Design and Implementation of an IoT-Enabled Solar-Grid Hybrid Smart Irrigation System for Multi-Crop Cultivation in Semi-Arid Areas
Case Study: Garoua Cameroon

by

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CERTIFICATE OF APPROVAL

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Declaration of Candidate

It is hereby declared that this thesis report or any part of it has not been submitted elsewhere for the award of any Degree or Diploma.

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This thesis is dedicated to each of our family members and the Cameroonian community in Bangladesh, the endless support of whom have led us this far in our academic journey, and have also been partly responsible for the successful completion of our thesis.

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List of Acronyms

IOT	Internet Of things
CO	Course Outcome
PO	Program Outcome
GDP	Gross Domestic Product
GSM	Global System for Mobile Communication
IDE	Integrated Development Environment
SPDT	Single Pole, Double Throw
ESP32	Espressif Systems
PWM	Pulse Width Modulation
GPIO	general-purpose input/output
ADC	Analog-to-digital Converter

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Abstract

The paper introduces a project of creating a precision irrigation system based on Internet of Things (IoT) connectivity and a hybrid solar-grid energy system. The study will seek to maximize the utilization of water in the multi-crop production through the use of real-time soil moisture sensors as well as threshold-based control logic, which will run on an ESP32 microcontroller. The power module of the system focuses on the solar energy and the system automatically switches back to the grid when there is not enough sunlight to power the system thus maintaining a constant power supply and energy security. The Blynk platform provides a complete IoT monitoring interface, which allows visualizing the data in real-time and controlling irrigation processes remotely. It is experimentally proven that the suggested system is effective in automating irrigation, water conservation, and self-sufficiency in energy usage. The findings show that this hybrid IoT-solar design will improve the efficiency of the resources and will be a big step towards climate-resilient and sustainable agricultural automation.

CHAPTER 1

INTRODUCTION AND BACKGROUND

The agricultural sector forms the backbone of many developing economies by providing jobs to people, a stable food supply, and economic stability to millions of people. However, in the semi-arid regions, the farmers are faced with the rising misfortunes occasioned by climatic changes, aridification and fluctuating energy availability. This has therefore rendered it increasingly strenuous to maintain a high level of agricultural output and sufficient income flows.

Manual watering regime as well as unregulated flood irrigation are still widely used traditional irrigation methods. Such ways use unnecessary amounts of water, require high quantities of labour, and do not meet the unique evapotranspiration needs of various crop species. With the rise in unpredictability in rainfalls, there is an increasing call to have effective, automated, and data-driven irrigation systems.

The development of Internet of Things (IoT) technologies has opened up new opportunities to accurate farming. Systems based on IoT can collect real-time measurements of soil, calculate them through embedded microcontrollers and automatically program irrigation timetables. Such systems can be made sustainable, especially when combined with renewable energy sources (especially photovoltaic arrays) to operate consistently without any connection to a traditional grid, which increases resilience in rural locations.

The study will design and develop a Smart Solar -Powered IoT -Based Multi -Crop Irrigation System, which is specific to semi-arid settings such as Garoua, Cameroon. The project attempts to soften the gap between the engineering innovation and society needs through simultaneous elimination of water shortage and energy insecurity.

Figure 1.1: Global Shift from Traditional to Smart Irrigation (source: www.linkedin.com)

1.1 Background History

Global Context

Globally, agricultural activities are increasingly moving to the paradigm of precision farming, whereby irrigation, fertilization, and pest control choices are made based on sensor data and automated processes. The advancement in the technological fields of IoT, cloud computing, and the amalgamation of renewable energy sources has radically changed the methodologies of farm management.

The examples of countries like Israel, India, and the United States have proven to implement intelligent irrigation designs that use soil moisture sensor, automated pumping and weather-sensitive algorithms to reduce water wastage and maximize on yield. According to the reports by the Food and Agriculture Organization (FAO, 2023), smart irrigation technologies have the potential to increase water-use efficiency up to 3050. It is impossible to imagine sustainable agricultural processes without such tools.

The Local Context: Agriculture in Semi-Arid Cameroon.

The economic system of Cameroon is agricultural in nature, where more than 60 per cent of the labour force is involved in agriculture. Similar to the case with the northern semi-arid province of Garoua, farmers are faced with extended dry seasons- November to April- with little or no rainfall and high temperatures of between 26 0 C and 40 0 C. These states result in gradual reduction in soil moisture, physiological strains in crops, and frequent yield shortages that are caused by drought.

The traditional irrigation practices which include bucket watering and the open channel floods are ineffective and cannot be sustained within such climatic parameters. In addition, the grid electricity is not reliable and high price of diesel fuel also restricts access to regular irrigation. These issues in totality reduce the productivity of the farms and make the people poorer.

The transition to smart irrigation systems based on IoT, which is solar-powered, can be described as a viable and sustainable path that will help to improve agricultural resilience in Garoua. These systems do not only maximise the use of water but also create energy independence and increase the climatic adaptability.

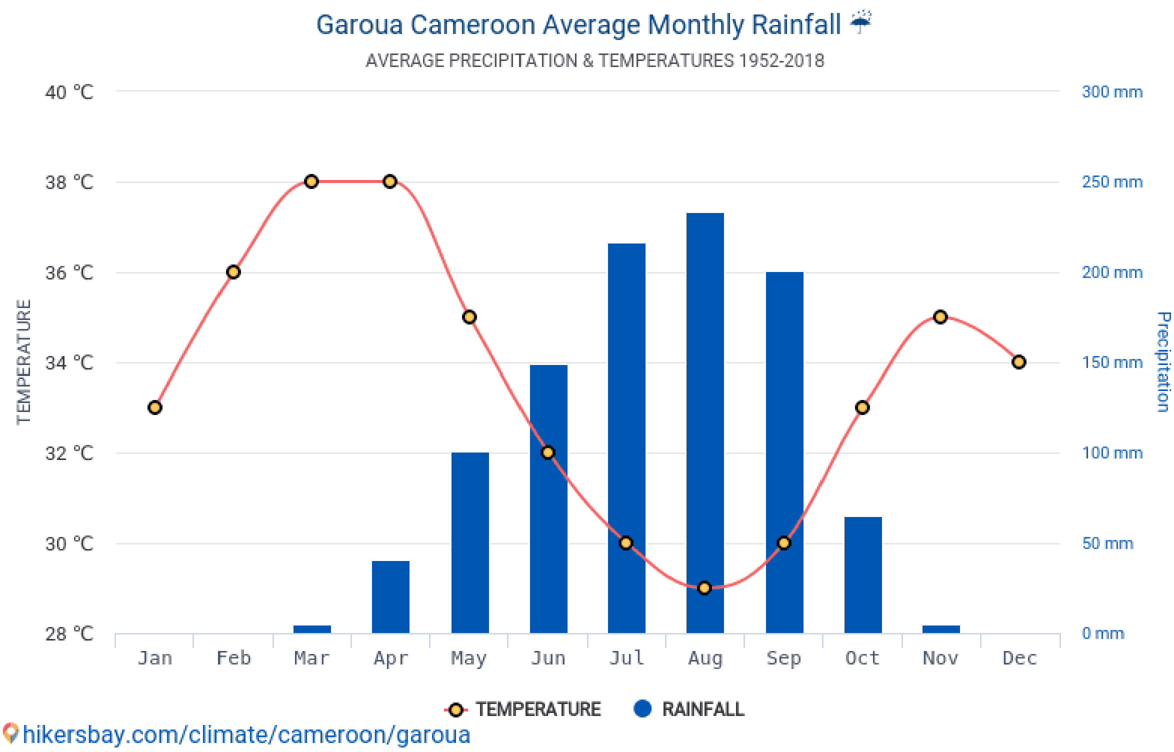


Figure 1.2: A climograph showing the average monthly temperature and rainfall in Garoua. A basic climate data set 1952-2018 for Garoua

	January	February	March	April	May	June	July	August	September	October	November	December
Day	33°C 91°F	36°C 97°F	38°C 100°F	38°C 100°F	35°C 95°F	32°C 90°F	30°C 86°F	29°C 84°F	30°C 86°F	33°C 91°F	35°C 95°F	34°C 93°F
Night	17°C 63°F	20°C 68°F	23°C 73°F	25°C 77°F	24°C 75°F	22°C 72°F	21°C 70°F	21°C 70°F	21°C 70°F	21°C 70°F	19°C 66°F	17°C 63°F

Table 1.1: Garoua Monthly temperatures 1952 - 2018

1.2 Problem Statement (Non-Technical View Point)

Farmers working in semi-arid areas like Garoua are highly reliant on rainfall patterns that are highly erratic and irrigation systems that are old-fashioned. Such traditional activities are characterized by excessive use of water, require constant manual work, and often lead to low agronomic performance. In addition, the intermittency of the electricity supply and high operation cost of the diesel-powered pumps also limit access to efficient irrigation systems.

Due to the fact that various crops, such as tomato, millet or cabbage, possess different hydraulic demands, the universal irrigation regime will tend to cause either over watering or under watering, thereby leading to crop stress and causing nutrient leaching. Without real time monitoring instrumentation, farmers will end up guessing and in the process; this encourages inefficiencies and increased depletion of resources.

This leads to reduced agronomic productivity, increased water shortage, and the household income, which directly affects the livelihoods of the smallholder agrarian stake. The challenge of the same requires a cost-effective, automated, and sustainable irrigation solution which can intelligently control a variety of crops and save on water and energy.

1.2.1 Limitations Of Existing Work

Though smart irrigation technologies were already researched and implemented on the global level, there are some important deficiencies, especially in the area of developing regions:

1. Expensive Implementation: Most commercial smart irrigation vendors come with high implementation costs, making them a luxury to the smallholder operators.

2. Single-Crop Limitability: The existing systems are mostly responsive to a single type of crop and do not respond to multi-crop irrigation regimes having dynamic water thresholds.

3. Energy Insecurity: The majority of platforms are only grid-connected and eventually rely on sun arrays that are disconnected, thus being less reliable in environments that are characterized by unstable power supply.
4. Absent Real-Time Feedback: The designs do not have real-time data visualization and remote control interfaces integrated into them as Internet-of-Things (IoT).
5. Minimal Local Accommodation: There is a lack of solutions that are sensitive to the particular climatic, edaphic, and socio-economic environments of the semi-arid African areas.

These limitations highlight a desperate need of a low-cost, multi-crop sensing irrigation infrastructure which runs on hybrid solar-grid energy source which is flexible to real-life needs of the area such as Garoua.

1.2.2 Motivation Of The project

The rationale behind this project is the pressing need to have strong agricultural systems that will protect food security and sustainability in the semi arid areas. The Sustainable Development Goals, namely, SDG 2 (Zero Hunger) and SDG 7 (Affordable and Clean Energy) highlight the need to be innovated in agricultural activities and implement renewable energy technologies, which are the focus of this effort.

The theoretical basis of the current study is based on the vision of providing farmers with less-expensive, automated, and smart irrigation systems that use IoT sensing to monitor several crops at a time and work on clean solar energy. The implementation of solar-grid hybrid system ensures that the system will be reliable even during bad weather or when there is a shortage of energy.

This project has been complementary to the Vision 2035 of Cameroon and the Agenda 2063 of the African Union that puts emphasis on sustainable farming and technology development. The general aim is to come up with a realistic, scalable, and community-based engineering solution to improve the efficiency of water-use, reduce the reliance on energy, and improve the socioeconomic welfare of farmers living in semi-arid areas.

1.3 Research Gaps

1. No Multi-Crop Sensing Systems:
There is a lack of literature regarding Internet-of-Things (IoT) based irrigation systems capable of distinguishing and controlling crop-based water needs in real-time.

2. Absence of good Solar-Grid hybrid Integration:
Not many irrigation systems incorporate renewable and conventional energy sources to guarantee constant functioning in the areas that have unstable or no grid power.

1.4 Research Questions

1. But how can the IoT-based multi-crop sensing be deployed to control crop-specific irrigation in the semi-arid areas?

2. What is the role of a solar-grid hybrid power system to improve the reliability and energy efficiency of smart irrigation systems among smallholder farmers?

1.5 Problem Identification (Technical Statement)

The technical issue that the current research will solve is the construction and installation of an IoT-based, solar -grid hybrid irrigation that can multi-crop sense and control. The difficulty is to combine real-time soil moisture, wireless communication, and automated water distribution with the help of microcontrollers. The system has to provide crop specific water control at a low cost, high reliability, and energy sustainability to the semi-arid agricultural setting of Garoua, Cameroon.

Figure 1.3:Triple Impact Farmer, Environment, Policy

1.6 Objectives (Technical Statement)

1. To model and implement an IoT-based multi-crop sensing smart irrigation system which will automatically adjust water supply to tomato, millet and cabbage depending on the moisture content during each time.

2. To design and test a solar-grid hybrid energy system, which ensures uninterrupted efficient and sustainable operation of the irrigation system in semi-arid climatic conditions.

   These are SMART objectives Specific, Measurable, Achievable, Relevant and Time-bound, which are aligned to the wider goals of integration of sustainable agriculture and renewable energy.

1.7 Scope (Boundary Of The Study)

- Data Scope: To collect and manage data in real time, the system makes use of temperature and humidity sensors, three soil moisture sensors (for tomato, millet, and cabbage), and an Internet of Things platform.
- Geographic/Operational Scope: Garoua, Cameroon, a semi-arid region selected for its agricultural significance and climate vulnerability, serves as the basis for both the prototype and the analysis.
- Limitations: The study excludes large-scale deployment outside of the test region, long-term economic assessment, and integration of AI-based weather prediction.

1.8 Expected Outcome And Socio-Economic Benefit

Technical Results:

- An operational model of an IoT-based irrigation system that combines solar and grid technology and has the ability to sense multiple crops.
- platform for real-time control and monitoring through Blynk IoT.
- measured gains in energy dependability and water-use efficiency over conventional irrigation techniques.

Benefits to Society and the Economy:

- Regarding Farmers: increased crop yields, less manual labor, and better water use.
- For the environment: less carbon emissions, less water waste, and the use of renewable energy.
- For Researchers and Policymakers: A model that can be expanded to support smart agriculture and incorporate sustainable technologies into national policies.
- Long-term, the project helps rural communities become more economically empowered, adapt to climate change, and ensure food security.
- For Policymakers and Researchers: A scalable model for promoting smart agriculture and integrating sustainable technologies into national policies.
  In the long term, the project contributes to climate adaptation, food security, and economic empowerment in rural communities.

1.9 Methodology (Technical Blueprint)

1. System Design: Using microcontrollers (such as NodeMCU or Arduino), create the circuit and sensor connections for multi-crop moisture sensing.
2. Energy Integration: Put in place a solar-grid hybrid power module that uses the grid as a backup and solar energy as its main source.
3. Software Development: Set up Blynk IoT for mobile monitoring, control, and data transfer.
4. Testing and Calibration: To identify the ideal threshold values, test the tomato, millet, and cabbage in the field.
5. Evaluation: Examine performance indicators like energy efficiency, system dependability, and water savings in comparison to conventional irrigation techniques.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In order to maintain agricultural productivity worldwide, irrigation is essential. The Food and Agriculture Organization (FAO) states that irrigation is crucial to maintaining food security because it is responsible for almost 70% of all freshwater withdrawals globally. Because of unpredictable rainfall patterns and scarce water supplies, effective irrigation management is essential in semi-arid areas like northern Cameroon. Conventional irrigation techniques, like flood irrigation or bucket watering by hand, are very ineffective and lead to soil erosion, water waste, and decreased crop yields.

The combination of the Internet of Things (IoT), renewable energy sources, and automation has culminated into the creation of smart irrigation systems that use sensors to scan the fitness of the field and to automatically adjust the water use. These types of systems generally consist of sensing devices (soil moisture, humidity and temperature sensors), decision making microcontrollers and actuators (pumps and valves) that can supply the needed water at the appropriate time.

The literature considered in this chapter has been based on four key themes:

1. History of irrigation technologies the history of the transition of the manual irrigation technique to modern solutions based on the IoT.
2. The role of IoT in agriculture describing how IoT can be used to conduct real-time monitoring, make decisions and automation.
3. Sensor and energy technologies that detect vital elements in smart irrigation systems.
4. Related works and research gaps evaluating existing studies to show the technical drawbacks and the contributions of the research.

Figure 2.1: Evolution of Irrigation Technologies from Manual to IoT-Based Systems (source:www. mr farmer)

2.2 Related Work

Many researches have been conducted on the use of IoT-based irrigation technology in precision agriculture. Nevertheless, most of them concentrate on single-crop control, single solar energy, or rather one-sided monitoring. The recent works on related works highlight the following:

- **IoT-Based Smart Irrigation Systems:**
  Some authors have used soil moisture sensors, temperature, and humidity sensors in collaboration with microcontrollers like Arduino or ESP8266 in order to automate the process of irrigation. Remote control is normally through GSM or Wi-Fi transmission of data. Despite these systems enhancing efficiency, they are normally optimized towards single crop irrigation and do not provide flexibility to fields with different crops that demand different moisture levels.

- **Solar-Powered Irrigation Systems:**
  Numerous studies suggest solar panels to run irrigation pumps in off-grid locations, thus increasing the sustainability level and decreasing the reliance on fossil fuels.

Nevertheless, the majority of them are solar-only, which makes them unreliable in the cloudy weather or nighttime when there is no hybrid energy source.

- **IoT Dashboards and Mobile Integration:**
  Other systems use mobile app or IoT like Blynk and ThingSpeak to display real-time data. Although these solutions enhance monitoring and interaction with farmers, most solutions only display the data and not to provide combined control over various areas or crop varieties.
- **Sensor Network Integration:**
  Other previous literature show that soil moisture sensors can be used to successfully automate the irrigation time. However, minimal designs have been based on multi-sensory to various crops in the same field, which is required in a design to maximize water allocation to diverse crops depending on their difference in water demands.
  Overall, despite being certain leaps in automation and renewable integration, the extents of the existing systems are still small, either focused on a single crop, a single source of energy, or the lack of flexibility in their control

2.3 Limitation Of Existing Work

Nevertheless, although technologies in the area of the IoT-based irrigation have improved, a number of major limitations can still be observed throughout the literature:

- Single-Crop Focus:
  The existing systems are mostly designed to deal with one type of crop only without considering the fact that multiple soils have varying moisture levels of different crops that can be planted at the same period.
- Energy Reliability Issues:
  Solar-powered systems though environmental friendly, often experience interruption in case of cloudiness or rainy seasons because of the lack of the integration (solar-grid), which means the irrigation will be inconsistent.
- Limited Real-Time Control:
  Most designs only focus on the data collection of sensors without providing interactive control or feed back and therefore limit practical usage in field activities.

- Hardware Constraints:
  Earlier systems used low capacity microcontrollers (e.g. arduino UNO) which are unable to handle a large number of sensor inputs or complex processing of the data needed to support large scales or multi crop.
- Scalability and Field Validation:
  Other research prototypes have only been tested in laboratory tests or small scales plots, hence limiting them to application in the real world under semi-arid or rural areas.
- Lack of Integrated Solutions:
  Multi-crop sensing has not been implemented together with hybrid energy management and IoT-based monitoring into a coherent and automated system that can be adjusted to different field conditions.

Method	Efficiency	Labour Required	Suitability in Semi-Arid Regions
Manual Flooding	Low	Very high	Poor
Sprinkler Systems	Medium	Medium	Fair
Timed Irrigation	Medium	Low	Limited
IoT Smart Irrigation	High	Low	Limited

Table 2.1: Comparison of Irrigation Methods

2.4 Our Research’s Contribution: Addressing and Resolving the Existing Research Gap

The given study directly mitigates the above limitations through offering a multi-crop IoT-based smart irrigation system on a solar-grid hybrid energy source. The following contributions are made:

- Multi-Crop Sensing and Control:
  The principle of Multi-Crop Sensing and Control is the basis of this method.In

comparison with the previous systems, the project has three soil moisture sensors which are to measure three different crops (tomato, millet, and cabbage). The sensors separately measure the soil moisture and irrigation can then be determined on a crop-specific basis regarding the water content.

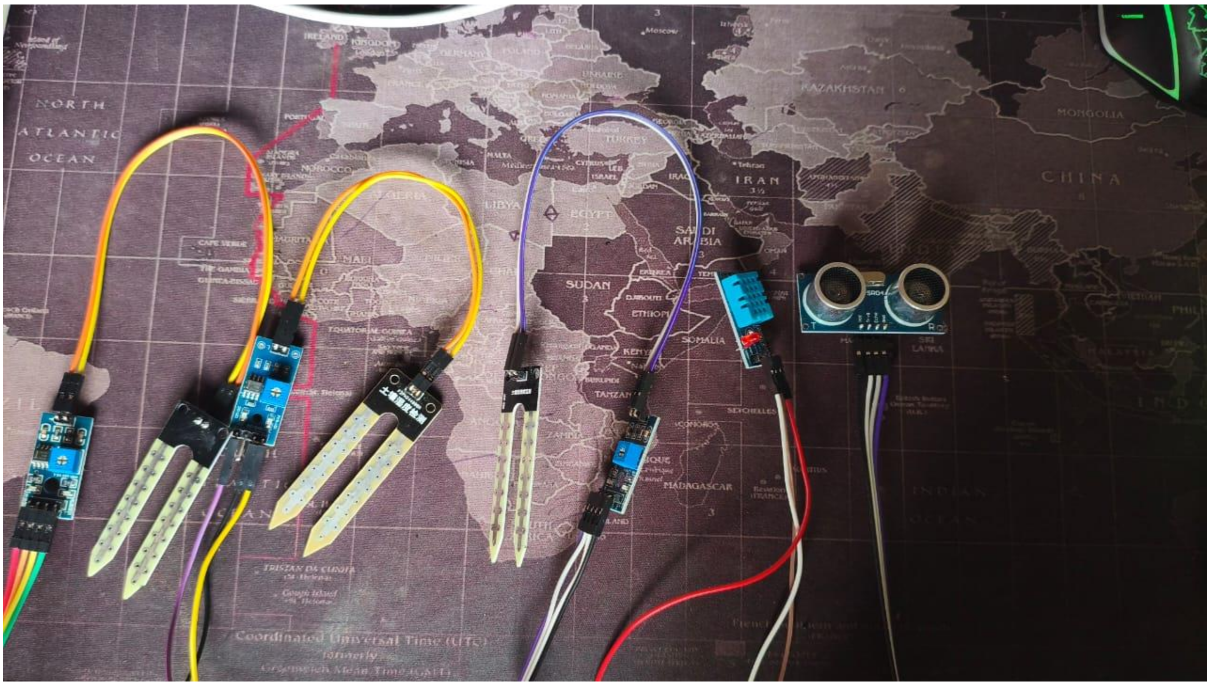


Figure 2.2: Different Sensors Used

- Hybrid Energy Integration:

  The system combines solar power with grid power which means that the system operates continuously even in times when there is a deficit of sunlight. The hybrid design is more reliable and sustainable in off-grid and semi-arid areas.
- Real-Time IoT Monitoring and Control:

  Real-time IoT monitoring and control uses the platform of the Internet of Things. With the help of the Blynk IoT platform, farmers will be able to access sensor data, be notified about the water level, and be able to remotely manage the irrigation pump. This will make the system more user-friendly and accessible to small-scale farmers.
- Automation and Resource Efficiency:

  The system automatically switches on or off the pump depending on the real-time information of soil moisture, thus ensuring the minimal usage of water and energy and maximum crop production.

- Scalable and Affordable Design:
  The system is based on ESP32 and has considerable processing potential, low price, and can be extended to add more sensors or bigger farm parcels.

CHAPTER 3

OVERVIEW OF METHODOLOGY

This thesis's methodology is divided into three main stages:

- System Design Phase: circuit architecture design, component selection, and functional requirements definition.
- Phase of implementation: ESP32 programming, hardware assembly, and Blynk IoT platform integration
- Phase of testing and validation includes performance evaluation, threshold value verification, and experimental trials.

3.1 Hardware Implementation

Sensors, actuators, controllers, and energy sources are physically assembled in the hardware section. Below is a description of each subsystem.

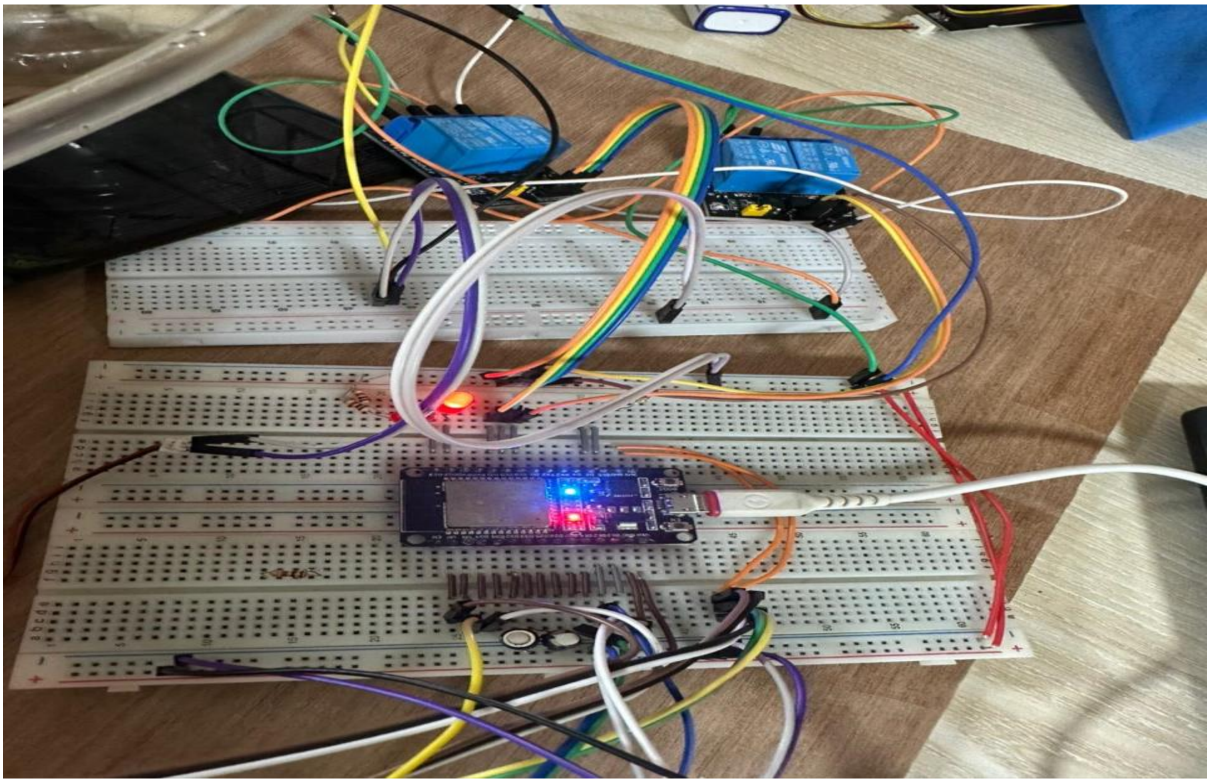


Fig 3.1: Hardware

3.1.1 ESP32 Microcontroller

The ESP32 acts as the brain of the system, coordinating all sensor inputs and actuator outputs.

Features used in this project:

Wi-Fi module for IoT connectivity with Blynk.

12-bit ADC pins to read analog moisture sensor values.

GPIO pins for relay control.

PWM capability (reserved for possible pump speed control).

The ESP32 is powered through a regulated 5V–3.3V converter connected to the solar-grid hybrid supply.

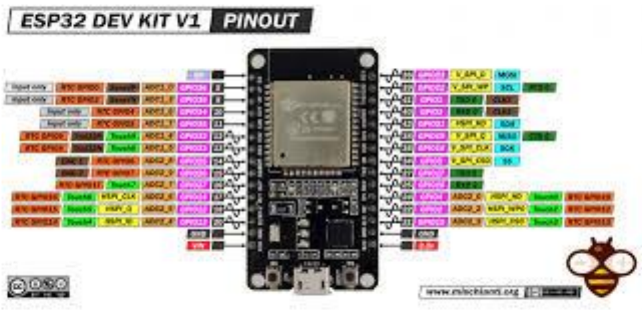


Figure 3.2: ESP32 Pin Mapping for Smart Irrigation (www.Renzo mischianti)

3.1.2 Soil Moisture Sensors

Three capacitive soil moisture sensors are deployed, one for each crop (tomato, millet, cabbage).

Operating voltage: 3.3–5V.

Output: Analog signal proportional to soil moisture content.

Placement: Inserted 5–7 cm into the soil near crop roots to measure root-zone moisture.

Calibration: Dry soil value recorded as 0%, fully saturated soil recorded as 100%.

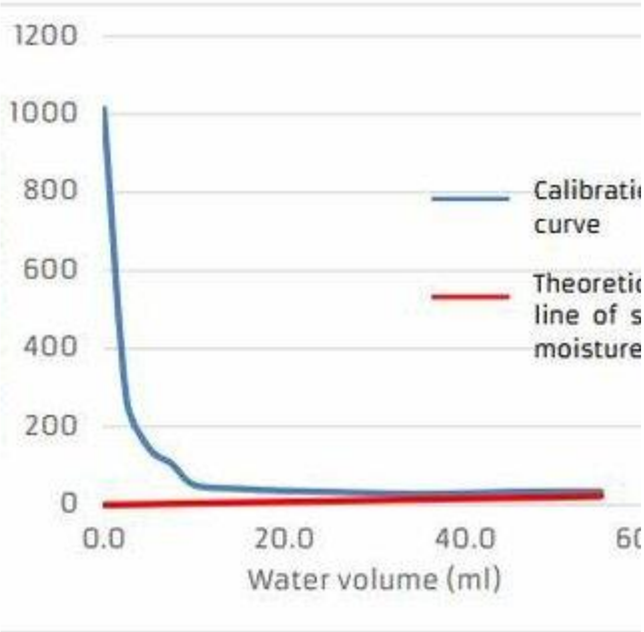


Figure 3.3: Soil Moisture Sensor Calibration Curve (source:www.researchgate.net)

3.1.3 Water Pumps

Three independent 12V DC submersible pumps are used.

Pump 1 → Tomato field.

Pump 2 → Millet field.

Pump 3 → Cabbage field.

Controlled via relay driver circuits connected to ESP32.

Each pump draws ~1.2 A during operation.

3.1.4 Relay Module

Dual-purpose:

Crop-specific pump switching (controlled by ESP32).

Solar-grid hybrid power switching (controlled by system power monitor).

Type: 5V SPDT relay module.

Isolation: Optocoupler-based for protecting ESP32 from high current surges.

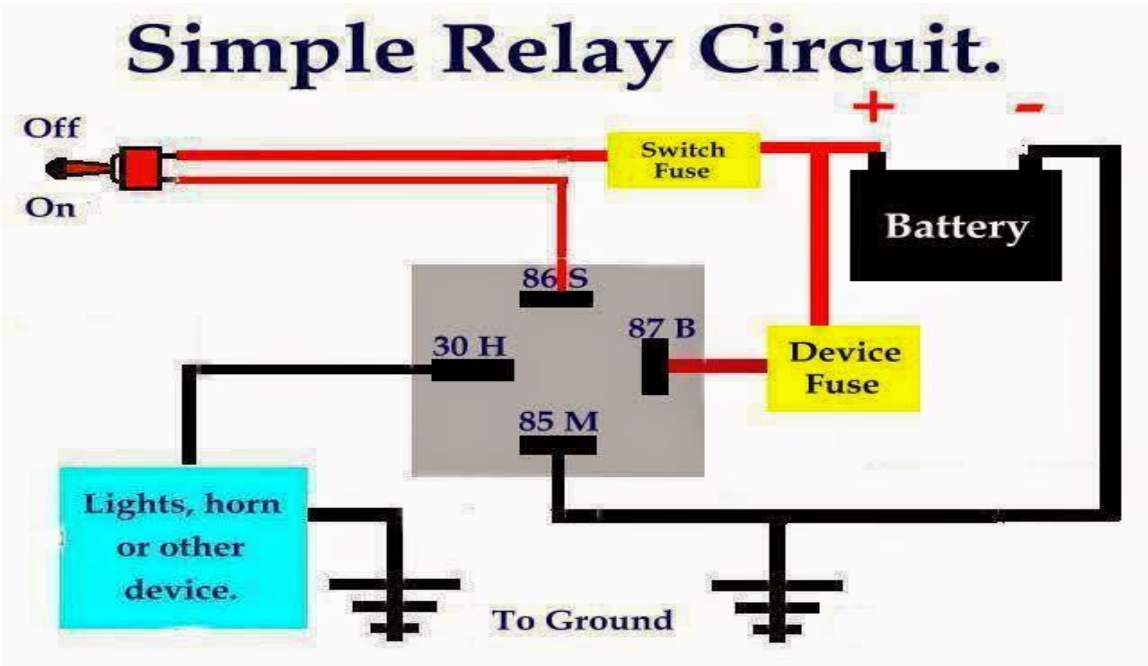


Figure 3.4: Relay Switching Circuit Diagram

3.1.5 Ultrasonic Sensor for Water Level Measurement

Model: HC-SR04 ultrasonic sensor.

Function: Measures water level in storage tank (max depth ~1.5 m).

Working principle: Sends ultrasonic pulse, measures time of echo return, and calculates distance.

Integration: Sensor output used to trigger low-water alerts in Blynk and prevent pump dry-run.

Formula: Distance = Time x Speed of sound

Water level = Tank depth – Measured distance.

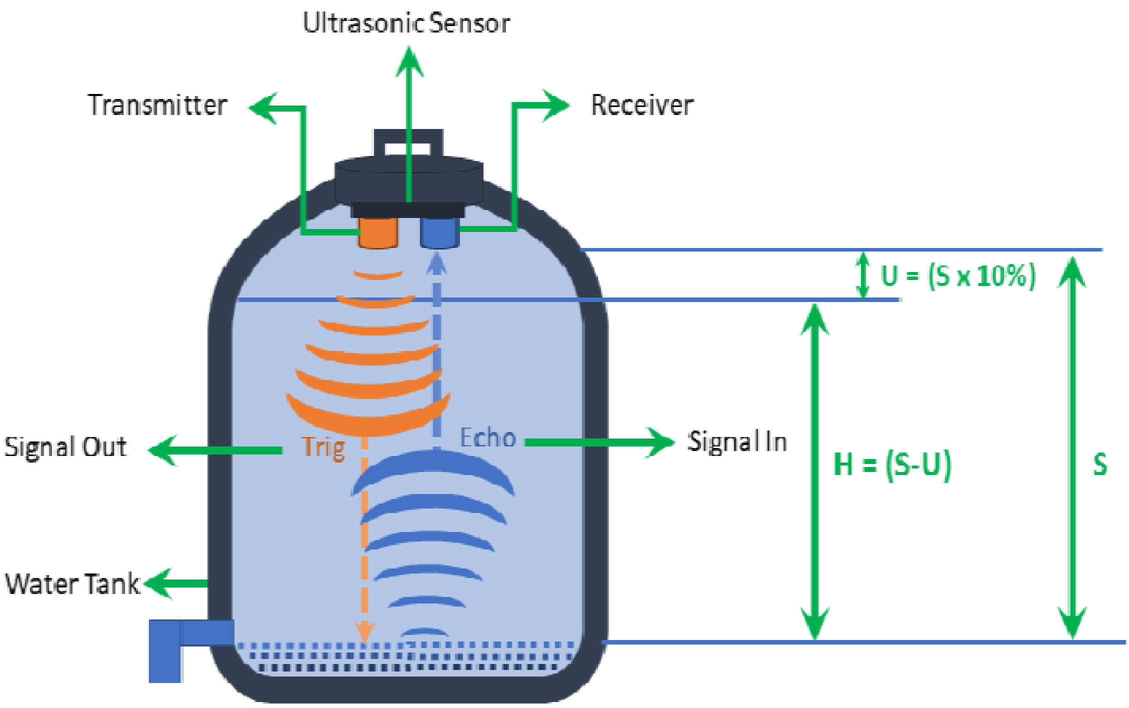


Figure 3.5: Water Level Measurement Principle (source: www.researchgate.net)

3.1.6 Temperature and Humidity Sensor (DHT11)

Provides ambient temperature and humidity data.

Purpose:

Logging environmental conditions in Blynk.

Future potential for predictive irrigation models.

3.1.7 Solar-Grid Hybrid Power Supply

Solar panel (50W, 12V) is the primary source.

Grid power acts as backup, connected via relays.

Charge controller ensures proper charging of a 12V/7Ah lead-acid battery.

Load is distributed as:

ESP32 + sensors: ~300 mA.

Pumps: ~1.2 A each.

Total daily consumption estimated at ~24 Wh.

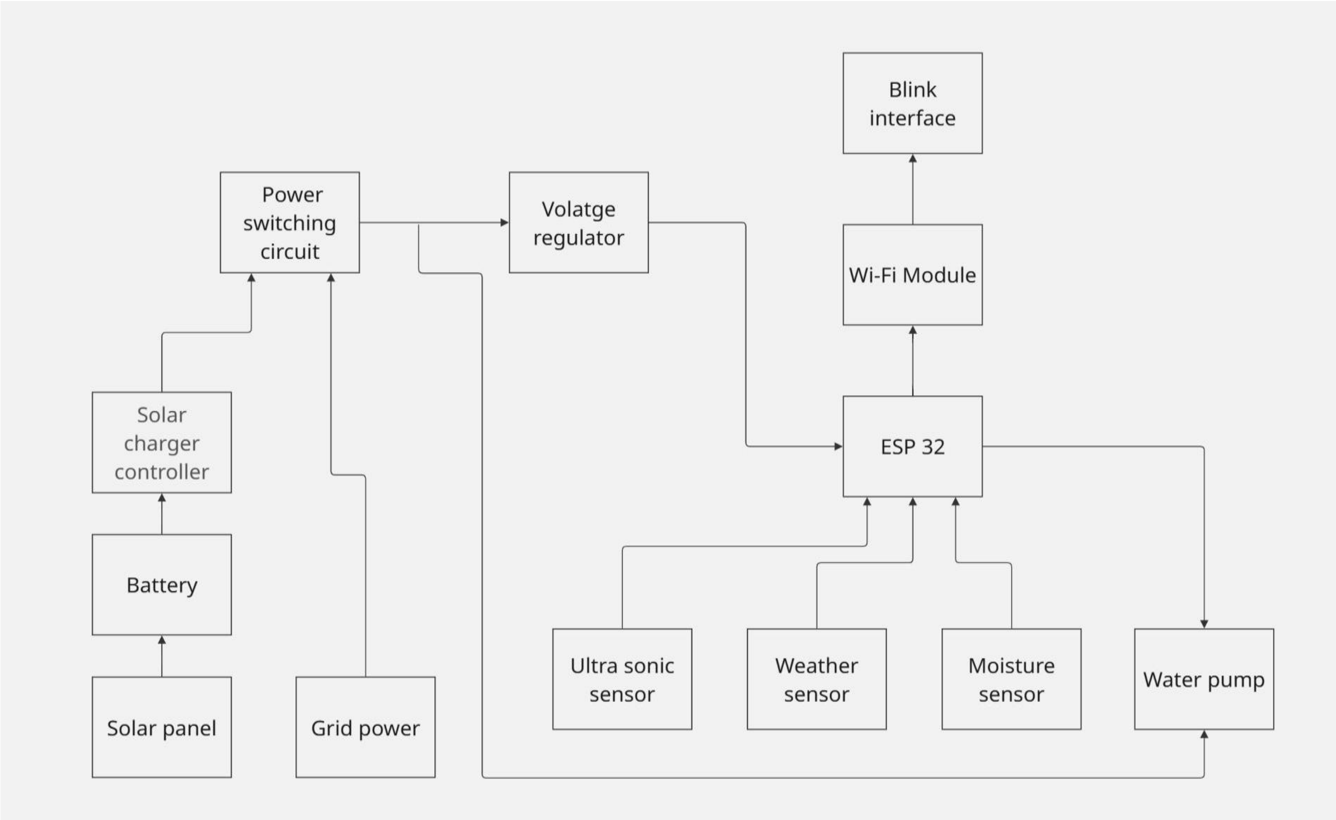


Figure 3.6: Solar-Grid Power Switching Block Diagram (for one moisture sensor)

3.2 Software Implementation

The software stack includes Arduino IDE for ESP32 programming and Blynk IoT app for remote control

3.2.1 Arduino IDE Development

ESP32 programmed using C/C++ in Arduino IDE.

Libraries used:

WiFi.h for connectivity.

BlynkSimpleEsp32.h for Blynk integration.

DHT.h for temperature/humidity sensor.

NewPing.h for ultrasonic sensor.

3.2.2 Irrigation Algorithm

Step 1: Sensor Data Acquisition

Moisture values read from analog pins (A0, A1, A2).

Temperature & humidity read from DHT11.

Water level calculated using ultrasonic sensor.

Step 2: Threshold Comparison

Tomato: start <50%, stop >80%.

Millet: start <25%, stop >55%.

Cabbage: start <60%, stop >75%.

Step 3: Pump Activation

Relay ON if soil moisture below threshold.

Relay OFF if above threshold.

Step 4: Power Source Selection

Solar is checked first.

If unavailable, switch to grid.

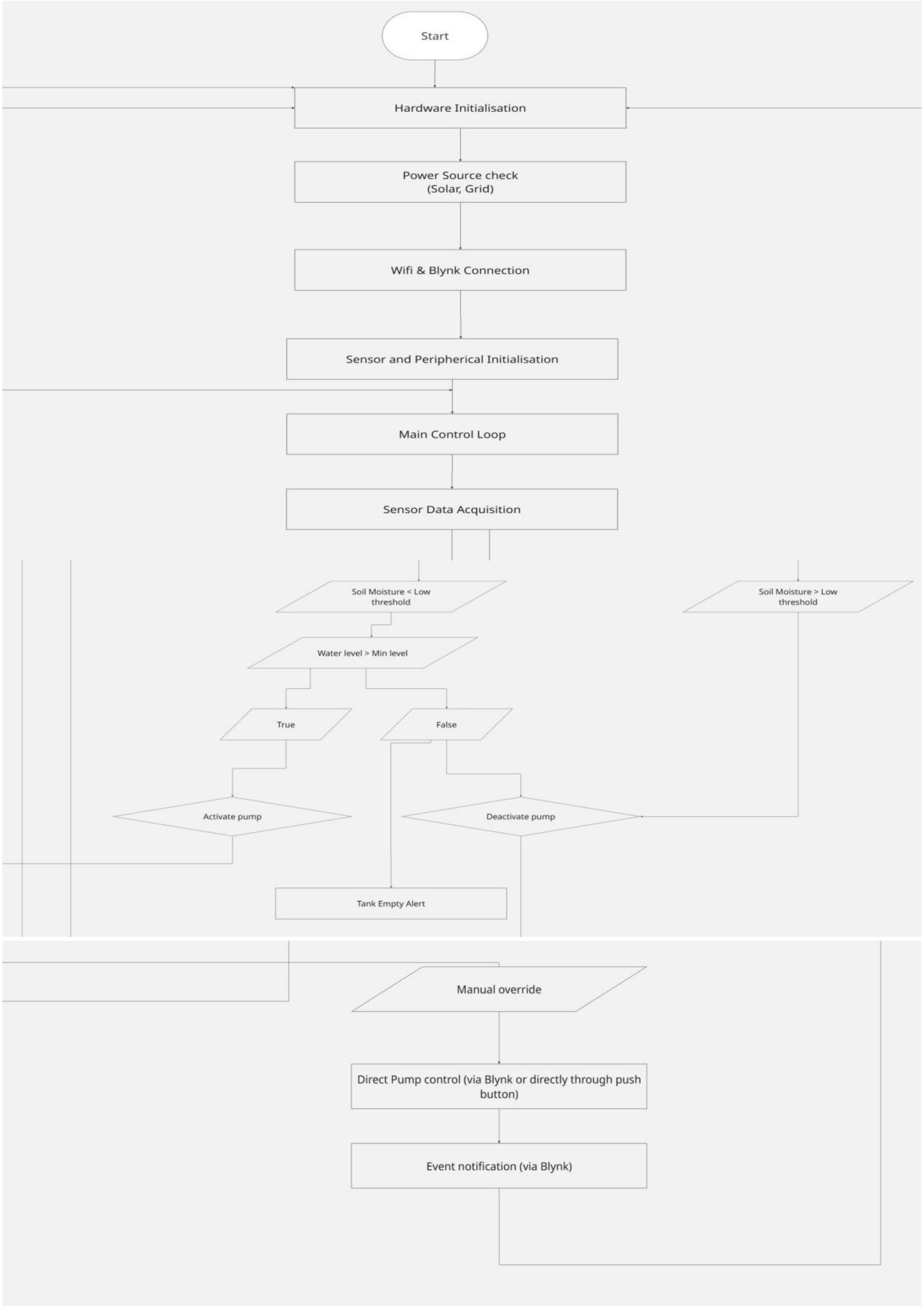


Figure 3.7: Flowchart of Irrigation Algorithm (for one moisture sensor)

3.2.3 Blynk Dashboard

Virtual pins assigned for sensor data:

V0 → Tomato moisture.

V1 → Millet moisture.

V2 → Cabbage moisture.

V3 → Tank water level.

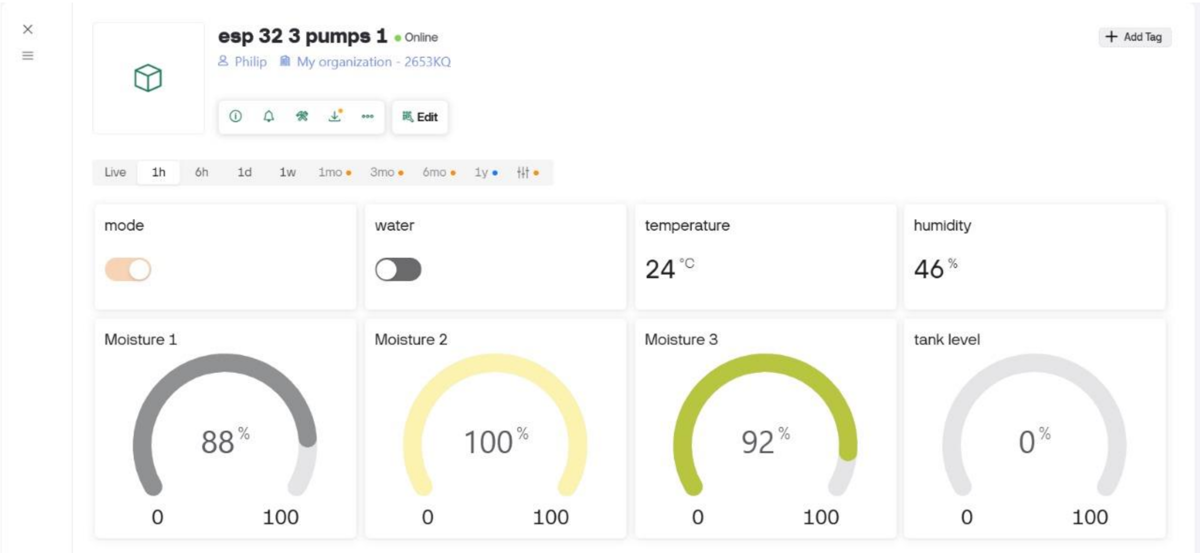
V4 → Temperature.

V5 → Humidity.

Control features:

Pump ON/OFF (manual override).

Notifications for low water and power switching.



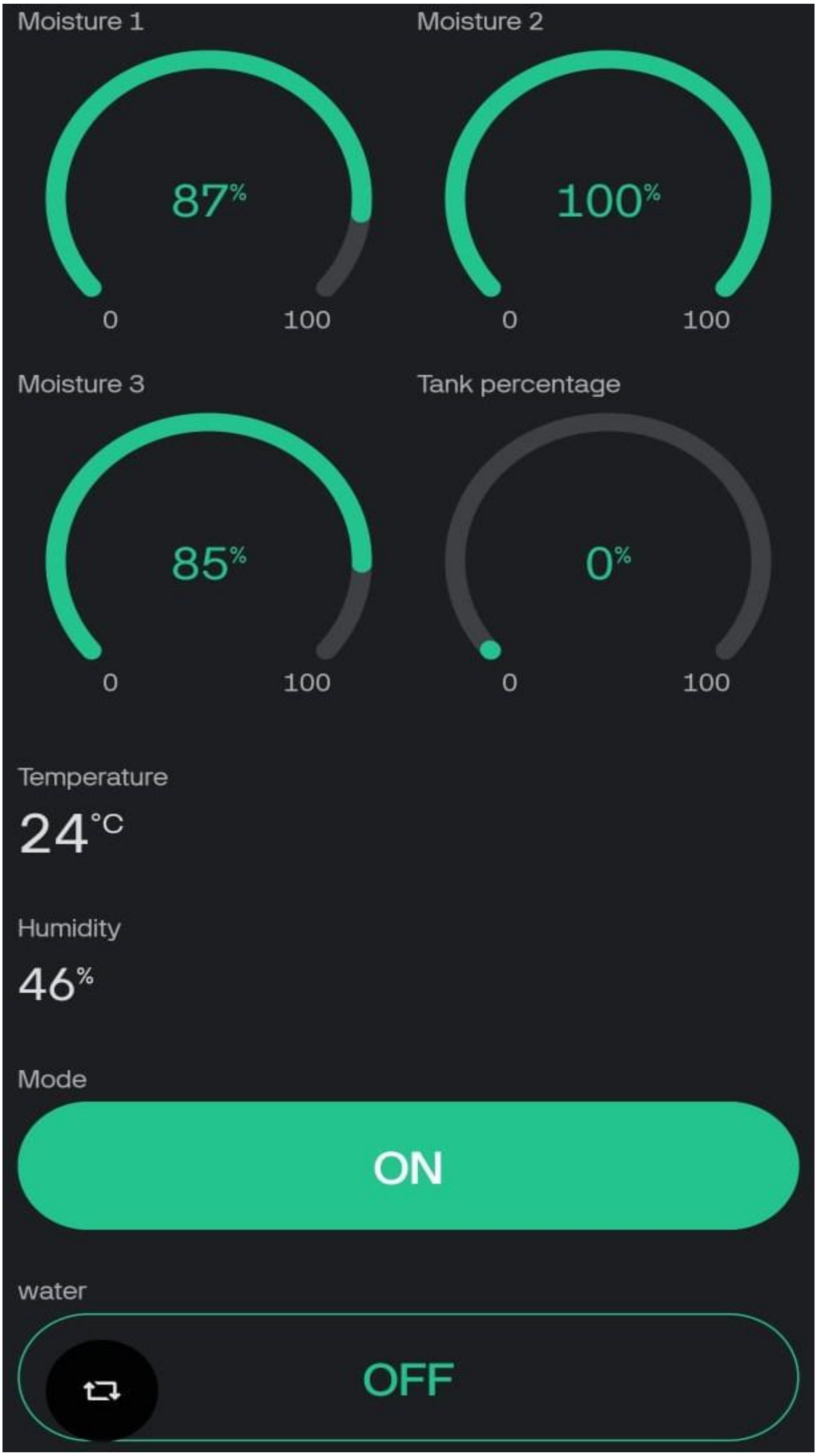


FIGURE 3.8: Screenshot of Blynk Dashboard

3.3 Irrigation Logic Validation

Testing Conditions:

Artificially dried soil to trigger pump ON.

Added water to soil until threshold reached → pump OFF.

Results (observed during trials):

Tomato pump triggered at ~49% moisture, stopped at ~82%.

Millet pump triggered at ~24%, stopped at ~56%.

Cabbage pump triggered at ~59%, stopped at ~76%.

This confirms that the programmed thresholds match real-world soil responses.

3.4 System Integration

The final prototype connects all subsystems: sensors, pumps, relays, solar-grid supply, and IoT monitoring.

Key integration challenges resolved:

Power fluctuations from solar panels are handled via capacitor filtering.

Moisture sensor noise is reduced using an averaging filter in software.

Pump dry-run prevention using ultrasonic tank sensor.

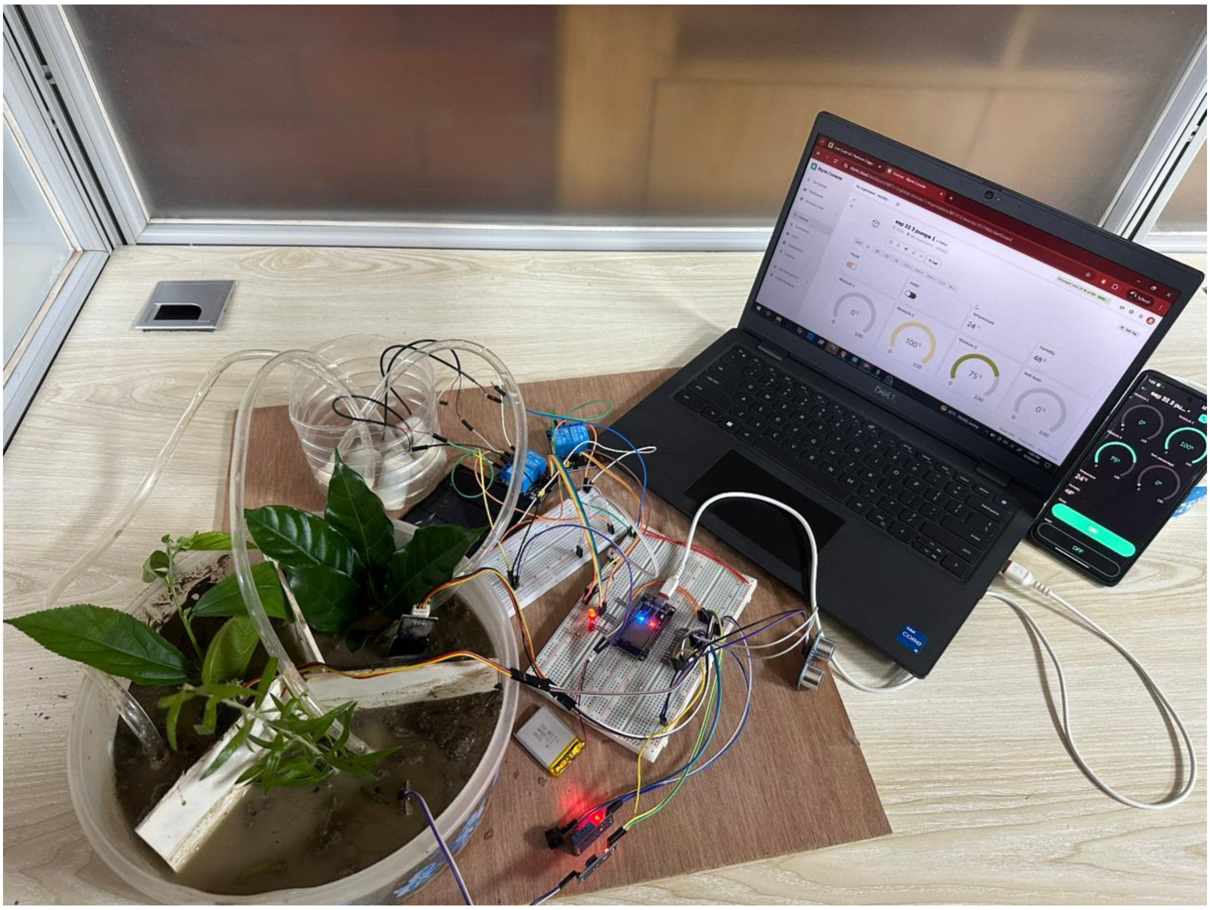


FIGURE 3.9: Final Prototype Setup

CHAPTER 4

RESULTS ANALYSIS

4.1 Overview

This chapter gives the performance analysis and functional validation of the developed Smart Solar-Powered Multi-Crop Irrigation System based on IoT.

The three critical areas that are considered in the evaluation are:

- The functionality of the irrigation control system to manage multi-crop.
- The stability in the operation of the hybrid (solar-grid) power management system.
- The monitoring and control using the IoT technology through the Blynk platform.

The validation was done in terms of real-time observation, threshold-based testing or testing the system end-to-end analysis.
The performance measures involve accuracy of response, power stability, sensor accuracy and stability of remote communication.

4.2 Finding From Data Analysis

The section identifies the main performance outcomes and trends that are monitored in case of testing of individual subsystems and the overall integrated environment.

(a) Irrigation Control System Performance

Observation:
The logic of the system was working as intended. The response to crop-specific soil moisture thresholds of each of the three pumps, which were used on tomatoes, millet, and cabbage plots, was correct.

- At 50% the tomato pump was switched on and at 82% turned off.

- Millet and cabbage pumps were also able to react with a similar degree of accuracy to their preset moisture limits.

Discussion:

The findings affirm that the system facilitates relevant irrigation whereby water is supplied at the time of need to each type of crop. It is an important development in multi-crop water management and sustainable agriculture since this adaptive control greatly minimizes the amount of water wasted with the traditional practices of manual/timed irrigation, and is also effective in making sure that each crop gets water at a rate that best fits its physiological requirements.

4.3 Hybrid Power Management System Operation

The hybrid power sub system was tested to run smoothly thus ensuring energy security.

Observation: At sufficient solar irradiance, the system could only continue operating with the sun power. When the battery voltage dropped below the programmed value; the automated switch circuitry successfully switched the load to the grid source without error, simulated by occluding the solar panel.

Discussion: Such findings support the fact that the system is resilient to energy, which is a critical design goal. This makes it a strong and reliable technology that can be applied in practice in agriculture because it can be used in less than ideal solar conditions.

(b) Hybrid Power Management System Operation

Observation:

The hybrid solar-grid subsystem had a fluent performance. The system was entirely solar powered, and the system used photovoltaic energy due to sufficient solar irradiance. The automatic switching mechanism also helped to ensure continuous functioning of the system when the battery voltage dropped below the safety threshold, which was tested by covering the solar panel.

Discussion:

From the observation done above, the energy resilience of the system was confirmed, which ensured constant irrigation at reduced solar irradiation. This is vital to remote agricultural scenarios, which confirms the usefulness and dependability of hybrid power integration.

(c) IoT Monitoring and Control Framework

Observation:

The ESP32 microcontroller successfully sent all sensor data such as soil moisture, temperature, humidity and water level to the custom-made Blynk IoT dashboard in real time. The remote turn-on and turn-off of the pump was made possible through the use of the manual override feature and users were notified of the low water levels through the use of push notifications as expected.

Discussion:

The integration will provide farmers with real-time access to the irrigation system. It helps avoid the need to inspect and thus leads to the use of data in making decisions and appropriate timely interventions. Therefore, IoT capability is a direct countermeasure to the inefficiencies of manual tracking of the traditional irrigation systems.

(d) Overall System Integration

Observation:

All the hardware and software subsystems, such as the sensors, microcontrollers, power modules as well as the communication links worked in unity. The process of simultaneous work (sensor acquisition, cloud communication, and pump control) was accomplished without problems and interruptions. There was also the use of advanced software filtering so that the noise created by the sensor would be regulated and thus stable and reliable readings were obtained.

Discussion:

The overall system is highly integrated and synchronized in all the modules that make it up.

Several challenges like the change in power and the interference of the signal are overcome which emphasizes the strictness of the engineering design and the willingness to use the system on a large scale.

4.4 Result Justification in Accordance with the Objective and Expected Outcome

The outcomes achieved directly are in accordance with the research objectives and desired project goals:

Objective	**Validation From Results**
To design and implement a multi-crop IoT-based smart irrigation system	Achieved through precise, threshold-based irrigation for three different crops (tomato, millet, cabbage), validating multi-crop sensing and independent control logic
To ensure sustainable and reliable operation using a solar–grid hybrid power source	Demonstrated through automatic power switching that maintained system operation even under low sunlight conditions.
To enable real-time monitoring and remote control for farmers	Accomplished with the Blynk IoT platform providing instant data visualization, alerts, and remote pump control.

CHAPTER 5

DEMONSTRATION OF OUTCOME BASED EDUCATION (OBE)

Outcome Based Education (OBE) is a way of teaching that focuses on what students can do after they finish a course or program. Instead of focusing on what students learn, it focuses on what they can do with what they learn. The abilities, skills, and competencies that students gain are the main signs of success.

In engineering education, OBE guarantees that graduates can use what they learned in school in real life, solve hard problems, and be responsible members of society. The framework establishes Course Outcomes (COs) that are directly associated with Program Outcomes (POs) and Knowledge Profiles (K3–K8). This guarantees that students not only gain technical expertise but also cultivate communication skills, teamwork, ethical awareness, and sustainability considerations.

This thesis illustrates the OBE framework by aligning the project—IoT-Based Solar-Grid Hybrid Smart Irrigation System for Multi-Crop Cultivation in Semi-Arid Regions—with the established Course Outcomes (COs), Program Outcomes (POs), and characteristics of complex engineering problem-solving and activities. This organized mapping shows how the project helps engineering education reach its academic, professional, and social goals.

5.1 Introduction

Outcome Based Education (OBE) is a way of teaching that focuses on getting students to reach certain learning goals. In engineering programs, OBE makes sure that students not only learn technical skills but also how to use those skills to solve difficult problems in a professional and moral way.

This chapter demonstrates how the undertaken project, IoT-Based Solar-Grid Hybrid Smart Irrigation System for Multi-Crop Cultivation in Semi-Arid Regions, addresses different course outcomes (COs), program outcomes (POs), knowledge profiles (K3–K8), attributes of complex engineering problem solving (P1–P7), and attributes of complex engineering activities (A1–A5).

The project integrates multiple domains of electrical and electronic engineering—IoT, renewable energy, embedded systems, sensors, and control systems—to solve a pressing societal issue: efficient irrigation in semi-arid regions. The following sections detail how the project maps to OBE components.

5.2 Course Outcomes (COs) Addressed

The following table shows the COs addressed in EEE 4700 for Project and Thesis.

COs	CO Statement	POs	Put Tick (√)
CO1	Apply knowledge of electrical and electronic engineering to the solution of complex engineering problems.	PO1	√
CO2	Identify a contemporary real life problem related to electrical and electronic engineering by reviewing and analyzing existing research works.	PO2	√
CO3	Determine functional requirements of the problem considering feasibility and efficiency through analysis and synthesis of information.	PO4	√
CO4	Select a suitable solution and determine its method considering professional ethics, codes and standards.	PO8	√
CO5	Adopt modern engineering resources and tools for the solution of the problem.	PO5	√
CO6	Prepare management plan and budgetary implications for the solution of the problem.	PO11	√
CO7	Analyze the impact of the proposed solution on health, safety, culture and society.	PO6	√
CO8	Analyze the impact of the proposed solution on environment and sustainability.	PO7	√
CO9	Develop a viable solution considering health, safety, cultural, societal and environmental aspects.	PO3	√
CO10	Work effectively as an individual and as a team member for the accomplishment of the solution.	PO9	√
CO11	Prepare various technical reports, design documentation, and deliver effective presentations for demonstration of the solution.	PO10	√
CO12	Recognize the need for continuing education and participation in professional societies and meetings.	PO12	√

5.3 Aspects of Program Outcomes (POs) Addressed

The following table shows the aspects addressed for certain Program Outcomes (POs) addressed in EEE 4700 for Project and Thesis.

	Statement	Different Aspects	Put Tick (√)
PO3	**Design/development of solutions**: Design solutions for complex electrical and electronic engineering problems and design systems, components or processes that meet specified needs with appropriate consideration for public health and safety, cultural, societal, and environmental considerations.	Public health	√
		Safety	√
		Cultural	√
		Societal	√
		Environmental	√
PO4	**Investigation:** Conduct investigations of complex electrical and electronic engineering problems using research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of information to provide valid conclusions.	Design of experiments	√
		Analysis and interpretation of data	√
		Synthesis of information	√
PO6	**The engineer and society:** Apply reasoning informed by contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to professional engineering practice and solutions to complex electrical and electronic engineering problems.	Societal	√
		Health	√
		Safety	√
		Legal	√
		Cultural	√
PO7	**Environment and sustainability:** Understand and evaluate the sustainability and impact of professional engineering work in the solution of complex electrical and electronic engineering problems in societal and environmental contexts.	Societal	√
		Environmental	√
PO8	**Ethics:** Apply ethical principles embedded with religious values, professional ethics and responsibilities, and norms of electrical and electronic engineering practice.	Religious values	√
		Professional ethics and responsibilities	√
		Norms	√
PO10	**Communication:** Communicate effectively on complex engineering activities with the engineering community and with society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.	Comprehend and write effective reports	√
		Design documentation	√
		Make effective presentations	√
		Give and receive clear instructions	√
PO11	**Project management and finance:** Demonstrate knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.	Engineering management principles	√
		Economic decision-making	√
		Manage projects	√
		Multidisciplinary environments	√

5.4 Knowledge Profiles (K3 – K8) Addressed

The following table shows the Knowledge Profiles (K3 – K8) addressed in EEE 4700 for Project and Thesis.

K	Knowledge Profile (Attribute)	Put Tick (√)
K3	A systematic, theory-based formulation of engineering fundamentals required in the engineering discipline	√
K4	Engineering specialist knowledge that provides theoretical frameworks and bodies of knowledge for the accepted practice areas in the engineering discipline; much is at the forefront of the discipline	√
K5	Knowledge that supports engineering design in a practice area	√
K6	Knowledge of engineering practice (technology) in the practice areas in the engineering discipline	√
K7	Comprehension of the role of engineering in society and identified issues in engineering practice in the discipline: ethics and the engineer's professional responsibility to public safety; the impacts of engineering activity; economic, social, cultural, environmental and sustainability	√
K8	Engagement with selected knowledge in the research literature of the discipline	√

The following table explains or justifies how the Knowledge Profiles (K3 – K8) have been addressed in EEE 4700/4800 (Project and Thesis).

K	Explanation/Justification
K3	Used circuit theory, control logic, and electronics fundamentals
K4	Applied IoT and renewable integration knowledge
K5	Designed threshold-based crop-specific irrigation
K6	Implemented real-world hardware (ESP32, solar, sensors)
K7	Considered health, safety, societal, and environmental impacts
K8	Reviewed IEEE/FAO/World Bank research on smart irrigation

5.5 Use of Complex Engineering Problems

The irrigation challenges addressed in this project qualify as complex engineering problems because they involve multiple layers of technical, social, and environmental considerations. Farmers in semi-arid areas like Garoua, Cameroon have to deal with unpredictable rain, limited water supplies, and unreliable energy sources, which all make irrigation a very important but difficult job. Traditional ways of watering plants can lead to either too much water, which wastes it and hurts soil fertility, or too little water, which lowers crop yield and puts food security at risk.

To make a smart irrigation system that could handle these problems, we needed to know a lot about electrical and electronic engineering (P1). The project had to deal with conflicting needs, like using less water while getting the most out of crops, keeping costs low for smallholder farmers while still using advanced IoT technology, and making sure that irrigation kept going even when solar energy was not always available (P2).

The solution also required creative and abstract thinking to come up with crop-specific irrigation thresholds and a way to switch between solar and grid power (P3). Additionally, designing for semi-arid African climates is not a common topic in most engineering classes (P4). The project also falls outside of standard codes and practices because crop-specific soil moisture thresholds are not defined by engineering standards but were derived from agricultural research and experimental validation (P5).

Additionally, the system impacts multiple stakeholders: farmers, who need ease of use and cost-effectiveness; communities, which depend on reliable food supply; and environmental bodies, which prioritize water conservation and renewable energy use (P6). The solution is therefore highly interdependent, involving hardware (ESP32, sensors, pumps, relays), software (Arduino IDE, Blynk IoT), renewable energy (solar panels), and agricultural science (crop thresholds). These interconnected parts must function harmoniously, making the problem a high-level complex engineering challenge (P7).

Thus, this project demonstrates the application of advanced engineering knowledge to solve a multi-dimensional real-world problem, satisfying all seven attributes of complex engineering problem solving (P1–P7).

5.6 Socio-Cultural, Environmental, And Ethical Impact

Engineering projects are not only technical in nature but also have far-reaching implications for society, culture, the environment, and ethics.This project, which is meant to create a smart irrigation system that works with both solar and grid power, will have a big effect on all of these areas.

From a socio-cultural point of view, the project helps farmers in semi-arid areas make more money. Farmers can get more consistent crop yields by using a reliable and automated irrigation system. This makes food less scarce and improves the health of the community. The system is especially useful in places where farming is the main source of income, which makes cultural and social resilience stronger. It also gives smallholder farmers more power by showing them how to use modern IoT-based technology in a way that is both cheap and easy to get, which helps close the digital divide.

The system is good for the environment because it reduces water waste by controlling soil moisture. Water is only applied when the soil moisture level drops below crop-specific thresholds, which makes sure that the water is used in the best way possible. Using renewable solar energy as the main source of power makes farming even less dependent on fossil fuels and lowers the carbon footprint of farming. The hybrid solar-grid design also ensures resilience during cloudy days, demonstrating adaptability to environmental variability.

From an ethical point of view, the system was made to be cheap and easy to grow, so that the benefits of new technology are not just for rich farmers but also for smallholders. This is in line with the moral idea of fairness in how technology is shared. The project also follows professional ethics by making sure that safety is a top priority (with proper insulation and relay isolation for pumps), that it follows sustainable practices, and that it takes public welfare into account.

5.7 Attributes of Ranges of Complex Engineering Problem Solving (P1- P7)

The following table shows the attributes of ranges of Complex Engineering Problem Solving (P1 – P7) addressed in EEE 4700 for Project and Thesis.

P	**Range of Complex Engineering Problem Solving**	**Put Tick (√)**
Attribute	Complex Engineering Problems have characteristic P1 and some or all of P2 to P7:	
Depth of knowledge required	**P1:** Cannot be resolved without in-depth engineering knowledge at the level of one or more of K3, K4, K5, K6 or K8 which allows a fundamentals-based, first principles analytical approach	√
Range of conflicting requirements	**P2:** Involve wide-ranging or conflicting technical, engineering and other issues	√
Depth of analysis required	**P3:** Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models	√
Familiarity of issues	**P4:** Involve infrequently encountered issues	√
Extent of applicable codes	**P5:** Are outside problems encompassed by standards and codes of practice for professional engineering	√
Extent of stakeholder involvement and conflicting requirements	**P6:** Involve diverse groups of stakeholders with widely varying needs	√
Interdependence	**P7:** Are high level problems including many component parts or sub-problems	√

The following table explains or justifies how the attributes of ranges of Complex Engineering Problem Solving (P1 – P7) have been addressed in EEE 4700/4800 (Project and Thesis).

P	**Explanation/Justification**
P1	The project cannot be solved without in-depth knowledge of electrical and electronic engineering (IoT, microcontrollers, renewable energy integration, sensor-based control), requiring systematic application of engineering fundamentals.

P2	The solution involves conflicting requirements such as minimizing water use while ensuring crop yield, balancing solar energy availability with grid reliability, and designing a system that is both low-cost and technically efficient.
P3	No obvious standard solution exists; abstract thinking and originality were required to formulate the multi-crop irrigation logic with crop-specific thresholds and to design hybrid solar-grid power switching.
P4	The issues addressed, such as irrigation for multiple crops in semi-arid climatic conditions of Garoua, Cameroon, are infrequently encountered and require case-specific adaptation.
P5	The problem is outside standard codes of practice; for example, crop-specific soil moisture thresholds are not defined by engineering standards but had to be derived from agricultural knowledge and experimental validation**.**
P6	The project involves diverse stakeholders with varying needs—farmers (cost, ease of use), communities (food security), and the environment (sustainability)—making it necessary to balance multiple perspectives.
P7	The project is a high-level engineering problem that integrates many sub-components: sensors, pumps, ESP32, IoT connectivity, solar-grid hybrid power, and crop-specific irrigation logic. These interdependent modules require a holistic solution.

5.8 Attributes of Ranges of Complex Engineering Activities (A1 – A5) Addressed

The following table shows the attributes of ranges of Complex Engineering Activities (A1 – A5) addressed in EEE 4700 for Project and Thesis.

A	**Range of Complex Engineering Activities**	**Put Tick (√)**
Attribute	Complex activities means (engineering) activities or projects that have some or all of the following characteristics:	
Range of resources	**A1:** Involve the use of diverse resources (and for this purpose resources include people, money, equipment, materials, information and technologies)	√
Level of interaction	**A2:** Require resolution of significant problems arising from interactions between wide-ranging or conflicting technical, engineering or other issues	√
Innovation	**A3:** Involve creative use of engineering principles and research-based knowledge in novel ways	√
Consequences for society and the environment	**A4:** Have significant consequences in a range of contexts, characterized by difficulty of prediction and mitigation	√
Familiarity	**A5:** Can extend beyond previous experiences by applying principles-based approaches	√

The following table explains or justifies how the attributes of ranges of Complex Engineering Activities (A1 – A5) have been addressed in EEE 4700/4800 (Project and Thesis).

A	**Explanation/Justification**
A1	The project involves the use of diverse resources: hardware (ESP32, sensors, pumps, relays), renewable energy (solar panels, charge controller), grid power, software (Arduino IDE, Blynk IoT), and human resources (farmers and engineers).

A2	Significant problems were resolved, such as integrating renewable and grid power, handling variable soil and crop requirements, and managing water scarcity, all of which involved wide-ranging and sometimes conflicting technical issues.
A3	The solution demonstrates creativity by applying engineering principles in a novel way designing a crop-specific irrigation system with hybrid energy sources and IoT-based monitoring for real-time adaptability.
A4	The system has significant consequences for society and environment: it improves farmer livelihoods, conserves water in semi-arid regions, promotes renewable energy use, and enhances food security, making predictions and mitigations challenging.
A5	The project extends beyond prior experiences by applying principle-based approaches to a new context: integrating IoT, renewable energy, and smart agriculture for multi-crop cultivation in resource-constrained, semi-arid environments.

CHAPTER 6

Conclusion And Future Work

6.1 Conclusion

The current research has managed to design and implement a smart irrigation system based on the Internet-of-Things (IoT) technology and a hybrid solar-grid power source, hence helping farmers to save on both water and energy. The project has definitely attained its major purpose.

The main objectives were achieved and they included:

1. System Design: The entire system architecture was developed based on the idea of sensors, an ESP32 microcontroller, actuators and a new hybrid power-management circuit.

2. Implementation: A working physical prototype was built and coded, containing three separate crop areas that were independent of each other, and a real-time IoT monitoring dashboard.

3. Validation: The main features of the system, including automated irrigation, flawless transition to a different power source, and remote monitoring, were tested and verified to work in compliance with the desired specifications.

The system demonstrates a concrete way of developing sustainable agriculture by saving water using precision irrigation, utilizing free solar power to save energy and grid reliance, and automating labor and intensive jobs to increase the productivity of the farmers.

6.2 Limitations

The limitations of our work included:

- Scarcity of Quantitative Data: The system was experimented with the aim to determine its viability as an operational system but this was not a full crop growth cycle. As a result, despite the initial evidence that indicated the existence of great water savings and energy efficiency, the actual measurements of the total water savings and energy efficiency could not be made through traditional quantitative methodologies.
- Controlled Testing Environment: The prototype was tested on a rather limited scale, and its performance and overall lifespan in terms of large-scale agricultural situations was not verified.

6.3 Future Work

To convert this effective prototype into an effective, fieldable solution, future studies need to focus on large scale implementation and addition of prediction applications. The next measure is the implementation of several units on the farms that are already active to perform longitudinal experiments, which would help to quantify water and energy savings and measure the effects on crop yields. At the same time, long-range, low-power communication protocols, including LoRaWAN or GSM, should be incorporated so that the system is capable of working in the area without Wi-Fi networks to increase its reliability.

The key goal of the further development should be focused on the enhancement of system independence and robustness. This will involve introducing predictive features that can be used to preemptively turn off irrigation before the occurrence of precipitation and exploration of straightforward machine-learned models that can be used to adjust irrigation timetables in real time. Finally, industrial-grade components must be used, waterproof sensors, and a new modular, custom-designed printed circuit board should be used to boost the hardware durability, flexibility, and robustness to be used in the permanent outdoor environment.

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