Software Engineering Department

Braude College

Capstone Project Phase A

Smart Irrigation System
Smart Farm

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Link to GitHub:

https://github.com/SharkZeedan/Smart-Farm

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Abstract

The escalating water crisis, intensified by climate change and inefficient irrigation practices, highlights the urgent need for innovative solutions in agriculture. This project proposes the development of a Smart Irrigation System designed to leverage Industrial Internet of Things (IIoT), Industry 4.0 principles, and advanced mechatronics to optimize water usage in agricultural practices. The system concept integrates real-time data collection from underground humidity and temperature sensors with weather forecast APIs to enable precise, data-driven irrigation scheduling tailored to plant-specific requirements.

The proposed architecture consists of four interconnected layers: Sensor, Edge, Cloud, and Application layers. Sensors, deployed by a robotic system, are envisioned to gather environmental data and transmit it via MQTT protocols to a cloud-based infrastructure for analysis. A user-friendly application interface is intended to provide farm managers with tools to monitor real-time data, receive alerts, and control irrigation processes through a secure platform integrated with Firebase.

This project aims to demonstrate the potential of IoT-based smart irrigation systems in promoting sustainable agriculture. By focusing on resource conservation and environmental sustainability, the project provides a conceptual framework for future advancements in precision irrigation and adaptive farm management.
Keywords: Smart irrigation, IIoT, sustainability, real-time.

1.Introduction

The escalating water crisis, exacerbated by climate change and unsustainable water management practices, poses a critical challenge to global agriculture [12]. Agriculture accounts for approximately 70% of global freshwater withdrawals, with droughts and water scarcity leading to widespread crop failures and food insecurity[10]. The UN predicts that by 2025, over 1.8 billion people will live in regions plagued by water scarcity, severely impacting agricultural sustainability and livelihoods[13]. Addressing these challenges requires innovative solutions that enhance water use efficiency and mitigate the impacts of climate change[14].

To address the challenges of water scarcity and inefficient irrigation, several key strategies are proposed by global organizations. The Food and Agriculture Organization (FAO) recommends focusing on water-efficient technologies, drought management tools, and the promotion of sustainable farming practices to mitigate water stress in [13]. A primary approach involves implementing smart irrigation systems that integrate real-time monitoring of environmental parameters such as soil moisture and weather conditions[5]. The present study aims to design, implement, and empirically validate an advanced irrigation system based on underground sensor technology. This system will be tested in both urban and suburban settings, providing data-driven irrigation solutions that respond to local water availability and crop [14].The goal is to reduce water waste while optimizing agricultural productivity through automated, responsive systems that can be monitored remotely via mobile applications [13].

The proposed irrigation system leverages advanced technologies to address several key challenges in modern agriculture. Specifically, it utilizes underground Internet of Things(IoT)-based sensors to continuously monitor soil moisture, soil temperature, and environmental factors, which are crucial for efficient irrigation[4]. One of the core strengths of this solution is its ability to remotely control irrigation, responding to real-time data from the sensors and adjusting water usage accordingly. This capability significantly reduces water waste, ensuring that irrigation occurs only when and where it's needed. In addition to automated controls, the system is designed to operate through a user-friendly mobile application, allowing farmers and agricultural managers to monitor and adjust the system remotely, from anywhere.

Our project combines IIoT , Industry 4.0 and mechatronics to optimize irrigation systems. IIoT enables real-time monitoring through underground sensors, automating irrigation and reducing water waste. Industry 4.0 principles allow intelligent automation for adaptive irrigation based on environmental changes[8]. Mechatronics enhances precision with advanced controllers for accurate water delivery.

Deploying IIoT technologies, such as humidity and temperature sensors, faces challenges like ensuring data accuracy and reliability under varying environmental conditions, including soil composition and temperature fluctuations. Stable communication between sensors and central systems can be hindered by interference, signal degradation, and power limitations, especially in remote areas. Integrating Industry 4.0 principles adds complexity, requiring robust algorithms, powerful computing infrastructure, and seamless interoperability among devices. Achieving scalability and flexibility in dynamic agricultural environments is also difficult. Despite these challenges, IIoT and Industry 4.0 technologies can optimize irrigation, improve water management, and reduce wastage, addressing water scarcity effectively.

Our project aims to revolutionize irrigation practices on a farm where irrigation is currently poorly controlled and monitored. By collaborating with the mechanical team, a robotic system will be deployed, equipped with sensors for humidity, temperature, light, and distance. This robot will collect critical environmental data and upload it to the cloud, where the software team will store it in Firebase. From there, we will analyze the data and present it in an intuitive and informative manner through our website. Additionally, we will integrate a weather forecast API to predict irrigation needs for the upcoming days, providing a proactive approach to water management. Our solution focuses on optimizing irrigation for a single type of plant, ensuring precise water delivery while offering the functionality to irrigate manually when alerts are received, addressing immediate needs efficiently.

2. Literature review

Before delving into the literature review, it is essential to acknowledge some existing solutions in the agricultural sector that leverage IIoT (Industrial Internet of Things) and Industry 4.0 principles to irrigate and monitor water usage smartly. These innovative solutions have paved the way for smarter and more efficient farming practices.Table 1 highlights some of these solutions,showcasing their features and used technologies.

Reference	System Type	Technologies	Sensors & Actuators.
CropX [19]	Smart Agriculture platform.	Cellular,Wifi.	Soil & Moisture Sensors.
HydroPoint [20]	Weather-Based irrigation.	Wifi,Cellular Networks.	Weather station Sensors.
Matellio [21]	IoT-Based irrigation.	Wifi &LoRaWAN.	Automated Valve System.
Netafim [17]	Digital Farming Platform.	Cellular Networks.	Flow Measurement Systems.
Valley Irrigation [18]	Precision Irrigation Management.	Wifi,4G/LTE.	Weather & Pressure monitoring Systems.
Proposed Solution	Robotic-enabled. Smart Irrigation & Website.	MQTT,Cloud,Wifi.	Humidity & Temperature Sensors,Automated irrigation Valves, Robotic Deployment Mechanism.

Table 1.Comparison of some of the features of the most relevant smart irrigation systems and the proposed solution.

The table serves as a foundation to evaluate and highlight the advancements and limitations of existing smart irrigation systems. By analyzing the technologies, sensors, and system designs outlined, we can identify gaps that our proposed solution addresses. For instance, while many systems leverage IoT [10] and communication protocols like WiFi and Cellular Networks, they often lack real-world implementation, scalability, or the integration of Industry 4.0 principles [1] . Our project stands out by embracing Industry 4.0 concepts, such as real-time data collection, automation, and intelligent decision-making, alongside integrating environmental data from soil moisture and temperature sensors with a robust MQTT-based communication protocol [23]. This ensures precise irrigation control tailored to plant-specific needs. Moreover, the table showcases the absence of predictive capabilities or user-friendly interfaces in some systems, which we address through weather API integration and a comprehensive dashboard for farm managers. This comparative analysis validates the relevance of our approach and underscores its potential to contribute to sustainable and efficient water management practices in agriculture while aligning with the advancements of Industry 4.0.

2.1 *Industry 4.0*

Industry 4.0 in agriculture, particularly in irrigation, is transforming how water resources are managed by integrating advanced technologies such as IoT, AI, cloud computing, and automation [15]. By enabling the real-time collection and analysis of data from sensors embedded in soil, weather stations, and irrigation systems, these technologies allow for precise control of irrigation schedules and water[1]. One such solution is *Netafim's Smart Irrigation System* [17], which uses IoT-based sensors to monitor soil moisture levels and automatically adjust water distribution based on weather forecasts and crop needs. This system helps farmers optimize water use, reduce waste, and improve crop yields.

In this context, Industry 4.0 technologies also integrate predictive analytics, which use historical data and machine learning algorithms to forecast future irrigation needs[9]. For example, precision irrigation solutions like *Valley Irrigation's Valley 4.0* [18]combine IoT sensors with advanced analytics to provide farmers with real-time insights into soil moisture levels and weather conditions, allowing them to make data-driven decisions regarding water use. These systems are designed to reduce water consumption while ensuring that crops receive the optimal amount of moisture.

By enabling automated, data-driven irrigation management, these Industry 4.0 solutions help address water scarcity issues, improve agricultural productivity, and contribute to sustainable farming practices. The incorporation of cloud-based platforms and advanced analytics further enhances the ability of farmers to monitor and control their irrigation systems remotely, offering greater flexibility and efficiency[2] .

2.2 *Soil Moisture Sensors*

Soil moisture sensors measure the amount of water present in the soil, providing critical data to optimize irrigation schedules . These sensors can be capacitance-based, resistive, or use time-domain reflectometry (TDR) to gauge moisture levels accurately. They are typically installed at root zones to measure water availability directly where plants absorb it [10]. Soil moisture sensors help prevent over-irrigation, reduce water wastage, and promote healthier plant growth by delivering water only when needed . Advanced models can integrate with IoT systems for real-time monitoring and remote data collection[6].

2.3 *IIoT*

IIoT (Industrial Internet of Things) is transforming the agriculture sector by providing real-time data collection , advanced analytics, and automation that enhance decision-making processes. This technology enables farmers to monitor soil moisture, weather conditions, and crop health with precision, which leads to optimized resource use and higher productivity[7]. One notable solution in this space is John Deere's Operations Center, which integrates IIoT into its farming equipment, such as tractors and harvesters[16]. The platform connects sensors, GPS, and machinery to a cloud-based system that tracks environmental data and offers actionable insights. These insights allow farmers to adjust irrigation schedules, track crop growth, and manage resources more effectively, ultimately improving crop yield while reducing water and resource waste[2] . This integration of IIoT not only boosts efficiency but also enables sustainable farming practices by providing a comprehensive view of farm operations in real time.The schedule of a basic system is demonstrated at Figure 1 below.

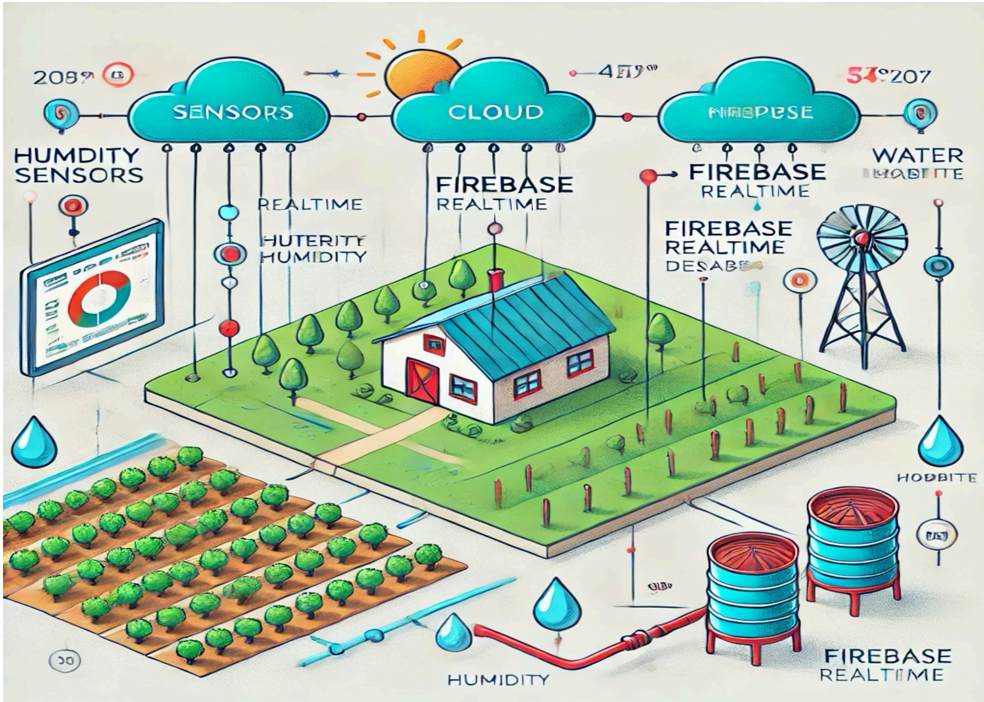

Figure 1. Architecture of a basic IOT functioning irrigation system

2.4 *MQTT Protocol*

The MQTT (Message Queuing Telemetry Transport) protocol is a lightweight messaging protocol widely used in Internet of Things (IoT) applications for efficient and reliable communication. It operates on a publish/subscribe model, which allows devices to exchange messages through a central broker. The protocol is designed for low-bandwidth, high-latency, or unreliable networks, making it an ideal choice for remote and resource-constrained environments. MQTT supports encryption through TLS and offers configurable Quality of Service (QoS) levels (0, 1, 2) to ensure reliable message delivery based on application requirements. Its lightweight design minimizes overhead, while its robust features enable secure and efficient data transmission across distributed systems.

In this project, the MQTT protocol is utilized as the primary communication protocol for transmitting data between field sensors and the central control system. MQTT's lightweight and efficient design enables real-time data transfer, making it ideal for managing irrigation schedules and monitoring environmental conditions. The protocol's configurable

Quality of Service (QoS) ensures reliable data delivery even in the face of network instability, which is critical for precise water management in agricultural settings.

The system leverages MQTT for its ability to handle real-time updates, such as soil moisture levels and weather forecasts, ensuring timely decision-making and irrigation adjustments. Additionally, its support for TLS encryption ensures secure transmission of sensitive agricultural data, aligning with the project's focus on secure and efficient communication.

Given the water-conscious nature of Israeli agriculture, where smart irrigation is crucial for desert and semi-arid farming, MQTT's robust data transmission capabilities ensure precise irrigation control. The use of MQTT complements the system's goal of conserving water while maintaining optimal crop yields under challenging environmental conditions.

MQTT over WiFi Specifications (Israel)

Parameter	Value
Frequency band	2.4 GHz and 5 GHz (WiFi) - MOC approved bands
Channels	13 channels (2.4 GHz), 24 channels (5 GHz)
Channel bandwidth	20/40/80 MHz (compliant with MOC standards)
Network security	TLS 1.3 (meets Israeli cyber security guidelines)
Data rate	Up to 150 Mbps (standard Israeli infrastructure)
QoS levels	0, 1, 2 (MQTT standard)
Range	100m direct, extended via Israeli telecom infrastructure
Latency	10-50ms (typical in Israeli network conditions)
Topology	Star/Tree with central broker
Operating temperature	-20°C to 60°C (suitable for Israeli climate)
Power source	220V AC (Israeli standard)
Interference immunity	Medium with local WiFi networks
Scalability	Up to 1000 nodes per broker
Compliance	MOC certified for agricultural IoT use

Figure 2. MQTT's Protocol Specs in Israel.

Resources of the figure have been collected from [25].

3. Engineering process:

3.1 *Design Thinking*

During our recent Design Thinking meeting [36], we as the software team converged with a group of mechanical engineers to collaborate on the smart irrigation project. The Design Thinking process includes five key steps: empathize, define, ideate, prototype, and test [37]. These phases guided our efforts to address the project's challenges and create a robust, innovative solution.

The session began with the **empathize** phase, where we sought to understand the needs, challenges, and perspectives of all stakeholders involved. Each team member brought unique insights into the project's potential implementation, with the software team outlining the application's architecture and data flow, and the mechanical engineers sharing intricate details about sensor design, humidity detection mechanisms, and potential valve control systems. Through active listening and open communication, we gained a deeper understanding of the project's context and goals.

In the **define** phase, we synthesized the insights gained during our discussions to articulate the main challenges and requirements for the smart irrigation system. We methodically worked through several assigned tasks, breaking down complex challenges and setting clear objectives to bridge the gap between software algorithms and physical engineering requirements.

The **ideation** phase was marked by vibrant brainstorming sessions, where we explored innovative solutions, including automated irrigation algorithms and real-time monitoring frameworks. We enthusiastically discussed general ideas and conceptual frameworks, considering unconventional approaches to optimize system functionality, from ground-level sensor placement to automated water management.

In preparation for the prototype phase, we mapped out our project's blueprint, transforming our collective expertise into a cohesive, cutting-edge technological solution. This blueprint laid the groundwork for creating early representations of our ideas, focusing on integrating sensors, data transmission, and control systems.

By the conclusion of the meeting, the synergy between our teams was evident, aligning us for the upcoming test phase. We anticipated evaluating and iterating on the system to refine its functionality and ensure it met all project goals. This collaborative journey not only strengthened our team dynamics but also ignited excitement for the transformative potential of our smart irrigation project.The prototype of our project is expected to be developed soon followed by the enhanced testing phase.

3.2 *Mechanical Perspective*

Since the mechanical engineering team plays a crucial role in bringing this project to life by deploying the sensors via a robotic vehicle to the farm and taking responsibility for transmitting sensor data to the cloud via MQTT [23], it is worth highlighting the collaborative efforts between us, the software team and the mechanical team. We engaged with them numerous times, both through Zoom meetings and in-person sessions at the college. Their expertise was invaluable in helping us understand the practical aspects of deploying the project, the communication protocols utilized, and the measures they implemented to ensure data accuracy during cloud transmission. They clearly demonstrated that their methods would enable reliable and real-time data updates, which are essential for the system’s success and efficiency. Their guidance greatly enhanced our understanding and strengthened the integration between the software and hardware components of the project.

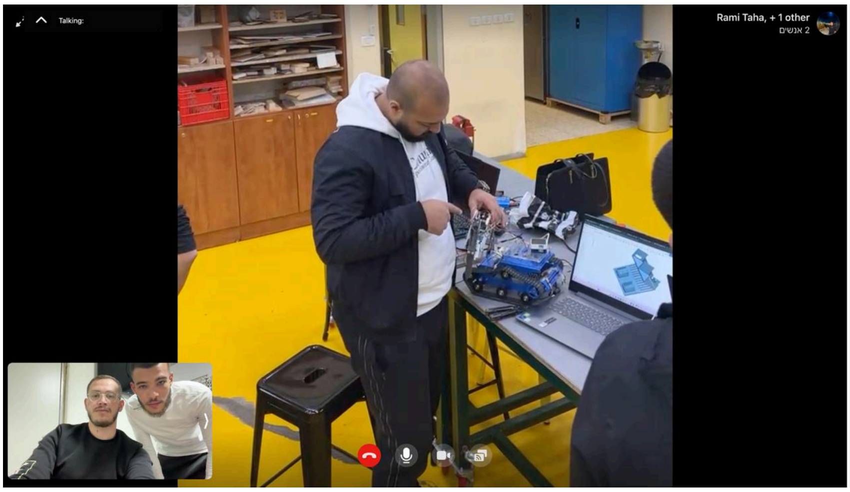

Figure 5. Demonstration meeting with Omar, a mechanical engineering student.

3.3 *Meetings with Uzi*

We first got to know Uzi during the Cloud Computing course. In this project, he served as the supervisor of the mechanical team. We met Uzi through a Zoom meeting with Keren and later in person during his course, where his students presented their PowerPoint projects. During our discussions, a significant gap in our initial planning was brought to light. While we had originally focused on displaying crucial information for the farm manager, Uzi introduced us to the capabilities of his students and the tools they had at their disposal, such as controllable water taps for the farm. This revelation fundamentally shifted our perspective, as it opened up the possibility of integrating remote irrigation control into our website. By enabling irrigation processes to be managed remotely, the data collected gained a far more impactful purpose, transforming the system from a passive information platform into an active, real-time farm management tool.

3.4 The Meeting With Keren

In our meeting with Keren, we outlined our intentions for building the smart irrigation project, its planned functionalities, and raised several questions that provided valuable insights. Keren shared that she is currently using an irrigation interface called GSI [28], which has significant limitations. The GSI interface irrigates the entire farm uniformly, without accommodating the specific water needs of individual plants. Furthermore, its alert system only displays notifications within the app, which Keren noted would be more effective if accessible outside the application as well. She also highlighted that the only data she currently receives is the total amount of water used.

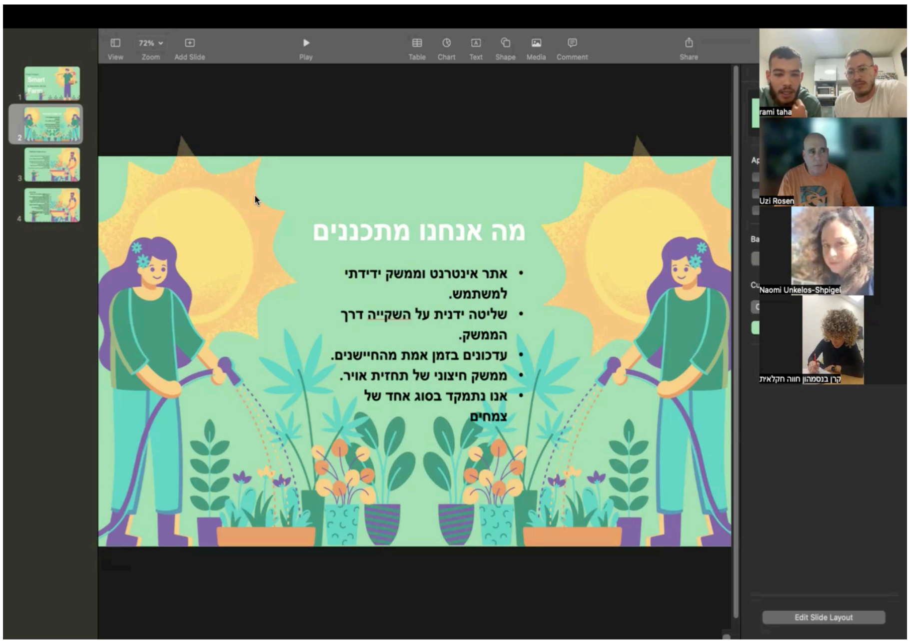

Figure 6. Project’s overall presentation with Keren.

Keren expressed enthusiasm for the weather API feature, as it would greatly enhance irrigation planning. She also emphasized the importance of sensor placement depth in the soil, explaining that deeper placement allows for more accurate moisture detection. A substantial discussion arose regarding the criteria for irrigating specific plants. To address this, we proposed conducting thorough research after finalizing the plant type. Additionally, we suggested that our interface would enable users to set numerical values for each critical criterion, allowing for customized and precise irrigation management tailored to the plant's needs.

After this conversation, we gained a stable foundation for establishing a clear workflow for our project, which is shown in the figure .As an engineering team, we initiate our Smart Irrigation Project by defining precise project requirements and timelines through supervisor meetings. This is followed by conducting extensive research and literature reviews to understand existing technologies and market solutions. In collaboration with Keren, the farm owner, we gather detailed insights into her specific needs and any resource limitations. Parallelly, we work closely with the mechanical team, who focus on developing the robotic systems, while our software team designs the sensor architecture and control systems tailored to the farm's requirements.

Throughout the process, we maintain regular progress updates with our supervisors to ensure alignment and address challenges promptly. As the project evolves, we continuously optimize our integrated solution based on performance feedback and testing outcomes. Before deployment, we carry out rigorous system testing to ensure functionality and reliability. This collaborative and iterative approach ensures that we deliver a robust, efficient, and innovative irrigation solution, seamlessly combining mechanical engineering excellence with advanced software capabilities.

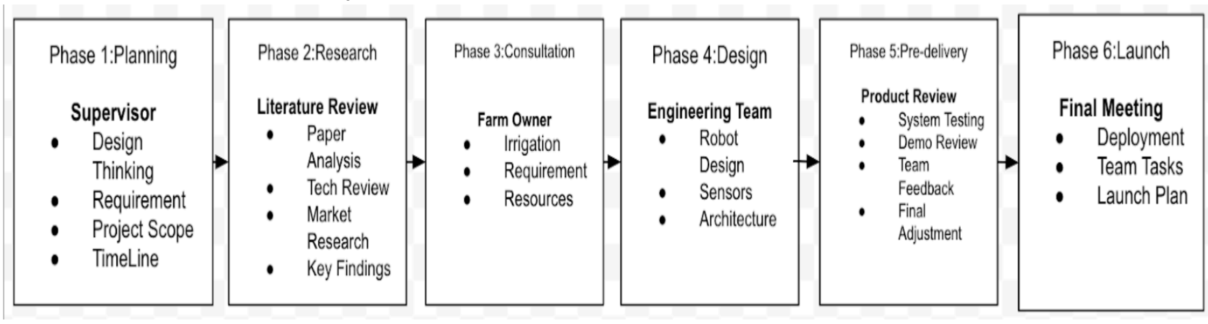

Figure 7. Project overall WorkFlow figure.

4. **Product Algorithm & Details**

4.1 Algorithm

The data collected from the farm's moisture and temperature sensors is transmitted to the cloud using MQTT protocols and stored in a predefined structure in Firebase. This organized storage ensures seamless access and processing of the data for further analysis. The data is systematically analyzed to extract meaningful insights, which are then presented through a user-friendly interface tailored for the farm manager and workers. This interface includes real-time sensor readings, detailed analytics, and weather forecast data, empowering users to make well-informed decisions.

A weather forecast API is integrated into the system to provide predictions about future rainfall. By combining real-time sensor data with these forecasts, users can anticipate irrigation needs more accurately. This feature helps optimize water usage, avoiding unnecessary irrigation during anticipated rainfall, and contributes to sustainable water management practices.

To tailor the irrigation process to the specific requirements of each crop, the farm manager defines essential parameters, such as the type of plant, moisture levels, and temperature thresholds. These parameters act as benchmarks against which the real-time data is compared. Alerts are triggered when the data indicates a deviation from the predefined conditions, ensuring timely interventions.

The system employs two levels of humidity sensors: shallow sensors to monitor surface-level moisture and deep sensors to capture moisture availability at greater soil depths. Since water tends to accumulate more at deeper levels, relying solely on shallow sensors may result in inaccurate readings. By combining data from both levels and calculating the average, the system delivers precise assessments, improving the accuracy of irrigation scheduling.

When a plant requires irrigation, the system sends an alert to the farm manager, specifying the plant and its needs. The manager can then decide whether to start the irrigation process or ignore the alert, considering factors such as ongoing manual irrigation or expected rain. If the manager opts to proceed, a request is sent to the responsible water valve via the cloud. The controller receives this command and initiates water flow to the specified area. The irrigation continues until the sensors detect that the moisture level has reached the desired threshold, ensuring the plant's optimal water requirements are met efficiently.

4.2 Weather Forecast API

In our smart irrigation project, we are leveraging an external weather forecast API to predict weather conditions for the upcoming days. This feature provides significant cost savings for farm owners by optimizing water usage. While the forecast is undoubtedly helpful, irrigation decisions are ultimately based on sensor data, as the sensors provide real-time, accurate information. Rainfall has a direct impact on the sensor readings, influencing the displayed information accordingly.

In regions like Israel, rainfall occurs primarily during a few months of the year, which often negates the need for irrigation during those periods. As illustrated in the figure below [No], the highest demand for irrigation occurs during the summer months (June to September) when drought conditions are prevalent. The figure highlights the used water for irrigation throughout the year, broken down by month, providing valuable insights for efficient water management [11].

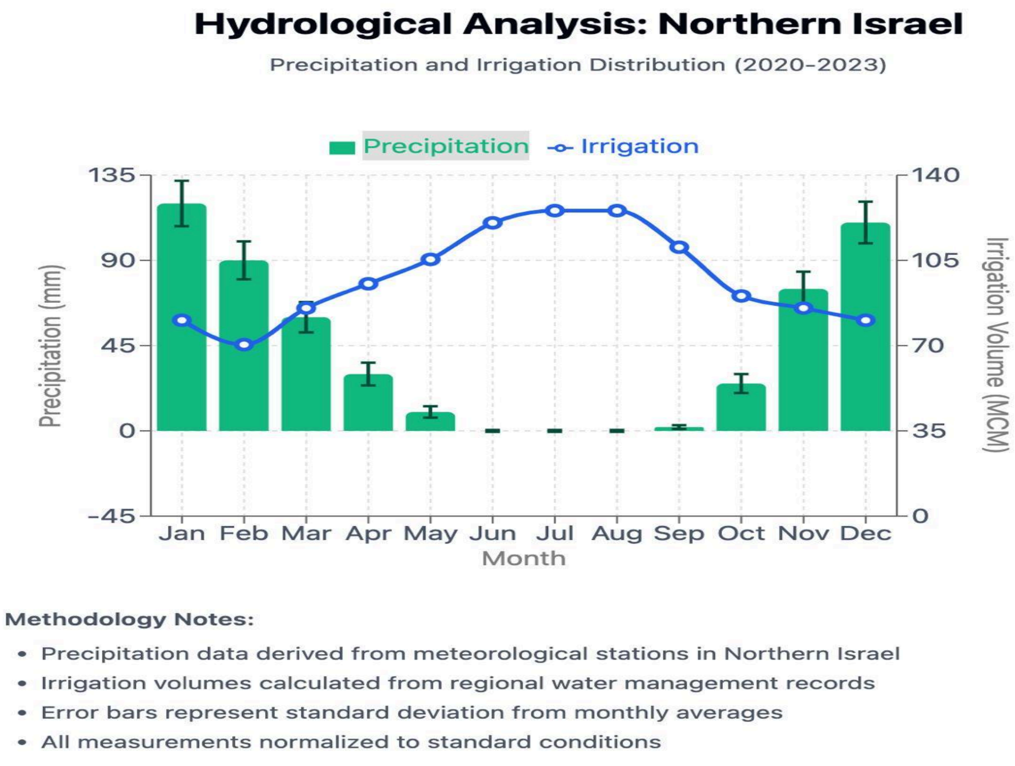

Figure 3. Rainfall and irrigation relation in northern Israel over a year.

Resources has been collected from the following website [26] about the average rainfall in israel, the percentage of water used in agriculture is found in the following resource [27].

This figure shows the estimated irrigation per day during a year when depending on rain forecasts.

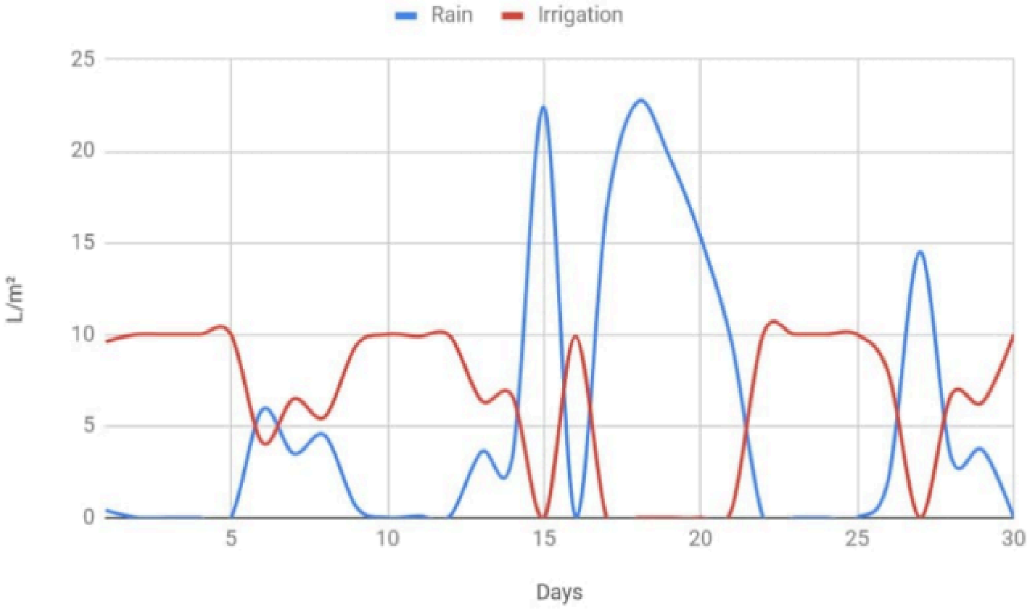

Figure 4. Estimated Irrigation Depending on Rain Forecasts.
Taken from the smart irrigation report [3]

4.3 *FR/NFR Requirements*

4.3.1 Functional Requirements

#	FR Requirement	Description
1	Real-Time Data Collection	The system should collect real-time data from humidity, temperature, and soil moisture sensors deployed in the field.
2	User Authentication and Management	The system should allow users to register, log in, and manage their accounts through a secure authentication process.
3	Cloud Data Transmission	The system should transmit sensor data to the cloud for processing and storage
4	Real-Time Data Display	The system should display real-time environmental data (soil moisture, temperature, humidity, etc.) on the user interface.
5	Manual Irrigation Control	The system should allow users to manually start or stop the irrigation process through the web interface.
6	Irrigation Alerts	The system should send alerts to users when irrigation is required, based on

		threshold values for soil moisture or other environmental factors.
7	Weather Forecast Integration	The system should integrate weather forecast data to predict irrigation needs for the upcoming days.
8	Irrigation Scheduling	The system should allow users to schedule irrigation tasks based on pre-configured parameters (time, duration, frequency).
9	Historical Data Access	The system should allow users to view historical irrigation data, including the amount of water used and irrigation timings
10	Dynamic Irrigation Adjustment	The system should dynamically adjust irrigation parameters based on changing environmental conditions like weather forecasts, soil moisture, or plant species requirements.

4.3.2 *Non Functional Requirements*

#	NFR Requirement	Description
1	Scalability	The system should be scalable, capable of handling a growing number of sensors and expanding the network to larger farm areas.
2	Availability	The system should be reliable, ensuring minimal downtime for data transmission and irrigation control, with a target uptime of at least 99.9%.
3	Performance	The system should process data and provide updates to users in real-time, with a response time of less than 2 seconds for all user interactions.
4	Security	The system will implement strong security measures aligned with ISO 27001, including data encryption, secure authentication, and protection against unauthorized access and cyber threats
5	Consistency and Standards by Nielsen[37]	The interface must maintain consistent layouts, color schemes, and navigation elements across all pages to reduce the learning curve and support ease of use.
6	Data Integrity	The system should ensure data accuracy and consistency, avoiding corruption or loss during transmission or storage.

7	Compatibility	The system should be compatible with a variety of IoT sensor devices and support multiple web browsers and mobile devices to maximize accessibility.
8	Maintainability	The system should be designed for easy maintenance, allowing simple updates, bug fixes, and sensor replacements without extensive downtime.
9	Energy Efficiency	The system should minimize power consumption of sensors and devices, particularly in remote farm areas, by employing energy-saving protocols and optimized hardware usage.
10	Accessibility	The system must be accessible from any device with internet access, including smartphones, tablets, and desktops, to ensure flexibility for users.

4.4 *Use-Case Diagram*

In the Use case diagram there are 3 players:

a) **Farm manager:**The manager can perform all the actions that the employee does, in addition to creating accounts and managing permissions.
b) **Farm Worker:**He is an actor who performs several actions, including Log out, View dashboard, Manage profile, View weather forecast, Sign in, Export data, Control irrigation, and Manage alerts.
c) **System:**The system is an actor that focuses on two actions: the first is storing data in the database, and the second is processing sensors' data.

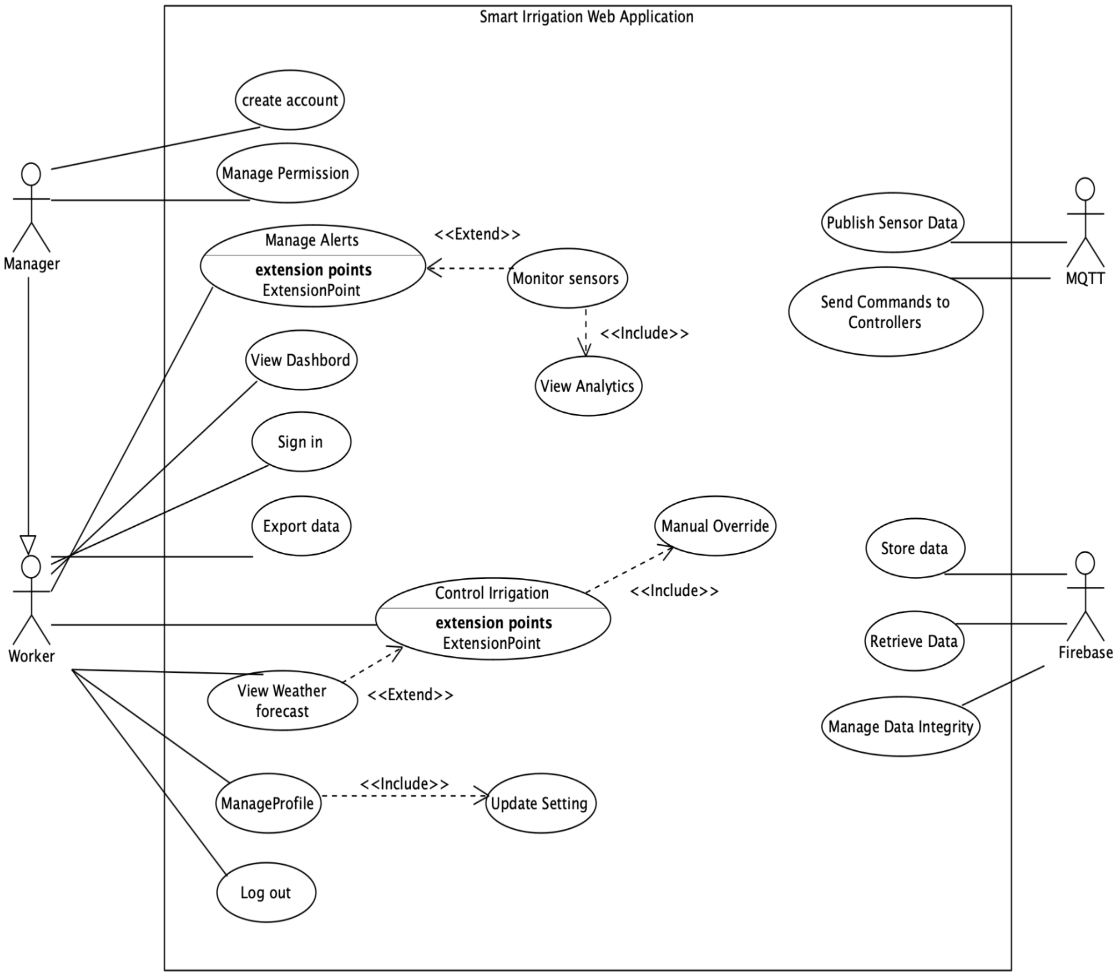

Figure 8. Use-Case Diagram

4.5 *Activity Diagram*

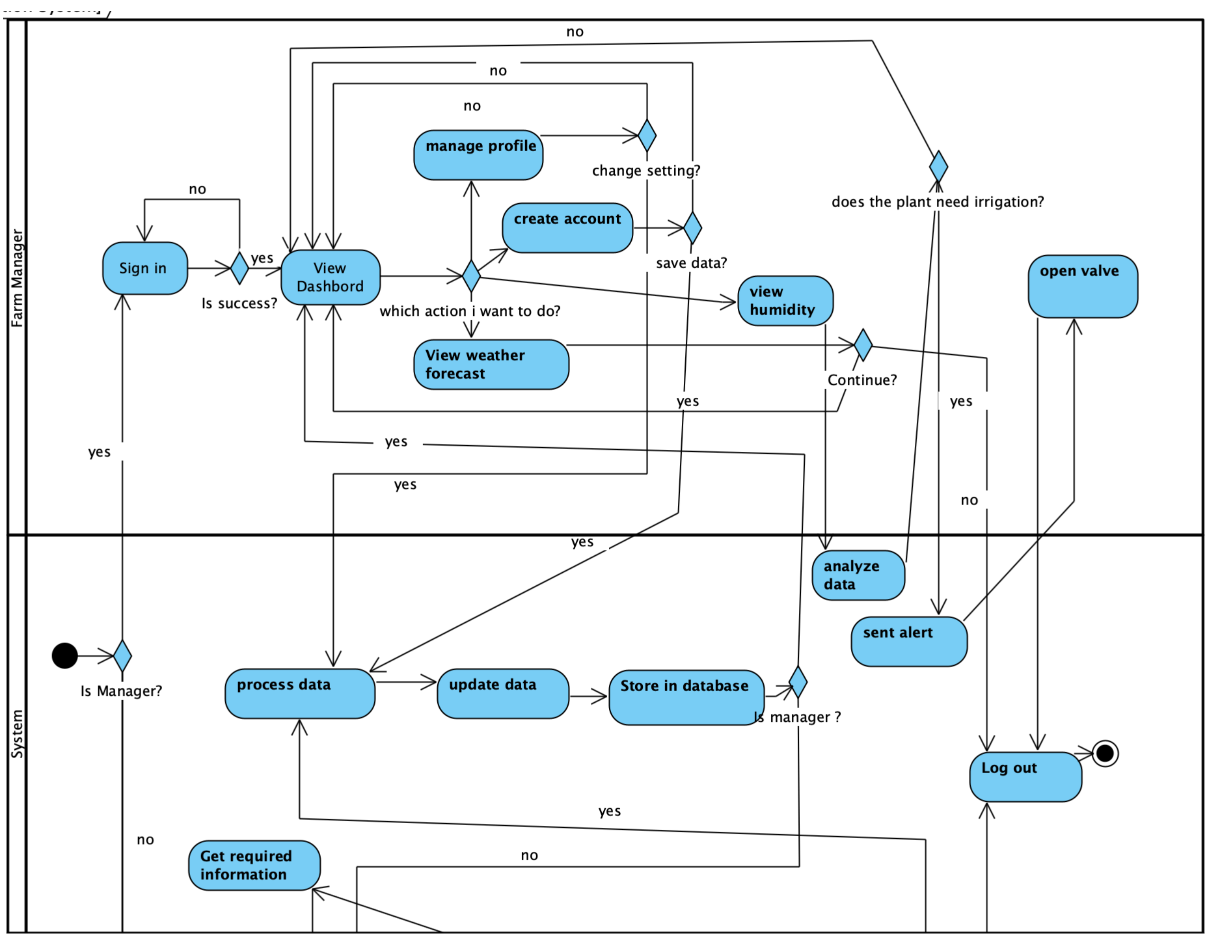

Figure 9.1 : Activity diagram-System & Farm Manager

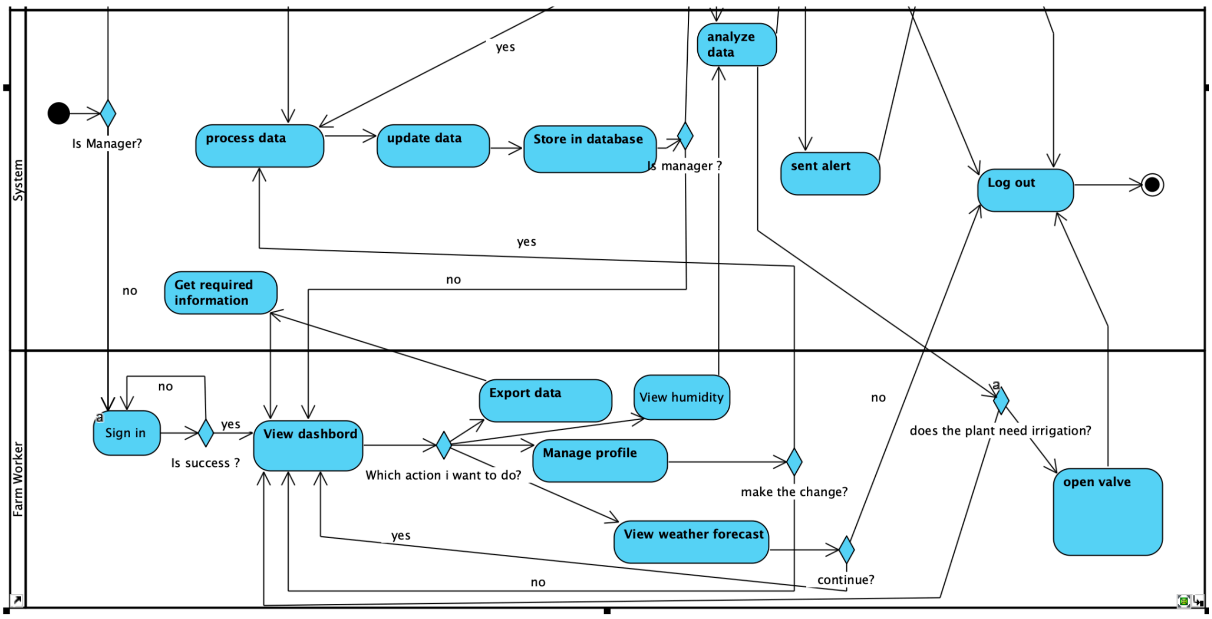

Figure 9.2 : Activity diagram-System & Farm Worker

5. Technological Review

5.1 *Client-Side Technologies*

5.1.1 *React*

React is a free and open-source front-end JavaScript library [29]. React is a library for helping developers build user interfaces as a tree of small pieces called components. This component is a mixture of HTML and JavaScript that capture all of the logic required to display a small section of a larger UI [30].

5.1.2 *Javascript*

JavaScript is a lightweight programming language commonly used by web developers to add dynamic interactions to web pages, applications, servers and even games. JavaScript's widespread applications in web, mobile app and game development make it a valuable language to learn [31].

5.1.3 *Tailwind Css*

Tailwind css is a low-level framework. Unlike other css frameworks like Bootstrap, Tailwind doesn't offer fully styled components like buttons, dropdowns and navbars. Instead, it offers a utility class which gives the option to create our own reusable components. Tailwind css provides a lot more flexibility and control over what the application looks like than other CSS frameworks [32].

5.2 Server-Side

5.2.1 *Node.js*

Node.js is an open-source, cross-platform JavaScript runtime environment and library for running web applications outside the client's browser. Developers use Node.js to create server-side web applications and it is perfect for data-intensive applications since it uses an asynchronous, event-driven model. Node.js operates on a single-threaded event driven architecture, utilizing an event loop to handle multiple concurrent operations without blocking. Node.js's non blocking, event-driven architecture makes it ideal for real-time applications, web servers, APIs and more [33].

5.2.2 *FireBase*

Firebase is a platform developed by Google that provides a variety of tools to help developers build and manage web and mobile apps. It includes features like real-time databases, user authentication, cloud storage, and app analytics. Firebase simplifies backend management by offering serverless solutions and real-time data syncing. It's widely used for building scalable, high-performance applications without the need for complex infrastructure [34].

6.Limitations and Challenges

During our project, we faced several challenges that required careful consideration and adaptation. One of the main difficulties was the communication barrier between the software and mechanical teams. We often struggled to bridge the gap, as the software team uses technical language that the mechanical team didn't fully understand, and vice versa.

Additionally, determining where to start in our planning process was a challenge, as we initially had difficulty aligning our goals and expectations. Another issue arose when we had to communicate with Keren to better understand the functionality of the project and what should be included, which slowed our progress. Furthermore, we encountered the problem of sensor placement—specifically, the depth of the sensor in the ground. The deeper the sensor is buried, the more moisture it detects, which could lead to inaccurate analytics.

We also found ourselves reliant on the mechanical team's success, particularly with the robot and data transmission, which added an element of uncertainty. Another obstacle was figuring out how to divide the content across the web pages and determine what data should be stored in Firebase. We needed to prioritize which information was most important, decide what to display on the main page, and define what the farm manager should see compared to other users. All these challenges tested our ability to collaborate and make decisions, but they ultimately helped us refine our approach.

7.Design and Implementation of the System

We are planning to design the system based on Keren's described scenario, referred to as the "Smart Irrigation Scenario" (see section 6.1), which serves as a foundation for our development. In the following section, we will delve into the various approaches involved in implementing the product in real-world settings, ensuring it aligns with the needs and conditions outlined by Keren. This discussion will encompass the different architectural layers of the system, including the integration of IoT sensors, data processing, and user interface components. Additionally, we will explore the role of the MQTT protocol in enabling efficient communication between sensors, the cloud database, and the application, ensuring seamless data transmission and real-time decision-making capabilities.Mainly focusing on the Application Layer.

7.1. *Smart Irrigation Scenario*

Before diving into the design and implementation of the system, it is important to note that the system is deployed on a farm in Carmiel, Israel. The farm grows a variety of plants, each with unique water requirements. Until now, these plants have been irrigated using a uniform approach, without taking into account the specific needs of each plant. This lack of differentiation in irrigation practices has led to inefficiencies, making the smart irrigation system an essential step toward optimizing water usage and improving plant health.

Figure 10. Project Deployment Environment.

The photo is taken from the facebook page of the farm.[35]

After discussing our intentions with Keren, we reached an agreement on the system's key functionality. The irrigation process should be either manual or automatic, depending on the user's preference. Alerts will be sent to the manager's mobile device when irrigation is needed, ensuring that these notifications are not limited to the website interface. When an alert is received, the manager will have the option to initiate the irrigation process through a button, which will trigger the pipes deployed by the mechanical team in the farm's field. Only after this step should the irrigation start. During data analysis, two important factors must be considered: the depth of the sensor and the air humidity. Keren highlighted that the deeper the sensor is placed in the ground, the more moisture it detects, and since air humidity directly affects soil moisture, both factors need to be accounted for in the analysis and displayed on the webpage.

7.2. *Designed Communications Architecture*

Figure 2 represents the communication architecture of the proposed system.In such a figure, every component is displayed in its layer.The arrows indicate the interacting layers or components.
Specifically, the proposed architecture in **Figure 10** composed of four layers:

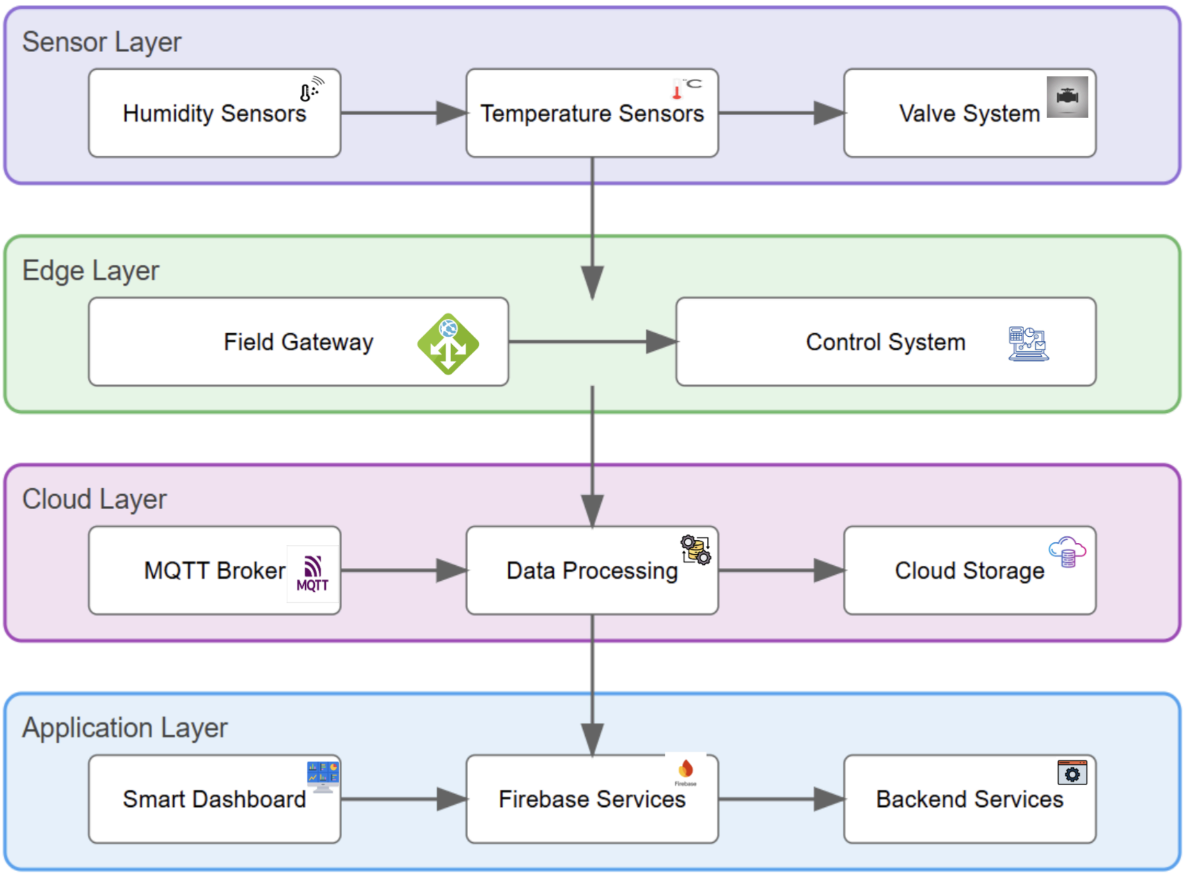

Figure 11. Project's Architecture.

Application Layer.The highest level of the system architecture combines a user-facing dashboard, Firebase services, and backend server components. The dashboard provides real-time monitoring and control interface, while Firebase handles authentication and real-time data synchronization. The backend server processes REST API requests, manages data, and controls irrigation logic. These components communicate through REST APIs and WebSocket connections to ensure responsive system monitoring and control.

Cloud Layer.This layer serves as the central nervous system, processing and distributing data through an MQTT [23]broker that handles all sensor readings and control commands. The data processing component performs time series analysis, detects trends, and generates alerts, while cloud storage maintains historical data, configurations, and system logs. All components interact continuously to provide system intelligence and data persistence.

Edge Layer. Operating at the field level, this layer consists of a Raspberry Pi [24] gateway and control system. The gateway acts as a local processing unit, buffering sensor data and running critical control logic, while the control system manages irrigation valves with built-in failsafe mechanisms. Both components maintain local decision-making capabilities even during cloud connectivity issues, ensuring system reliability.

Sensor Layer.The foundation layer interfaces directly with physical hardware through various protocols. Humidity sensors (I2C) and temperature sensors (OneWire) continuously monitor environmental conditions, while the valve system (GPIO/PWM) controls water flow. This layer generates raw data and executes control commands from upper layers, forming the physical interface between the digital system and the agricultural environment.

7.3 *Mechanical POV*

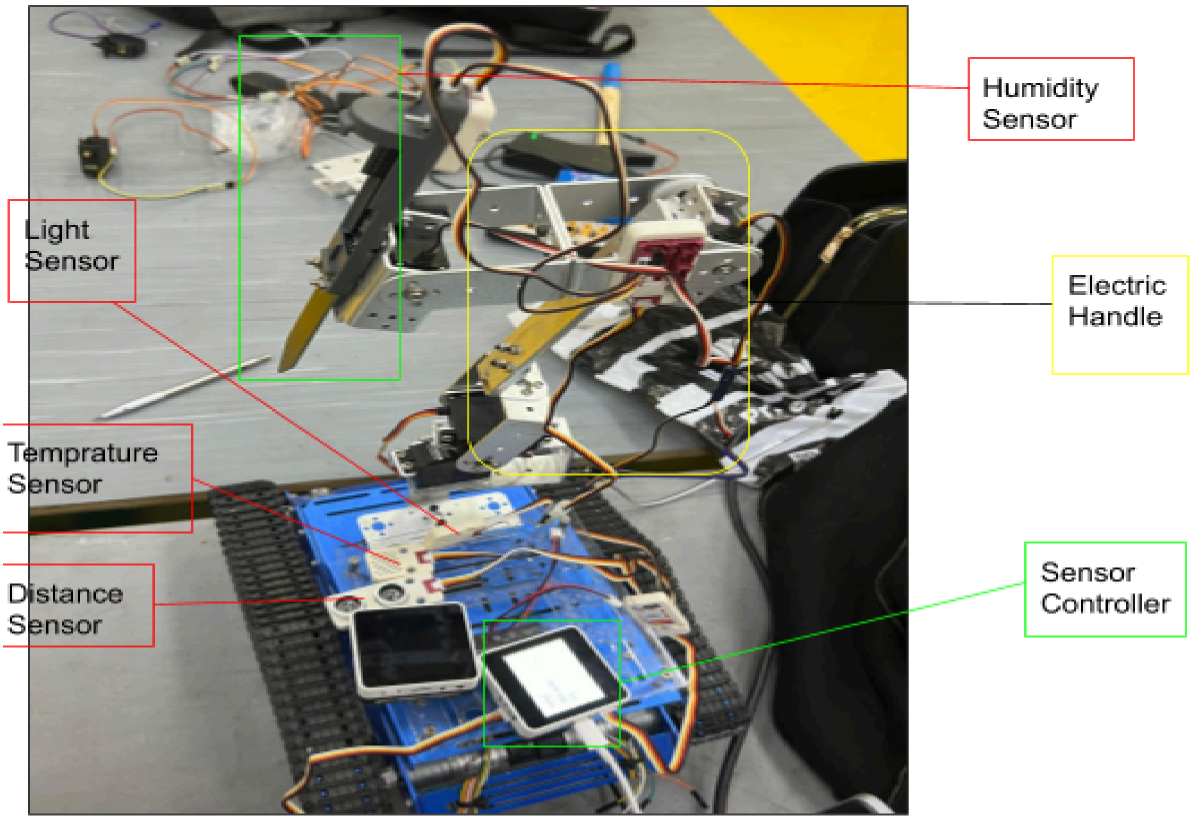

Figure 12. The Mechanical Product and its Internal Components

The sensors and controller are designed to deliver precise data on soil moisture and humidity, ensuring accurate monitoring of environmental conditions. This data is crucial for optimizing irrigation processes and maintaining ideal soil conditions for plant growth.

7.4 *Implemented Communications Architecture*

To deploy our proposed smart irrigation system, four distinct layers were implemented as illustrated in our architecture diagram 2. The sensor, edge, and cloud layers function in alignment with the framework outlined in the Designed Communications Architecture section 2. Moreover, the responsibility for deploying the sensor infrastructure rested with the mechanical engineering team, who ensured the seamless transmission of accurate, real-time data to the cloud. This meticulous groundwork facilitated the software team's ability to efficiently manage and process the data within the cloud environment.

Application Layer. Our current focus is on implementing the application layer, as depicted in the figure above. This layer encompasses three key aspects. First, it processes data from the sensors by retrieving refined information stored in the cloud. Second, it incorporates a well-structured Firebase database that securely manages user credentials, including usernames and passwords, allowing farm managers to access the system in an authenticated manner. The database also stores vital sensor data and tracks water usage over time. From a backend perspective, the application ensures real-time data monitoring and includes an alert system to notify managers when irrigation is required. The backend seamlessly interacts with Firebase to provide continuous real-time data support. Finally, the application's dashboard offers farm managers a clear and comprehensive view of critical data related to their crops and irrigation schedules, alongside additional pages tailored to manager-specific functionalities.Notice The illustrative figure below 8.

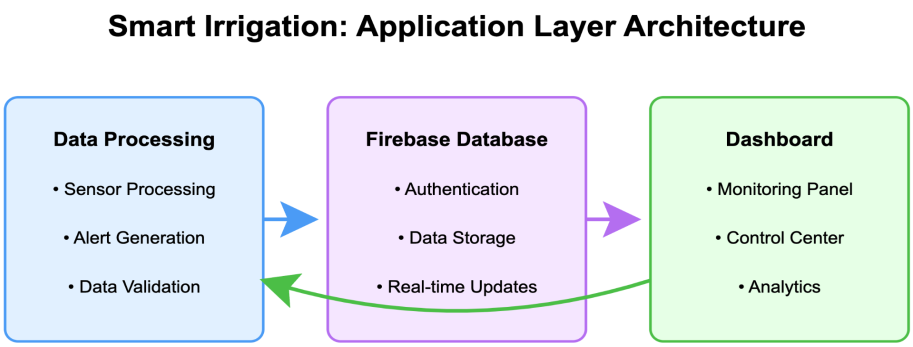

Figure 13. Application Layer Architecture.

7.5 *Enabled features*

The proposed smart irrigation system provides numerous advantages with respect to traditional systems thanks to the intelligent automation of the irrigation process. Specifically, the following are some of the most relevant features of the proposed system that enable the development of advanced irrigation applications:

- The system can adjust dynamically to changing environmental conditions, such as soil moisture, ground temperature, or real-time weather conditions.
- The system is able to adjust the irrigation process dynamically to adapt it to the species that are grown on each individual green area.

- In case of having directional irrigators on the IoT nodes, it is possible to establish specific dynamic irrigation patterns with the objective of watering very specific areas.
- The system can be easily scaled, thus being able to cover large areas by autonomously connecting to the nearest gateway.
- It is straightforward to add additional IoT sensor nodes (which do not need to embed irrigation actuators, but only sensors like rain or leaf moisture sensors) in order to provide accurate data on the monitored green areas, thus enhancing the accuracy of the decisions made on the irrigation.
- Real-Time Monitoring of the farm environment, including soil moisture, temperature, and humidity, provides up-to-date data that helps with immediate decision-making.
- Predictive Analytics based on weather data and soil conditions help forecast irrigation needs and optimize water use for future days, reducing waste.
- Custom Irrigation Adjustments based on specific plant needs, allowing the system to cater to different crops or species with varying irrigation requirements.
- Alerts and Notifications can be sent to farm workers or managers when irrigation is needed, ensuring timely responses to changing conditions.
- The system enables the integration of various sensor types, providing a comprehensive view of farm conditions, including rain, leaf moisture, and other environmental factors that enhance irrigation decisions.
- Data Logging and Reporting features allow farm managers to track historical irrigation data and analyze the effectiveness of irrigation over time, supporting better planning and resource management.
- Remote Access and Control enables farm managers to manage the irrigation system from any location, whether through a mobile app or web interface, providing flexibility and convenience.
- Manual Override options allow users to adjust irrigation settings manually in case of emergency or when automatic scheduling needs to be adjusted for specific events or weather anomalies.
- The system enables efficient water resource management by ensuring that irrigation is provided only when necessary, reducing water waste and promoting sustainability.

7.6 *screens*

The following screens are live and fully operational, showcasing the current functionality and design of the application. They are accessible for review and interaction, reflecting the implemented features and overall user experience.However, we are seeking full viability and more updates and changes are yet to come.These images are to showcase our main idea about the website’s functionality and the agreed upon construction and style of certain pages.

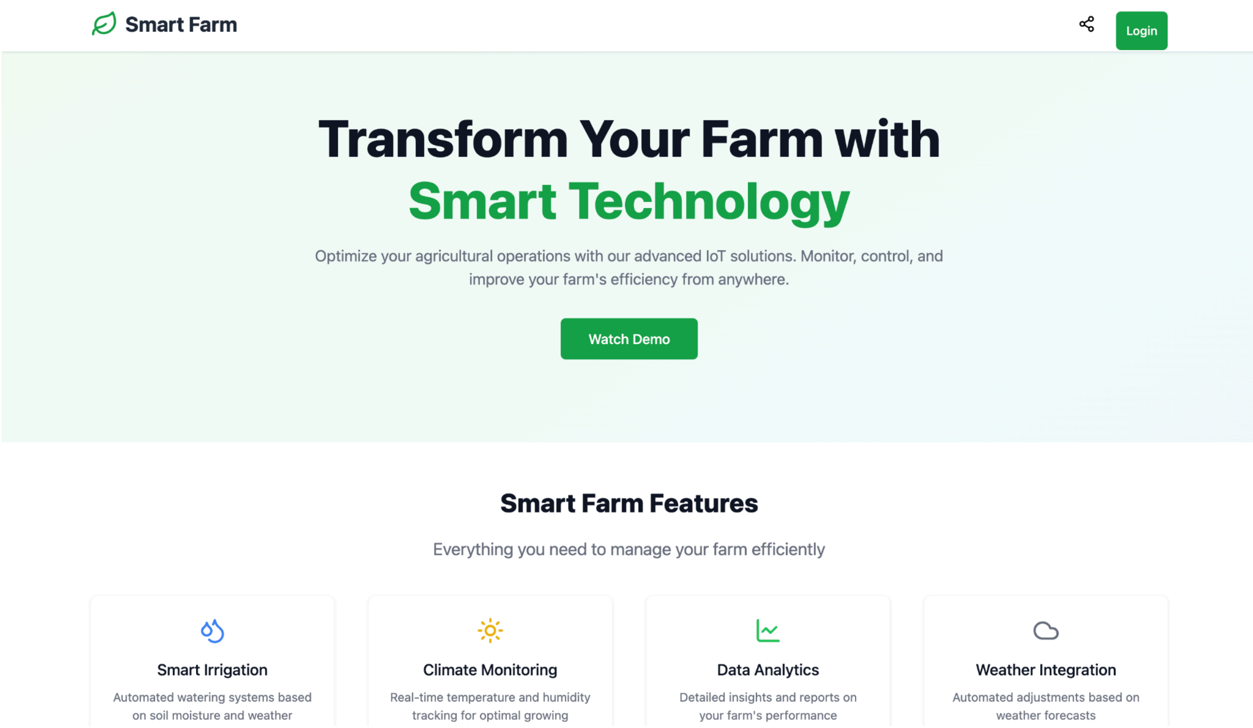

Figure 14 . Website's Entry Page.

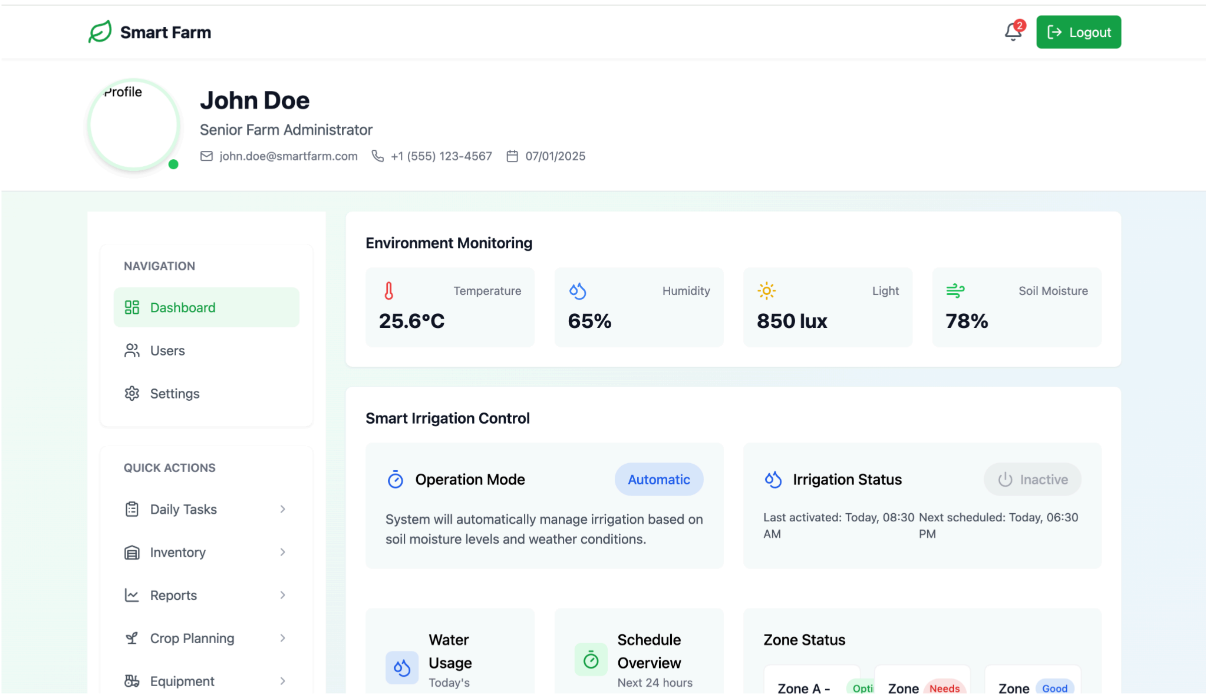

Figure 15. Manager's Dashboard.

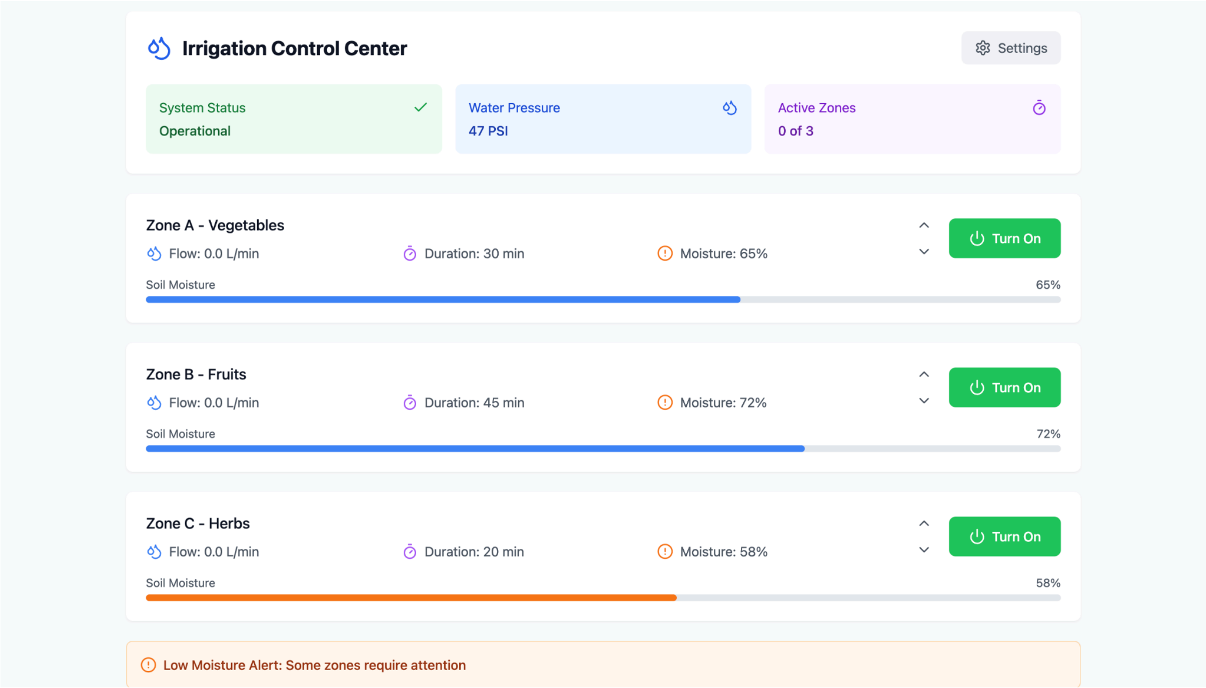

Figure 16. Irrigation Controller.

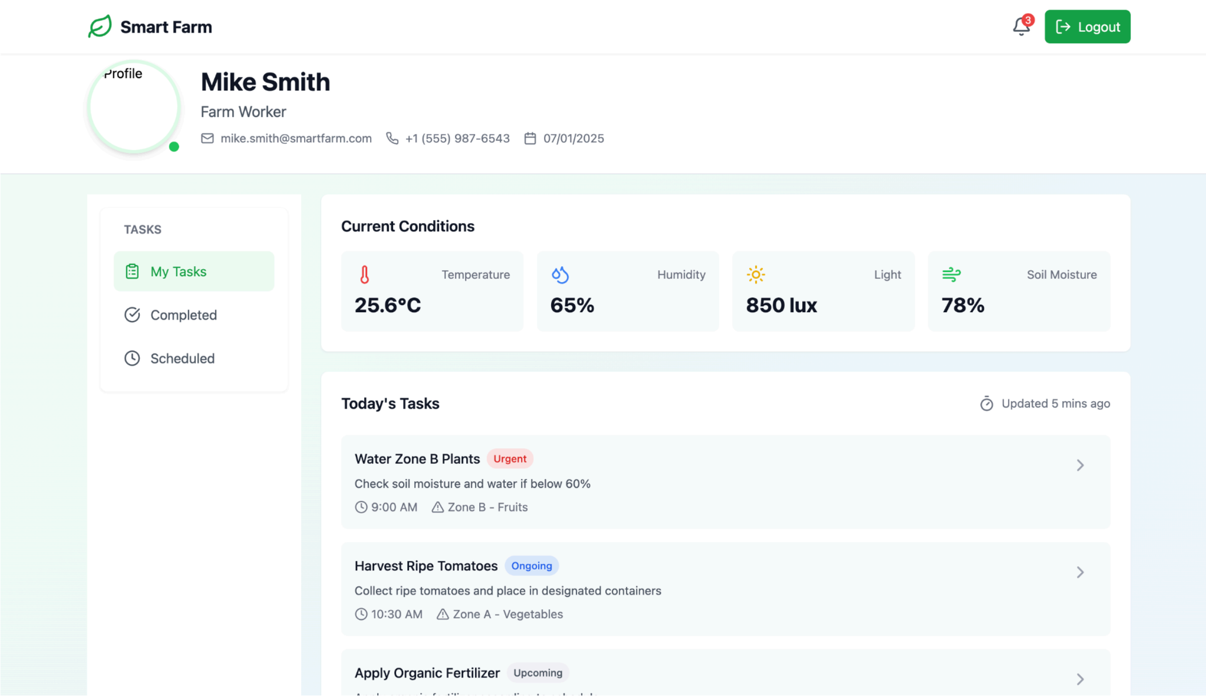

Figure 17. Worker’s Dashboard.

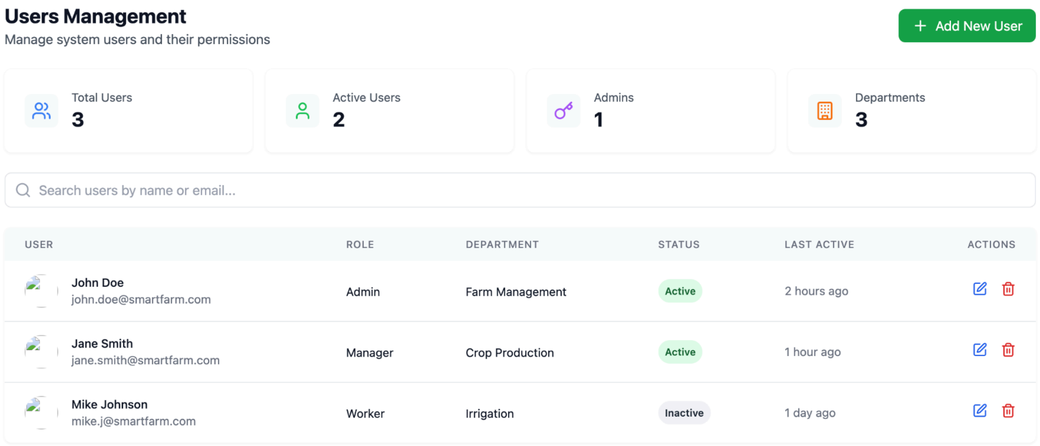

Figure 18. User's Info & Details.

8. Testing Plan

In this section, we are outlining a detailed series of test cases and establishing a well-defined plan to ensure the system's quality and alignment with user requirements. This approach is designed to proactively identify and resolve potential issues, thereby minimizing the risk of future challenges or regrets.

8.1 *Objectives*

- **Ensure System Reliability**.Verify that the system consistently performs its intended functions, including sensor data collection, irrigation control, and user interactions, without errors or interruptions.
- **Validate User Experience**.Ensure the user interface is intuitive, responsive, and accessible, allowing managers and workers to navigate the website, monitor data, and control irrigation effortlessly.
- **Guarantee Data Accuracy**.Confirm that the data collected from sensors and external sources, such as weather APIs, is accurate, timely, and correctly displayed for informed decision-making.
- **Enhance Security and Privacy**.Validate that user accounts, sensitive farm data, and system functionality are protected against unauthorized access, data breaches, and cyber threats.
- **Test System Scalability and Performance.**Ensure the system can handle increased loads, such as more sensors, users, or data volume, while maintaining optimal performance and functionality.

8.2 *Testing Approach*

The test approach for this project focuses on ensuring seamless connectivity between the React JavaScript components that make up the web application. We will conduct thorough testing to verify that each component interacts correctly with others, ensuring smooth data flow and functionality across the system. Additionally, we aim for high code coverage, testing not only the core features but also edge cases and error handling scenarios. This approach will help identify potential issues early, ensuring that all aspects of the application are thoroughly tested for performance, reliability, and correctness, ultimately leading to a robust and well-functioning user experience.

8.3 *Test Cases*

#	TestID	Precondition	Expected Result	Description
1	SuccessSignUp	The user has no existing account with the provided credentials.	The user should be successfully registered, and an account should be created in the system	Confirms successful user registration.
2	SuccessLogIn	User has an active account with valid credentials.	User logs in and is redirected to the dashboard.	Verifies successful login with valid credentials.
3	FailLogIn	User enters invalid credentials (username/password).	Error message is displayed for invalid credentials.	Ensures unauthorized access is blocked.
4	RoleAccess	User logs in with a specific role (e.g., manager or worker).	User access is restricted based on their role.	Ensures only authorized features are accessible by specific roles.
5	StartIrrigation	User is logged in and has the necessary permissions.	User can start and stop irrigation manually.	Tests the functionality of manual irrigation control.
6	ForeCast	Weather API integration is functional.	System adjusts irrigation based on weather data.	Confirms weather forecast integration and response.
7	DataDisplay	Sensor data and weather information are available.	Environmental data is displayed accurately in real-time.	Ensures the dashboard reflects up-to-date system data.
8	IrrigationAlert	System detects irrigation need	Alerts are sent when irrigation is required.	Confirms timely notifications for irrigation needs.

9. AI Tools Used

Throughout the course of this project, we extensively utilized three advanced AI tools—ChatGPT, Claude, and ChatPDF—to support our efforts and enhance the overall quality of our work. Each tool played a distinct and complementary role in helping us achieve our objectives. ChatGPT was instrumental in generating creative and innovative ideas, guiding the direction of our project, and providing us with access to invaluable resources, including academically relevant reports and related research materials. This greatly contributed to broadening our understanding of the topic and laying the groundwork for the project.

ChatPDF, on the other hand, was used to simplify and streamline the analysis of complex reports by summarizing them into more digestible formats. It also proved invaluable in clarifying challenging or misunderstood concepts within the reports, ensuring that we had a complete grasp of the material. Claude was primarily employed for the generation of visual aids such as graphs, figures, and tables, which were essential for presenting and analyzing data in a clear and professional manner.

By effectively integrating these AI tools into our workflow, we were able to refine our main concept, address areas of uncertainty, and solidify the core pillars of our project. These tools not only enhanced our efficiency but also enabled us to approach the project with greater confidence and precision, ultimately sharpening our vision and supporting the achievement of our goals.

10.Conclusion

This article proposed a smart irrigation system designed to optimize water management and enhance agricultural efficiency by leveraging IoT-based solutions integrated with cloud computing and real-time data analysis. The system utilizes a network of temperature and humidity sensors deployed across the farm, transmitting data to a cloud-based infrastructure for storage and analysis. A website interface was developed and described in detail to allow seamless interaction for farm managers and workers, enabling future developers to replicate and enhance the system.

To validate the proposed system, comprehensive testing was conducted, including real-time data collection from IoT sensors, automated irrigation control, and integration with weather forecasting services to predict irrigation needs. The results demonstrated the system's reliability in monitoring soil conditions and its effectiveness in automating irrigation processes based on dynamic environmental conditions. Additionally, the platform provides users with the ability to monitor environmental data, customize irrigation parameters, and receive timely alerts for irrigation requirements.

The findings highlight the significance of integrating environmental sensors and weather data to achieve precise irrigation while minimizing water waste. Challenges such as ensuring sensor accuracy, system scalability, and seamless connectivity between React JavaScript components were addressed during the development process, showcasing the robustness of the system architecture. Future work will focus on adding advanced predictive capabilities, such as AI-based models to optimize water usage further, and incorporating additional sensor nodes to improve decision-making accuracy. This work provides valuable insights and guidelines for developing scalable smart irrigation systems in agricultural scenarios.

11.Gratitude and Credit

Keren Bensamhon Meshrki, who was responsible for providing real-world data from the farm in Karmiel, played a crucial role in enabling the practical application and validation of the system. Her invaluable support went beyond just sharing data; she also generously dedicated her time to meet with us over Zoom, offering detailed explanations and insights about the farm's operations and conditions. Her willingness to answer our questions and provide clarifications significantly enhanced our understanding and ensured the system was

tailored to address real-world challenges effectively. We deeply appreciate her collaboration, expertise, and commitment, which were instrumental in the success of this project.

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