices and farm environment controllers**: To monitor and control the farm environment through IoT devices and controllers, Arduino and sensors at different places were used. For example, light, humidity, and temperature sensors were placed in the center region of the farm; pH, EC/TDS sensors were installed in the water; root moisture sensors were attached at the root of the plants; water flow sensor was kept in the water flowing pipe; CO_2 gas sensor was placed at the near floor region of the farm since CO_2 is heavier than air.

The farm environment controllers were responsible for regulating the environmental attributes. For example, the light controller controls the light (natural or ultraviolet) entry to the farm or some specific region; the temperature controller could reduce or increase the overall temperature as per requirement; the pH controller regulates the pH level of the water. The sensors provided the sensor data immediately to the farm controllers and the controllers decided automatically as per the predefined configuration. Hence, the sensor data was sent to the API server to upload it to the blockchain in specific time intervals.

To get the environmental data humidity sensor, light sensor, temperature sensor, CO_2 gas sensor, moisture sensor, water flow sensor, pH sensor, and EC/TDS sensor are being used. Arduino is the microcontroller working as the brain of the IoT and environment controllers. As the controllers, there are motors and actuators, like when more water flow is needed the water pump is turned on; when light is more than needed the light source can be dimmed, when EC/TDS is less the EC/TDS dispenser will mix more EC/TDS to match up the expected level. Arduino collects the environmental data using the sensors and sends it to the API server to store in the blockchain and it gets the ideal environment data from the blockchain via the API server. Then it

Algorithm 1 Check Sensor Data and Formulate Decision

```
Procedure checkSensorDataAndFormulateDecision():
    Input: {sensor_name, sensor_reading, min_threshold, max_threshold}
    Decision Formulation:
    $ideal\_value \leftarrow \frac{min\_threshold+max\_threshold}{2}$
    if sensor_reading < min_threshold then
        $adjustment\_percentage \leftarrow \frac{ideal\_value}{sensor\_reading}$
        controllers[$sensor\_name$].$increase\_value\ \_by$($adjustment\_percentage$)
    else if sensor_reading > max_threshold then
        $adjustment\_percentage \leftarrow \frac{sensor\_reading}{ideal\_value}$
        controllers[$sensor\_name$].$decrease\_value\ \_by$($adjustment\_percentage$)
    else
        continue
    return
End Procedure
```

compares the current environment data with the ideal values and then formulates the decision on sending control commands to the environment controllers.

Algorithm 1 shows the approach for formulating decisions by the environment controllers. Values measured by the sensors, the minimum and maximum threshold values are considered as input. These minimum and maximum values are fetched from the blockchain for a specific type of plant. Firstly, the middle value (average of minimum and maximum values) for the ideal data band is calculated. Next, the adjustment percentage is calculated by determining how far off the current value is with respect to the ideal middle value. Then, there can be three scenarios: (i) the sensor reading is less than the minimum threshold, (ii) the sensor reading is greater than the maximum threshold, and (iii) the sensor reading is in the ideal data band; decisions are formulated for these scenarios as: (i) increase and (ii) reduce respectively the level of the environment attribute according to the adjustment percentage, (iii) do nothing. If the adjustment percentage is higher, then the change will be drastic which means the system will try to make the environment ideal for the plan as soon as it can.

(b) **Blockchain**: Among the three types of blockchain (Al Mamun et al., 2022) (public, private, and consortium), private blockchain was chosen for this framework. In a public blockchain (Al Mamun et al., 2022), anyone with internet connectivity can become an authorized user to access the blockchain. The main limitation of the public blockchain for this research area is: that data are uploaded slowly and anyone can access the blockchain anonymously. The second type is private (Al Mamun et al., 2022) which is restricted through some access control rules in a closed network. This type of blockchain is suitable for an organization where one or more administrators can control the authorization of the users over the network. The third type is consortium blockchain (Al Mamun et al., 2022) where more than one organizations are involved. Here, anyone with internet connectivity can not access blockchain rather he/she must be a registered one. For this research, Hyper Ledger Fabric (Androulaki et al., 2018), an open-source enterprise-grade distributed ledger framework from the Linux Foundation, was hosted as the private blockchain.

The Hyperledger Fabric was appropriate for the IoT-based vertical farming system for several reasons. Firstly, Hyperledger Fabric is designed for permissioned networks. For having this feature, it is possible to configure the blockchain as such the authorized participants can join and interact with the network keeping sensitive business-related information private and allowing specific data to be publicly accessible. Secondly, Hyperledger Fabric's channel architecture allows the creation of private communication channels among the network participants. This feature is useful in separating data access among different entities. Different private channels for different entities/stakeholders of the vertical system can be implemented. For example, the channel for the farm owner and fertilizer provider can be private and won't be accessible to other farm owners or consumers. Thirdly, Hyperledger Fabric provides a highly modular and customizable architecture. So it's possible to configure and design the blockchain as per the system's needs. Fourthly, the smart contract is called a chaincode in Hyperledger Fabric which is used to define business logic and rules. It allows multiple programming languages to write chaincodes that provide flexibility in the development process.

Blockchain was configured and implemented using the Hyperledger Fabric framework where Kafka was used as the ordering service. For accessing the world state of the blockchain, CouchDB was used. To write the chaincodes (smart contracts), golang was used. The blockchain gets invoked by the API server. By the APIs, the CRUD (create, read, update, delete) operations can be performed. The plant data is stored in the blockchain and also the ideal and stored plant data can be fetched from it to compare.

(c) **API Server**: To access the blockchain, an API server was developed using Fabric Node.js SDK. The API server ensures communication among all other components. The API server is used to save data to and read data from the blockchain; the web app uses the API server to get data from the blockchain and save data to the blockchain; IoT devices use APIs to send sensor data to the blockchain to store and get the ideal data from the blockchain.

(d) **Web Application**: A web application was developed to access farm data over the blockchain and system. The web app had two types of accounts: one was to view and control the farm data (for farm owners/farmers) and another was to only view the plant data (for consumers). In the admin web app, all the plant data (the values perceived by the sensors) can be viewed in real time. Based on the data, the owner can make decisions if required though the system makes the decisions automatically. The ideal plant data is also displayed in comparison with the current plant data. In the consumer web app, any user can scan a QR code and view the historical status of the plant and get to know if the plant was produced following the proper methods or environment.

The system can be accessed through a web portal. The front end was developed in *EJS* (Embedded Java Script)[1]. EJS is an effective, elegant, and easy template language to generate HTML markup with CSS and JavaScript. For this system, HTML5, W3.CSS[2], and ECMAScript 2020[3] was used. Figure 5.2 presents the dashboard accessible from the admin account showing the current status of all plants in a vertical

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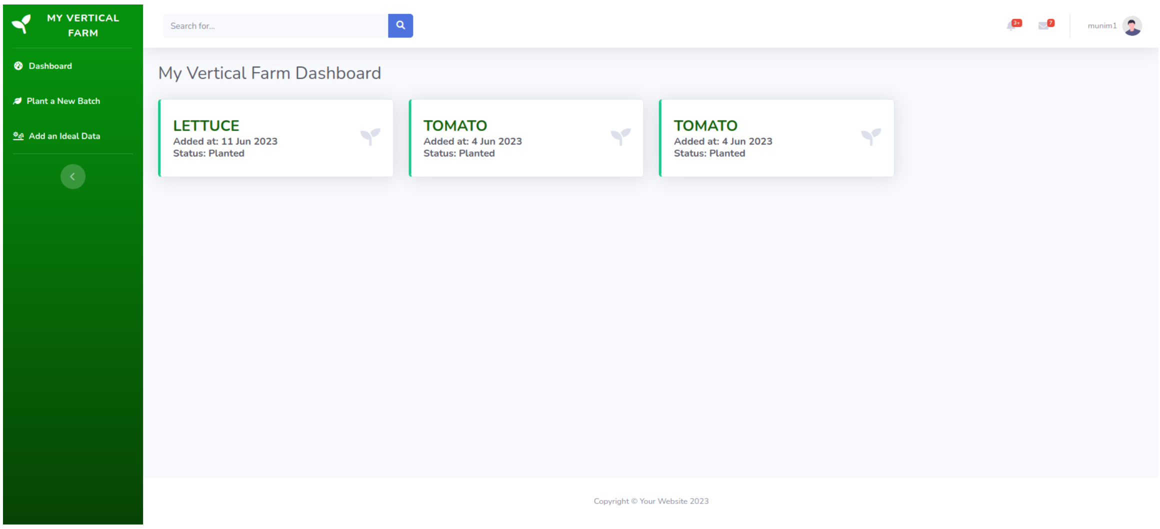
[1] https://ejs.co/

[2] https://www.w3schools.com/w3css/w3css_versions.asp

[3] https://www.w3schools.com/js/js_versions.asp



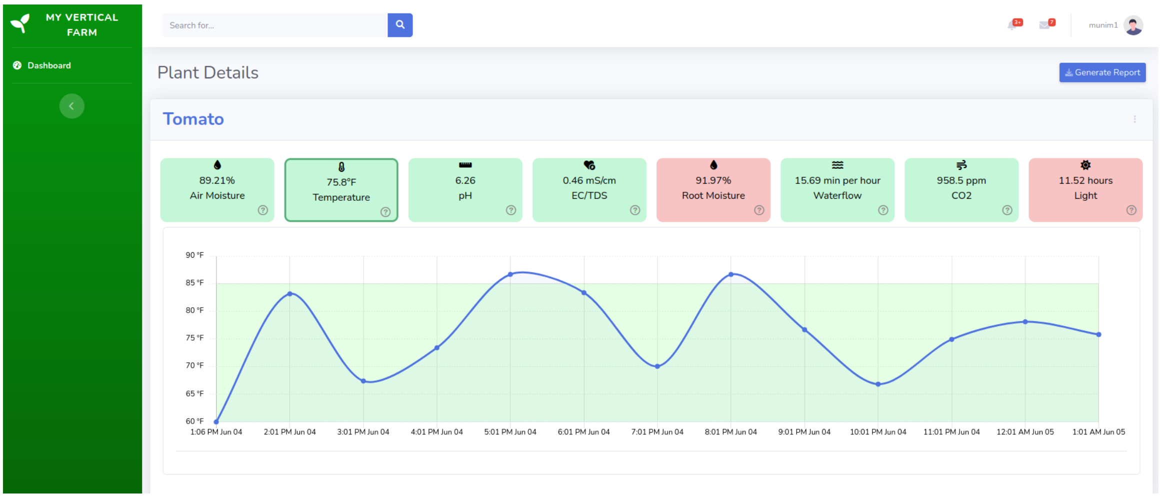
LETTUCE
Added at: 11 Jun 2023
Status: Planted

TOMATO
Added at: 4 Jun 2023
Status: Planted

TOMATO
Added at: 4 Jun 2023
Status: Planted

Fig. 5.2. The admin dashboard of the web portal

farm and Figure 5.3 shows the values of different parameters for a plant. These data can be accessed after logging into the web application (Figure A.1), it shows all the plants planted on the farm and upon clicking on a plant the user can see the details of that batch of plants. Each of the parameters is displayed in separate cards where the card contains the name of the parameter (i.e., Root Moisture), the value of that parameter (i.e., 91.97%), the ideal range of that parameter on the tooltip, and the card will be colored as green if the current value falls under the ideal data range or red otherwise (Figure A.2). Upon clicking on a parameter card, a line chart will be displayed with the historical data of that parameter. The ideal data band is displayed in the chart with a light green color so that it can easily be understood if the data falls out



89.21%
Air Moisture

75.8°F
Temperature

6.26
pH

0.46 mS/cm
EC/TDS

91.97%
Root Moisture

15.69 min per hour
Waterflow

958.5 ppm
CO2

11.52 hours
Light

Fig. 5.3. Values of different parameters for a plant


(a) (b)

Fig. 5.4. Prototype (hardware) of the proposed system

of the ideal data range then how far off the current data is or any previous data was and if the data falls under the ideal range, it is also visible very easily. Hovering the mouse pointer on a data point, the value of that time is displayed on a tooltip (Figure A.3). Using the web application, an admin user is also able to store the ideal plant environment values in the blockchain so that it can be used for that plant.

After developing all these components, they are needed to be integrated as such all the components can interact and communicate among themselves as per the system design. A prototypical version of a vertical farm involving three parameters light, temperature, and root moisture was developed (Figure 5.4).

CHAPTER 6

SIMULATION AND EVALUATION OF THE PROTOTYPE

This chapter depicts the evaluation of the developed prototype. Firstly, the environment setup for the simulation of the prototype is presented. Next, the evaluation in terms of effectiveness, latency, reliability, and security is presented.

6.1 Environment Setup

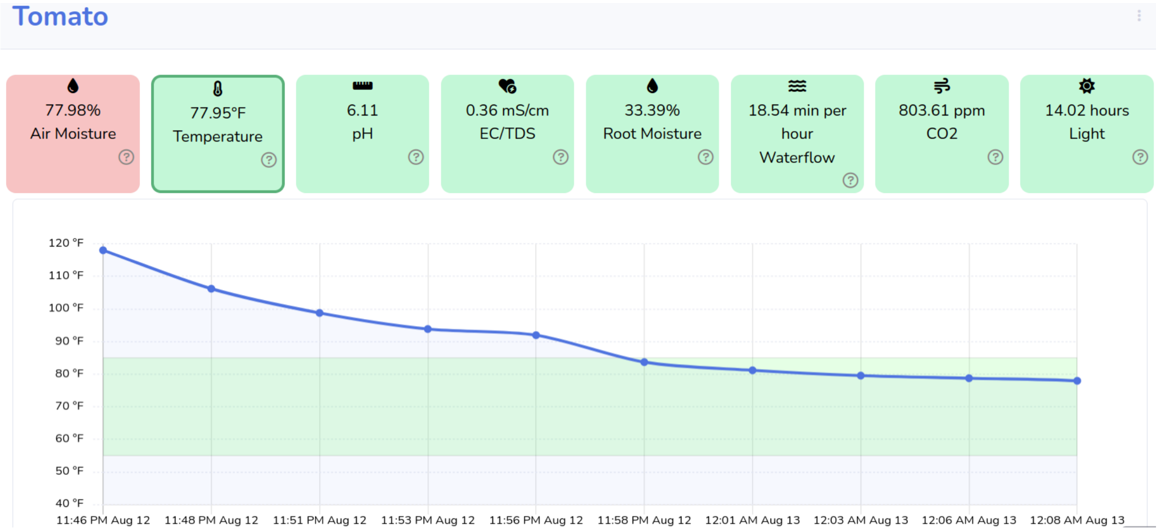
The prototypical system was simulated on a Linux VM where the host was a Windows PC. The host computer was running Windows 10 Pro with an 11th Gen Intel(R) Core(TM) i5-1135G7 @2.40GHz processor and 16GB RAM. Ubuntu 22.4 was running on the virtual machine with 8GB RAM.

6.2 Evaluation Study

To evaluate the system, three parameters (air temperature, light, root moisture) were considered in a lab environment where it was considered that the environment was conducive for the plant for other attributes except for those three. For effectiveness and reliability analysis temperature was considered; for latency analysis, all three attributes were considered. The temperature was configured as 120°F where the ideal temperature was 55°F to 85°F).

6.2.1 Effectiveness Analysis

To evaluate the effectiveness of the system under the experimental condition, the temperature sensor and controller were considered since all other attributes of the environment were suitable for the plant. The temperature sensor was determining the high temperature near 120°and the microcontroller immediately generated a control command to cool down the environment. The high temperature was stored in the blockchain and after some time with the help of the controller, the temperature was brought down to 80°F. At this point, the microcontroller stopped generating control commands since the temperature was in the ideal


Tomato

77.98%
Air Moisture

77.95°F
Temperature

6.11
pH

0.36 mS/cm
EC/TDS

33.39%
Root Moisture

18.54 min per hour
Waterflow

803.61 ppm
CO2

14.02 hours
Light

Fig. 6.1. Details of the plant temperature data in the web portal (day 2 iteration 2)

Table 6.1: Detailed data for effectiveness analysis (temperature)

Day	**Time Needed (seconds)**			
	Iteration 1	**Iteration 2**	**Iteration 3**	**Average**
1	690	735	765	730.00
2	711	765	698	724.67
3	702	712	719	711.00
4	713	714	719	715.44
5	719	703	708	709.94
6	725	701	699	708.33
7	731	684	692	702.33
Average				**714.53**
Standard Deviation				**9.69**

temperature range (55°F to 85°F). The whole process was iterated three times for seven days in a row (Table 6.1). The average time taken for cooling down the environment was 714.53 seconds (11.9 minutes) and the standard deviation was 9.69 seconds which indicates that the system was stable.

Figure 6.1 presents the second iteration of day 2 of the evaluation study. The temperature was stored in the blockchain during the cooling process at predetermined intervals of time (90 seconds), and the web application retrieved this data to generate the line chart. The transition of temperature from high to ideal temperature shows that the temperature dropped quickly while it was extremely high and slowly when it was getting close to the ideal temperature. This demonstrates how effective the system is because the speed at which the

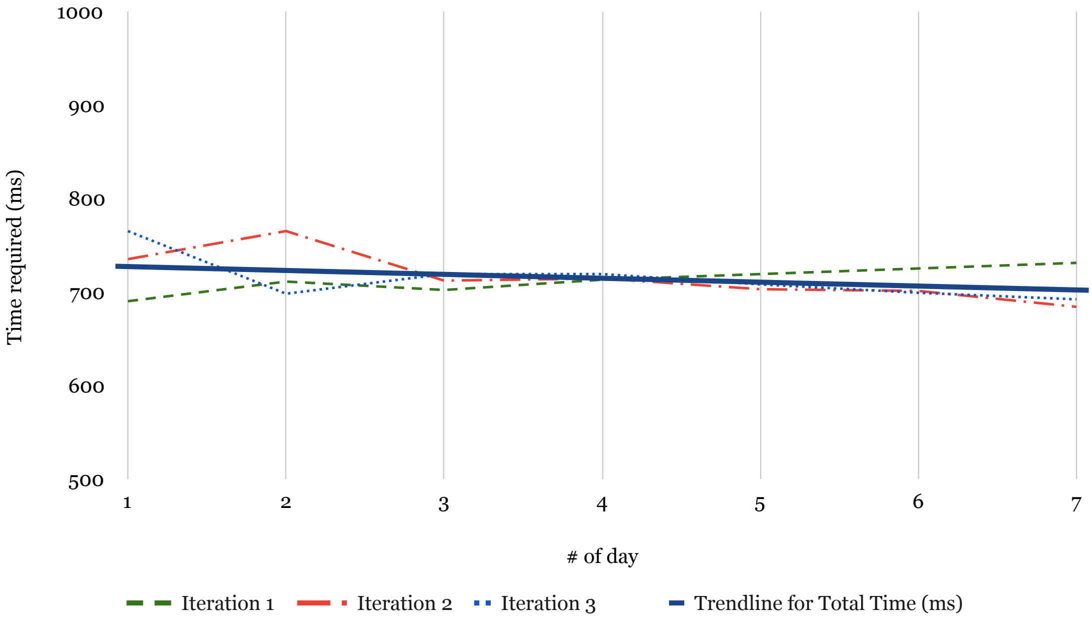


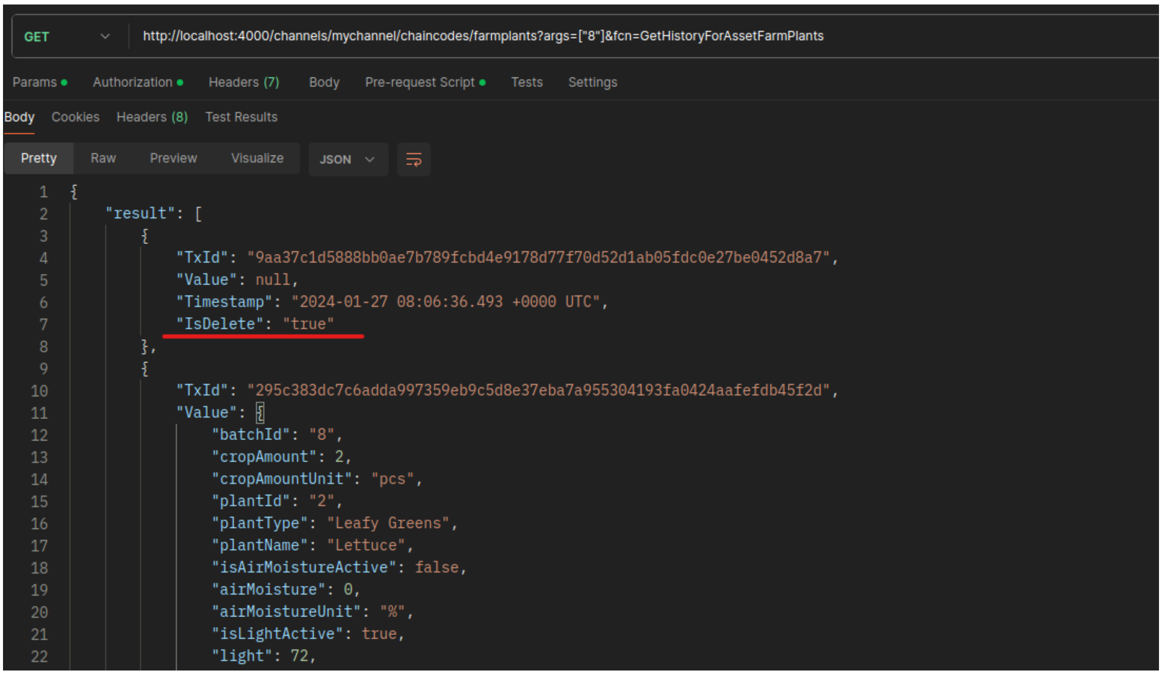
Fig. 6.2. Reliability analysis (experimental data)

temperature decreases is determined by the differences between current and ideal values; the greater the difference, the faster the temperature changes according to the Algorithm 1.

6.2.2 Reliability Analysis

Reliability of a system refers to providing a continuous consistent performance by the system (Laprie and Kanoun, 1996). The experimental finding for effectiveness analysis shows the reliability of the system (Figure 6.2). The three dotted lines (green, red, and blue) depict the values of iterations 01, 02, and 03 respectively for seven days. The trendline is shown by the thick blue line. The almost straight trendline states that the total time required for each iteration is almost the same. This proves the reliability of the system.

The blockchain is immutable in nature (I. Islam et al., 2020). Once data is inserted or updated into a blockchain, the history of the data cannot be erased (Figure 6.3). Even if one data is deleted, it only changes the $isDeleted$ flag to $true$ keeping all the previous history intact. Such architecture of the blockchain makes the data reliable, trustworthy, and verifiable to the users. In the case of this system, the plant data is visible to the consumer before purchasing or consuming and any party in the entire production-to-consumer chain



```
{
    "result": [
        {
            "TxId": "9aa37c1d5888bb0ae7b789fcbd4e9178d77f70d52d1ab05fdc0e27be0452d8a7",
            "Value": null,
            "Timestamp": "2024-01-27 08:06:36.493 +0000 UTC",
            "IsDelete": "true"
        },
        {
            "TxId": "295c383dc7c6adda997359eb9c5d8e37eba7a955304193fa0424aafefdb45f2d",
            "Value": {
                "batchId": "8",
                "cropAmount": 2,
                "cropAmountUnit": "pcs",
                "plantId": "2",
                "plantType": "Leafy Greens",
                "plantName": "Lettuce",
                "isAirMoistureActive": false,
                "airMoisture": 0,
                "airMoistureUnit": "%",
                "isLightActive": true,
                "light": 72,
```

Fig. 6.3. Reliability analysis (block specification)

can easily verify the data.

For example, in the experimental setup, the proper and quick handling of the high (non-ideal) temperature was possible to observe from the web portal. The agri-producer or farmers thus can rely on the system to take immediate and accurate actions and the consumers (and other entities in the supply chain) can rely on the agri-product to be organic and healthy.

6.2.3 Latency Analysis

For latency analysis, three test cases involving parameters temperature, light, and root moisture were considered. The latency was measured from two perspectives: data storage time and block access time.

Time for data storage in the blockchain involves two parts: time to send data to the server and the creation of a block. Figure 6.4 shows the average time of data sending time and block creation (one to fifteen blocks) for three parameters. From the total time of data storage, the trend line depicts that the data storage time is almost constant and 1.6 seconds on average.

The average block access time is depicted in Figure 6.5. The detailed data for block access time analysis can be found in Table B.1.

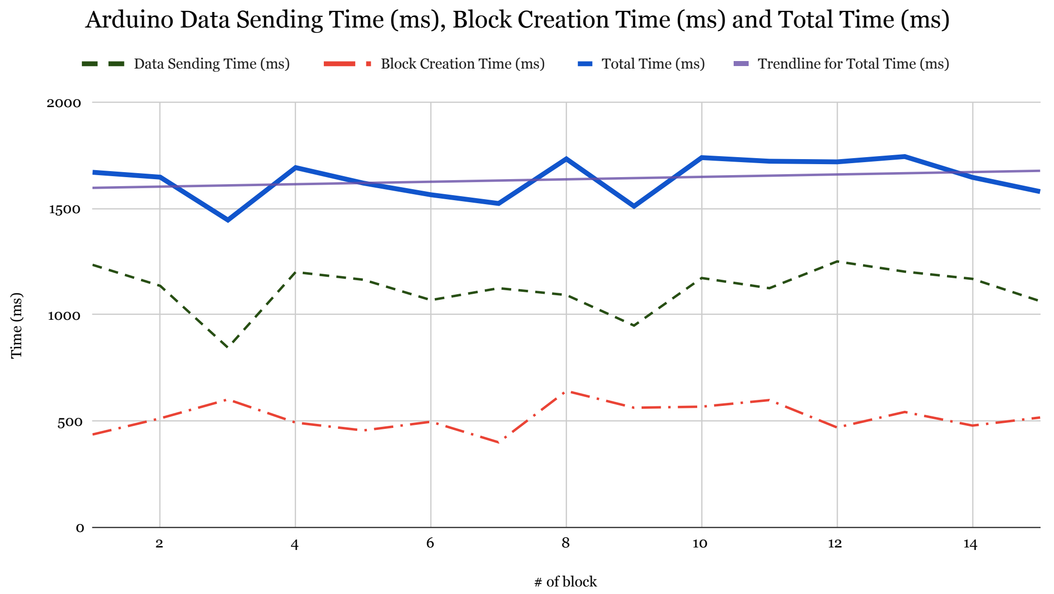


Fig. 6.4. Latency analysis (Block creation time)

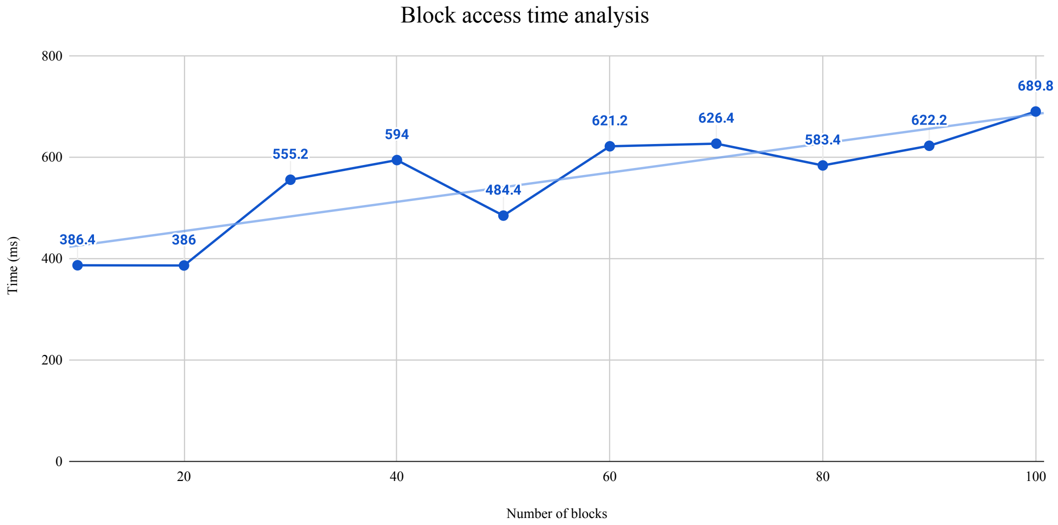


Fig. 6.5. Latency analysis (Block access time)

6.2.4 Security Analysis

Storing data over the blockchain ensures the security of the system and data. Again, to store any block, the block must be verified by the other users since no unauthenticated user can access the system as well as the blockchain. In this proposed system, a new block is generated whenever there is any data insertion or update occurs while the smart contracts are executed only after the agreement of the transaction participants. As such no blocks can be added without verification.

For the experimental setup, due to the integration of blockchain, the temperature data was not accessible to unauthenticated users who were even in the same network. Once the data was saved in the blockchain, it was not possible to tamper the data. Even if any authorized user somehow could tamper with the data, the history of the data modification would be visible making the system very easily auditable.

Though blockchain integration in any information system using proof of work requires more energy consumption, it provides the most transparent transactions. Hence, it is important to analyze the key security concerns like Denial of Service (DoS), Sybil, mining, short-range, long-range, coin age accumulation, etc. attacks, while blockchain is not vulnerable to most of these cyber attacks (Nair and Dorai, 2021).

6.2.5 Comparison with existing systems

A comparison with nine other similar existing systems is presented in Table 6.2. Among them, five systems used IoT only as technology, one used CPS and IoT, and three used blockchain and IoT similar to this research. Most of them (n=8) did not perform any performance analysis of their proposed system whereas the studies mostly implemented automation (n=8) in the vertical farming management system. Seven studies developed a prototype of a vertical farming system while a few (n=2) could ensure data transparency.

Table 6.2: Comparison with existing studies

Ref	**Technology used**	**Performance analysis**	**Automation**	**Prototype developed**	**Data transparency**
Bhowmick et al. (2019)	IoT	✗	✓	✓	✗
Hanif bin Ismail and Thamrin (2017)	IoT	✗	✓	✓	✗
Hasanat et al. (2022)	IoT	✗	✓	✓	✗
Ng et al. (2023)	IoT	✗	✓	✓	✗
Yusuf et al. (2022)	IoT	✗	✓	✓	✗
Haris et al. (2019)	CPS/ IoT	✗	✓	✓	✗
Caro et al. (2018)	Blockchain & IoT	✓	✓	✗	✓
Pranto et al. (2021)	Blockchain & IoT	✗	✓	✗	✓
Umamaheswari et al. (2019)	Blockchain & IoT	✗	✗	✓	✓
This System	Blockchain & IoT	✓	✓	✓	✓

CHAPTER 7

DISCUSSION AND CONCLUSIONS

This section provides concluding remarks from various perspectives: thesis outcomes, implications, limitations, and potential opportunities for future work. Initially, the outcomes of this research are outlined. Then, thesis implications are articulated followed by the limitations and future research opportunities.

7.1 Thesis Outcomes and Implications

The thesis outcomes can be discussed as below:

a. **Research gaps and future research opportunities:** The extensive review of the studies related to this research derives the existing research gaps in vertical farming. This will also imply future research directions to improve the performance of a virtual vertical farm.

b. **A set of features along with the parameters required for vertical farming:** Based on the literature review, a set of features required to automate are derived. For example, collecting plant data, real-time and automated farm, efficient supply chain management, etc. Again, several parameters (i.e., light, temperature, moisture, water level, humidity, etc.) that would be required to monitor vertical farming are also extracted. Continuous monitoring of these parameters is essential to ensure the ideal food production environment.

c. **An IoT and blockchain-based framework:** This research presents an IoT and blockchain-based automated framework for smart vertical farming. The framework might additionally assist consumers in distinguishing fresh food items and increasing their consumption reliability.

d. **Evaluation of the framework:** The evaluation of the prototype from latency and performance perspective shows that the system is quite well performed to implement on a large scale. Again, storing data over the blockchain ensures data transparency and security.

e. **Addressing Global Challenges:** The study recognizes ongoing global challenges in agriculture, including population growth, resource deficiency, climate change, and global warming. To face these challenges all over the world, combining emerging technologies (like IoT and blockchain) for vertical farming can be a great solution. By offering a sustainable, efficient, and safe food production solution, the framework contributes to food security and environmental sustainability efforts.

f. **Facilitate future research opportunities:** The proposed framework has the potential to revolutionize agricultural practices. Continuous research, studies, design, development, and integration of these technologies may assist in ensuring a more sustainable future.

7.2 Thesis Limitations

The limitations of this thesis can be outlined as:

- **Food quality assessment was not performed:** This research included a thorough literature review to derive the required parameters for monitoring a smart vertical farming system. Later, considering the parameters an IoT and blockchain-based framework was also proposed. However, this framework did not consider the food quality with the farm monitoring as well as the quality of the foods produced from vertical farming was not evaluated.

- **Prototype considered a limited version of vertical farming:** The prototype was developed involving IoT and blockchain technologies but only three parameters were considered instead of the eight parameters that were outlined in the literature review. Again, in the hardware version only one type of plant (lettuce) was planted. Moreover, a lighting module is required to grow a multilayer plant which was not adequate (Cambriglia, 2023).

- **Prototype is accessible from a single platform:** According to the design, the prototype was accessible through the web portal only. Farmers and end users can't get access to the virtual vertical farm through a mobile app.

- **Containers in single PC were considered as different nodes:** From the designing point of view of blockchain, multiple nodes have access to the blockchain. However, the blockchain was not distributed over different nodes (devices) throughout the prototype development. In the prototype, a single PC was used to produce *Docker* containers, and each container communicated with the blockchain as a separate node.

7.3 Future Work

The following directions could be explored by prospective future research:

a. Involving more features: In the future, more features from the listed features in Section 4.2 could be integrated into the system architecture to generate a more insightful evaluation of the framework. For example, to perform feasibility and outcome analysis, a prototype involving the assessment of both the food production environment and food quality would be developed.

b. Developing concrete implementation in large scale: Currently, the framework is implemented in a prototypical version. In the future, this system can be implemented as a real-world project with the actual blockchain access that will help to measure the system performance and cost accurately resulting in the real-life challenges of this framework.

c. Integrating Quick Response (QR) code: While providing the users to check the production environment of food, there can be printed the link as a QR code on the label. This will also provide better usability for the customers.

d. Developing the system for different platforms: The future work will involve designing the architectural framework in both mobile and web application versions. Currently, web application ensures effectiveness and efficiency. But for more user satisfaction as well as User eXperience (UX) (Munim et al., 2020), the system would be implemented through usable mobile user interfaces.

e. **Ensuring a better usability of the system:** The future work will involve investigating the usability of the system through evaluation studies (Bhowmick et al., 2019; Jahangir et al., 2023; Munim et al., 2023). Based on the study findings and design guidelines, the system interfaces can be improved.

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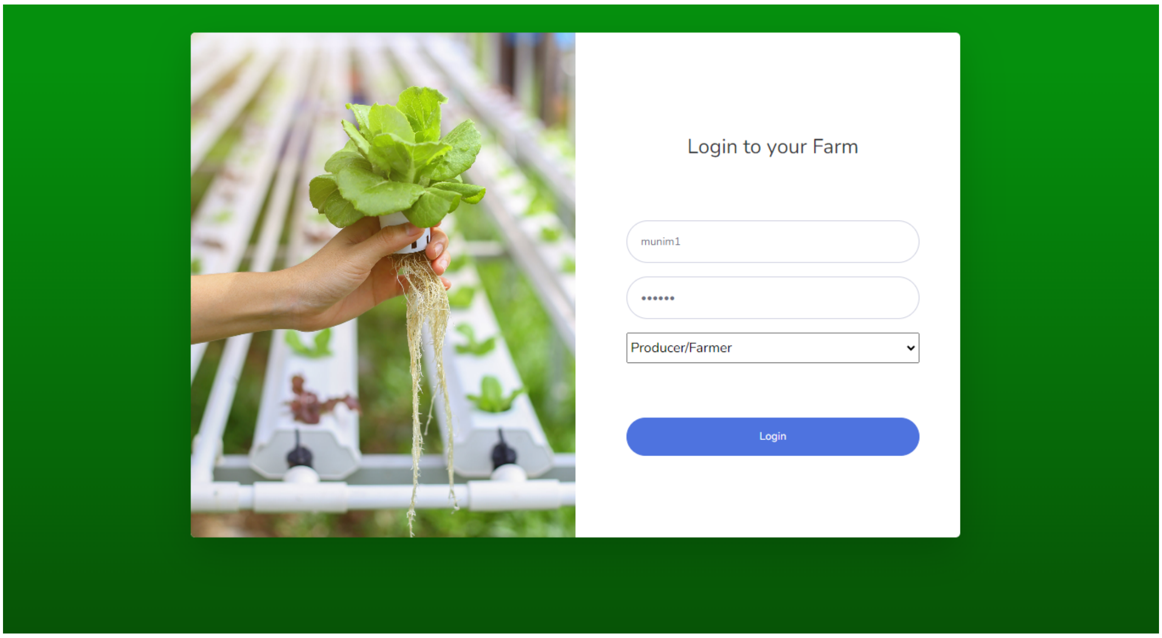
Appendices

APPENDIX A

Screenshots of the System



munim1

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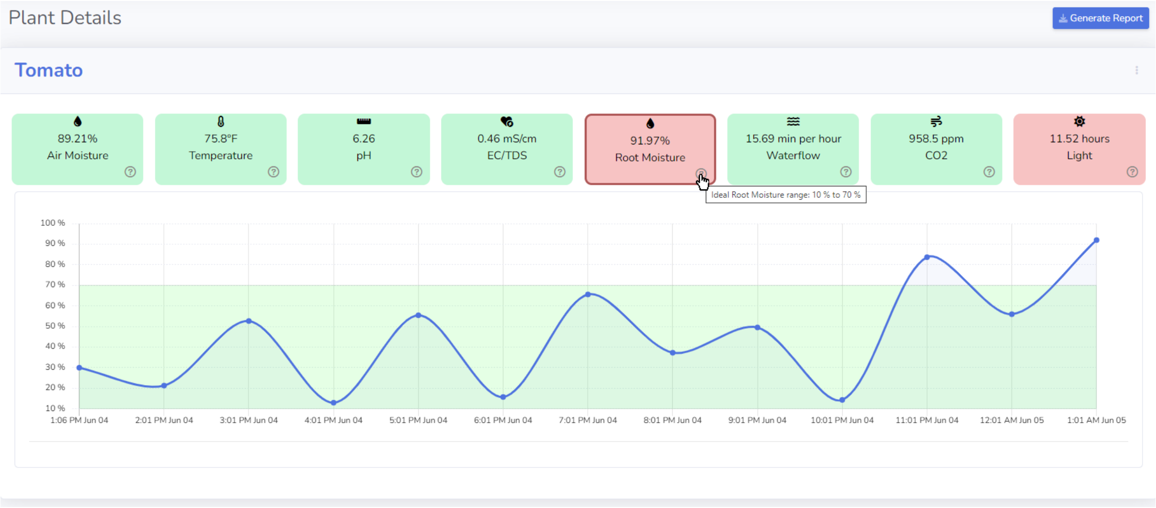
Producer/Farmer

Fig. A.1. Login page of the web portal



89.21% Air Moisture

75.8°F Temperature

6.26 pH

0.46 mS/cm EC/TDS

91.97% Root Moisture

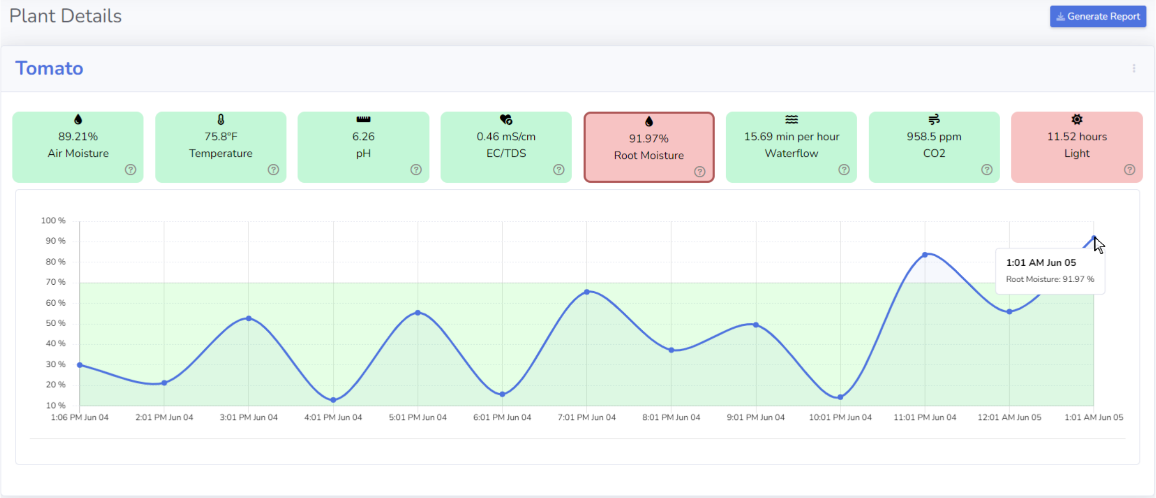
15.69 min per hour Waterflow

958.5 ppm CO2

11.52 hours Light

Ideal Root Moisture range: 10 % to 70 %

Fig. A.2. Ideal data range in a tooltip



89.21%
Air Moisture

75.8°F
Temperature

6.26
pH

0.46 mS/cm
EC/TDS

91.97%
Root Moisture

15.69 min per hour
Waterflow

958.5 ppm
CO2

11.52 hours
Light

1:01 AM Jun 05
Root Moisture: 91.97 %

Fig. A.3. Current data in the chart is displayed in a tooltip

APPENDIX B

Evaluation Study Datasheet

Table B.1: Detailed data for block access time analysis

#	Number of blocks	Data size (KB)	Time (ms)					Average (ms)
			Iteration 1	Iteration 2	Iteration 3	Iteration 4	Iteration 5	
1	10	8.43	376	422	339	425	370	386.4
2	20	16.56	467	324	483	291	365	386
3	30	24.7	530	501	475	472	798	555.2
4	40	32.83	718	654	522	483	593	594
5	50	40.97	499	416	477	490	540	484.4
6	60	49.1	573	495	916	520	602	621.2
7	70	57.22	578	474	616	714	750	626.4
8	80	65.36	735	598	527	498	559	583.4
9	90	73.49	770	727	636	433	545	622.2
10	100	81.62	625	658	703	712	751	689.8