UNIVERSITE JOSEPH KI-ZERBO

ECOLE DOCTORALE INFORMATIQUE ET CHANGEMENTS CLIMATIQUES

BURKINA FASO

La Partie ou la mort, nous vaincrons !

MASTER RESEARCH PROGRAM

SPECIALITY: INFORMATICS FOR CLIMATE CHANGE (ICC)

MASTER THESIS

Subject:

Implementation of a Smart Irrigation System for Reducing Watering Waste Vegetable Crop in Ouagadougou: Case of Onion and Tomato Culture.

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DEDICATION

To God, the most powerful.

I also dedicate it to the memory of my father, the late **Ousseni SAVADOGO**

I love you.

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ABSTRACT

Market gardening is the most common form of agriculture in Burkina Faso, especially in Ouagadougou, with production mainly focused on tomatoes and onions. However, farmers face difficulties in managing the optimal amount of water needed during irrigation to ensure proper crop growth and yields. In this work, the objective is to develop and implement a smart irrigation scheduling system in order to optimize water use while increasing the productivity of vegetable crops such as tomatoes and onions. Thus, after a literature review on irrigation systems, an investigation was carried out to analyze the performance of irrigation techniques. We first visited the Ministry of Agriculture of Burkina Faso, where we were given a list and had the opportunity to meet field experts with knowledge of market gardening practices. Based on these insights, proposals were made regarding the requirements an intelligent irrigation system should fulfill to achieve optimal water savings while boosting agricultural productivity. Following this analysis, we designed and implemented a smart irrigation system to optimize water use and monitor it in real time. Two ESP32 microcontrollers were used. The first integrates a soil moisture sensor and a GPS module. It measures the soil moisture of tomato or onion plants and sends commands to the second ESP32. This second controller is connected to a solenoid valve and a flow meter, and it triggers irrigation only when necessary**.** All collected data is then stored on Firebase and visualized in real time through a mobile application developed with Flutter. The experiment allowed for continuous monitoring of soil moisture, the amount of water used, and the status of the solenoid valve, thus confirming the system's ability to collect and transmit useful data for irrigation management.

Key words: ESP32 microcontroller, Smart irrigation system, Soil moisture sensor, Water optimization, Burkina Faso

RESUME

Le maraîchage est la forme d'agriculture la plus courante au Burkina Faso, en particulier à Ouagadougou, avec une production principalement axée sur les tomates et les oignons. Cependant, les agriculteurs rencontrent des difficultés à gérer la quantité optimale d'eau nécessaire pendant l'irrigation pour assurer une bonne croissance des cultures et de bons rendements. Dans ce travail, l'objectif est de développer et de mettre en œuvre un système intelligent de programmation de l'irrigation afin d'optimiser l'utilisation de l'eau tout en augmentant la productivité des cultures maraîchères telles que les tomates et les oignons. Ainsi, après une revue de littérature sur les systèmes d'irrigation, une enquête a été réalisée pour analyser la performance des techniques d'irrigation. Nous avons d'abord visité le ministère de l'Agriculture du Burkina Faso, où une liste nous a été fournie et où nous avons eu l'opportunité de rencontrer des experts de terrain possédant des connaissances sur les pratiques maraîchères. Sur la base de ces informations, des propositions ont été faites concernant les exigences qu'un système intelligent d'irrigation devrait remplir pour permettre une économie optimale d'eau tout en améliorant la productivité agricole. À la suite de cette analyse, nous avons conçu et mis en œuvre un système intelligent d'irrigation pour optimiser l'utilisation de l'eau et la surveiller en temps réel. Deux microcontrôleurs ESP32 ont été utilisés. Le premier intègre un capteur d'humidité du sol et un module GPS. Il mesure l'humidité du sol des plants de tomate ou d'oignon et envoie des commandes au second ESP32. Ce second contrôleur est connecté à une électrovanne et un débitmètre, et il déclenche l'irrigation uniquement lorsque cela est nécessaire. Toutes les données collectées sont ensuite stockées sur Firebase et visualisées en temps réel via une application mobile développée avec Flutter. L'expérimentation a permis de surveiller en continu l'humidité du sol, la quantité d'eau utilisée et l'état de l'électrovanne, confirmant ainsi la capacité du système à collecter et transmettre des données utiles pour la gestion de l'irrigation.

Mots-Clés : Microcontrôleur ESP32, Système d'irrigation intelligent, Capteur d'humidité du sol, Optimisation de l'eau. Burkina Faso

ACRONYMS AND ABREVIATIONS

CIWR:	Crop irrigation water requirement
CWR:	Crop water requirement
DHT11:	Digital temperature and humidity sensor
Eto:	Potential Evapotranspiration
FAO:	Food and Agriculture Organization
GHG:	Greenhouse Gas
GPP:	Gross Primary Productivity
GPS:	Global Positioning System
GSM:	Global System for Mobile Communications
IoT:	Internet of Things
IPCC:	Intergovernmental Panel on Climate Change
Kc:	Crop coefficient
LCD:	Liquid Crystal Display
LSIS:	Laser Spray Irrigation System
PCB:	Printed Circuit Board
WRI:	World Resources Institute
WUE:	Water-Use Efficiency

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Introduction

Context and justification

According to the Intergovernmental Panel on Climate Change (IPCC), climate change is a change in the state of the climate that can be identified by changes in the mean and/or It refers to changes in things like temperature and rainfall that vary over time and last for a long period often decades or more. This change can be viewed from two perspectives: either as a natural process or as human activity (anthropogenic) that alters the composition of the global atmosphere, contributing to climate variability over time, in addition to natural factors(Ahove & Bankole, 2018).This variability leads very often to water scarcity, and this is not good for crop irrigation(Leal Filho et al., 2022). In West Africa, Agriculture is one of the most important activities that people engage in to produce food and earn a living. Most of the time, those agricultural practice is based on rainfall-agriculture (Leal Filho et al., 2022). A Scientific researcher worked on climate model projections, and his work shows, some parts of Africa are projected to suffer drought and rainfall variability by the end of 2025(Dosio et al., 2021).This climate change is bringing several problems, such as malnutrition and danger to human life. Moreover, farmers' mismanagement of water resources further compounds their obstacles.

Most farmers in Africa who manually water their farmland often waste water and fail to consider critical factors such as soil moisture, temperature, relative humidity, and other key aspects essential for efficient farming(Ahmed et al., 2023). Studies made by the World Resources Institute (WRI), show that agricultural practices are one of the sectors that contributed to the rise in global greenhouse gas (GHG) emissions over time. For example, greenhouse gas emissions rose from 14% in 2000 to 17% in 2020. This demonstrates that we are facing numerous challenges. With Africa's growing population, we must find ways to feed them while also addressing the need to reduce the greenhouse gas (GHG) emissions generated by agricultural activities affecting our atmosphere.

We're becoming less mindful of the water we use, even though it’s becoming a scarce resource around the world. Moreover, the FAO tells us that by 2050, water consumption in the agricultural sector will increase by 50%. However, climate change, and population growth, combined with urbanization are projected to decrease these water resources(Assaf et al., 2012).

As the remaining water that we have is not enough, People are not managing well; instead, they fight for it.

Irrigation in Africa, especially in Burkina Faso, most of the time involves water waste due to outdated irrigation practices that we call traditional methods. Without data-driven systems, farmers struggle to monitor and control water distribution. Those outdated practices involve water wastage and harm to crop yield. Traditional methods are, most of the time, manual, not systematic. It means they rely on human intervention and fail to adapt to real-time environmental conditions such as soil moisture and weather changes(Karpagam et al., 2020). This likely leads to overwatering in some areas and underwatering in others, ultimately reducing crop yield can involve water waste.

Overwatering gardening contributes to soil degradation, and then the soil will lose its nutrients, such as nitrogen, phosphorus, and potassium, making them unavailable to plants. We know plants need those nutrients for better growth.

This work will be focused on how smart system irrigation can efficiently reduce gardening water waste and improve vegetable crop watering.

Research questions

For this study, the **main research question is**: How can the implementation of smart irrigation reduce gardening water waste and improve vegetable crop watering in Ouagadougou (Burkina Faso) in the face of climate change?

In this main research question, **(03) three specifics** are derived:

- What is the actual performance of the irrigation techniques used in Ouagadougou?
- What are the requirements for an irrigation system to effectively improve vegetable crop watering and reduce water waste?
- How can a smart irrigation system be developed to reduce gardening water waste and improve vegetable crop watering?

Research hypothesis

Main hypothesis

The implementation of a smart irrigation system can enhance the reduction of gardening water waste and improve vegetable crop watering efficiency in Ouagadougou (Burkina Faso) in the face of climate change.

Specific Hypothesis

- The irrigation techniques have **deficiencies** in their implementation.
- Efficient requirements can be proposed to effectively improve vegetable crop watering and then reduce gardening water waste.
- A smart irrigation system can be developed to reduce gardening water waste and vegetable crop watering.

Research Objectives

Main Objectives

Develop a smart irrigation system for reducing gardening water waste and improving vegetable crop watering in Ouagadougou.

Specific Objectives

- To analyze the current irrigation methods and techniques used in Ouagadougou (Burkina Faso).
- To propose efficiency requirements for an irrigation system addressing gardening water waste and vegetable crop production in Ouagadougou.
- To develop a user-friendly smart irrigation system for efficient water use in vegetable crop watering in Ouagadougou.

Thesis Outline

This thesis is divided into three parts. First, the chapter one focuses on water resource management as well as the irrigation methods and techniques used in Ouagadougou. Next, the second part presents the materials and methods used to implement an intelligent irrigation system for the optimal use of water in vegetable farming. Finally, the last part is devoted on the results and discussion. We will conclude with a summary and perspectives related to our study project

CHAPTER I LITERATURE REVIEW

In this Chapter, we will begin with a general overview of water resources, emphasizing their pivotal role in agriculture and water management. After that, we are going to provide an overview of the intelligent irrigation systems already implemented, highlighting their benefits and limitations. Then, we are going to analyze the irrigation techniques and methods used in Ouagadougou, taking into account the specific challenges related to climate and local conditions.

I.1 Climate change and water resources

Water is essential for the growth and progress of countries and communities. People need water to live, both for drinking and for growing food and making things in factories. Having clean water to drink is necessary for everyone, and this connects to how we take care of all our water sources(Melaku Melese, 2016).

Alterations of Precipitation patterns, increased evaporation rates, and rising temperatures are some climatic variables that significantly impact water resources. These changes lead to both water availability and heightened demand(Abrams et al., 2008). According to Melaku, 2016 Climate change alters the spatial and temporal distribution of water, reducing water availability for farming. It reduces the amount of water or the timing of when water is available for use, which will have more effects on agriculture, industrial, and urban development. Moreover, this effect on the climate can exacerbate the spread of waterborne diseases (Melaku Melese, 2016). Climate fluctuations can also affect the use of agricultural land associated with irrigation systems. Climate change will greatly complicate the design, operation, and management of water-use systems (Melaku Melese, 2016)

According to the Intergovernmental Panel on Climate Change (IPCC), scientific evidence shows that rising greenhouse gas concentrations in the atmosphere are driving changes in Earth's climate, leading to higher temperatures as well as changes in how much rain falls and where it falls.

Climate change is contributing to reducing soil moisture, especially in Northern, Southern, and Western Africa. Due to climate change, the increase in natural disasters leads to droughts, and this will likely exacerbate the availability of water (Melaku Melese, 2016).

Agriculture is one of the sectors most affected by climate change, especially in developing countries, since their agriculture depends on rainfall. Moreover, population pressures are another problem that requires intensified agriculture. Warmer temperatures will lead to increased water evaporation, intensifying the need for irrigation precisely as water becomes even less available(Melaku Melese, 2016).

I.2 Challenges in Managing Water Resources

Water resources are essential for every living thing on Earth, but managing them presents challenges. Those challenges are mostly exacerbated by factors such as rapid population growth, climate change, urbanization, and geopolitical tensions. More people are moving toward the cities, increasing the demand for water and, as a result, putting stress on existing water infrastructure and resources (Brears, 2024). Urban areas face challenges in maintaining water quality and ensuring equitable distribution, necessitating advanced planning and management strategies (Brears, 2024). Political tensions and conflicts can make it difficult to manage water resources effectively. That means when there are disputes between countries or groups, they may not cooperate on sharing or protecting the water supply(Zaman, 2023).

International treaties and cooperation are essential for managing water resources that cross national borders. When countries share rivers, lakes, or groundwater, agreements help make sure the water is used fairly and sustainably(Dinar, 2024). Another factor that may challenge water resources is related to the technology that we use to manage water. Technological advancements can help solve water scarcity, but they often need a lot of money to implement. These technologies may help us perform desalination and wastewater recycling, which provide alternative sources of freshwater(Dinar, 2024b)

Agriculture is already the biggest user of water, accounting for about 70% of global freshwater use. However, due to climate change, the competition for this resource is becoming more intense, as a result, affecting water variability, and evolving diets, which increase water demand(Basheer et al., 2024). Agricultural water use is not always monitored effectively. This means there is a lack of accurate data on how much water is being used for farming, which makes it hard to manage water resources efficiently (Foster, T et al., 2024).

I.3 Importance of Efficient Water Usage

Water resources face many challenges, but their efficient use provides significant benefits for all living things on Earth. Efficient water usage is essential for sustainable development, especially in agriculture, where water scarcity is causing a lot of challenges when it comes to water supply in those sectors.

Improving water-use efficiency (WUE) is crucial for improving food security, conserving natural resources, and mitigating the impacts of climate change(Alharbi et al., 2024).

Efficient water management can considerably reduce water wastage, which is important as agriculture consumes about 70% of global freshwater (Kilemo, 2022).

Efficient water management reduces irrigation costs and labor and helps farmers to get an income. WUE enhances the conservation of natural resources and maintains ecosystem health, which is vital for long-term sustainability (Callejas Moncaleano et al., 2021). On the other hand, WUE contributes to resilience against climate change impacts, particularly in regions prone to drought (Alharbi et al., 2024).

WUE plays an important role in the carbon-water relationship, it is essential for managing fragile ecosystems, mostly where human activities have reduced (like the Tibetan Plateau) by 20.2%. Furthermore, It can enhance gross primary productivity (GPP), which is vital for ecosystem health and resilience (Wang et al., 2020).

I.4 Definitions of irrigation types

I.4.1 Irrigation

Irrigation is defined as a process of supplying water to cultivated plants in order to increase yield and reduce water stress for the plant. It also means adding water to land in a controlled way, usually to support farming. Primarily, the production of crops in semi-arid land(Doolittle, 2017).According to the World Bank (2017), in Burkina Faso, where about 80% of the population relies on agriculture for their livelihood, this process is widely used to irrigate farms.

All plants need water to survive, and they absorb it through their roots. For growing plants, we need to take into account the right amount of water at the right time to grow well. There are so many ways to water plants; some are easy, and some are complex. Among them, some of these ways are very old, while others are new. Whether the way is old or new, simple or hard, farmers must think about many things before deciding how they will water their plants(Doolittle, 2017).

I.4.2. Drip Irrigation

Drip irrigation is a method of delivering water directly to the roots of plants through pipes with small openings called drippers. This system helps reduce water loss due to evaporation and runoff. In other words, it's a controlled way of irrigating crops by supplying water right to each plant through a network of tubes or pipes[1].

I.4.3 Smart Irrigation

It is the process of supplying water to a plant according to its specific water needs at various growth stages, soil types, and climate by using micro irrigation sensors and controllers (Hwang, 2017).

According to Tazhina and Parker (2020), smart irrigation is defined as a system that automatically starts/interrupts irrigation combined with the use of soil moisture sensors. On the other hand, it can also be described as the use of IoT sensors to monitor soil moisture levels around plants and track weather conditions, aiming to enhance the efficiency and effectiveness of water usage[2].

I.5 Methods of irrigation system

I.5.1 Traditional Method of irrigation system.

Traditional methods are done manually, farmers pull out water from the wells by themselves or using cattle and carry it to farming on their field[3]. These methods may vary from one area to another and include: Surface irrigation, and Sub-surface irrigation. All these techniques involve water wastage and lead to the propagation of diseases such as fungal formation due to over-moisture in the soil (Kshirod Kumar et al., 20128).

Surface Irrigation, such as the furrow irrigation system, has been implemented by Hassen (2004), and in his study, he found that the water application was excessive and much higher than the crop water requirements. The efficiency of water application was poor compared to the huge amount of money they used to construct the structure.

On the other hand, Maupoux (2010) found that the water application efficiency for furrow systems is low.

I.5.2. Modern irrigation

Modern irrigation systems are essential for improving water efficiency, lowering water consumption, and increasing agricultural productivity. These systems integrate advanced technologies such as Drip irrigation, sprinkler irrigation, and IoT-based controls.

Research made by TWL irrigation industry (2023), and the results show that the drip irrigation method is the best type of irrigation in terms of the most efficient methods as far as water consumption is concerned[4]. This method is expensive because of the price of hardware and the installation, while poor people are not able to afford it. Even though much less water is lost through evapotranspiration and, therefore, less water is needed, drip irrigation remains financially difficult on a large scale[4].

Sprinkler irrigation isn’t as efficient as drip irrigation. However, it is better than the traditional one. On the other side, when it comes to water farms on a large scale, Sprinkler irrigation is required because of the price, installation, and hardware[4].

I.5.3 Smart irrigation system

Smart irrigation system takes modern irrigation to the next level. It is based on the Internet of Things and Big Data, combined with advanced sensory technologies and automation. Those advanced technologies used by this system include[4]: pH sensors, soil moisture sensors, humidity, and temperature sensors (DHT11), GSM modules, and cetera. These technologies help farmers to better understand crop growth and take into account environmental impact to make irrigation more effective and efficient. On the other hand, smart irrigation allows monitoring of the health of crops from space, helping to determine their irrigation needs.

See below the example of the architectural design of a smart system for irrigation

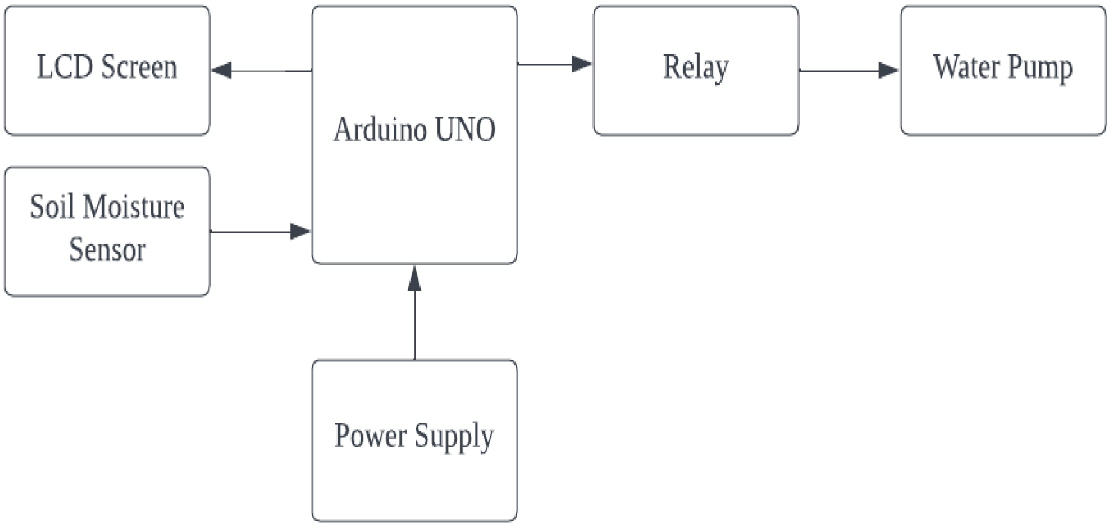

Figure 01: Block Diagram of the system architecture(Basheer et al., 2024)

From the block diagram above (Figure 1), the irrigation system is controlled by an Arduino (microcontroller) board, which is connected to all the other components in the system. The microcontroller is the heart of the system and performs three main tasks for this system: collecting sensor readings, sending signals to the LCD, and sending signals to the relay. The soil moisture sensor is used to detect the moisture level of the soil and send the value to the Arduino board. Once the Arduino board receives the moisture level, it compares the value with a set threshold. If the moisture level is below the threshold, the Arduino board sends a signal to the relay to open the circuit to the water pump, turning on the water supply. If the moisture level is above the threshold, the Arduino board sends a signal to the relay to close the circuit to the water pump, turning off the water supply (Jhanjhi et al., 2020).

The LCD screen also lets you see whether the motor is running and shows how much moisture is in the soil. It allows us to know whether the motor is on or off and whether the level is low, humid, or high. For the water control, we use a relay, and this acts as a switch, controlling the power supply to the water pump based on the information that the microcontroller sends to it(Basheer et al., 2024).

This system has some limits:

- Limited Scalability (Inability of the system to cover a large area so that the use of water can be done efficiently)
- Difficulty in Large-Scale Monitoring
- Difficult to use with an irrigation system already implemented
-

▪ **Smart system irrigation of tomatoes yields**

This system below (figure 2) has been implemented to irrigate tomato crops and optimize irrigation across soil moisture prediction and a mobile app for farmers, enhancing crop yields and real-time monitoring and control of irrigation systems are made more efficient with the integration of 5G technology(Singh et al., 2023).

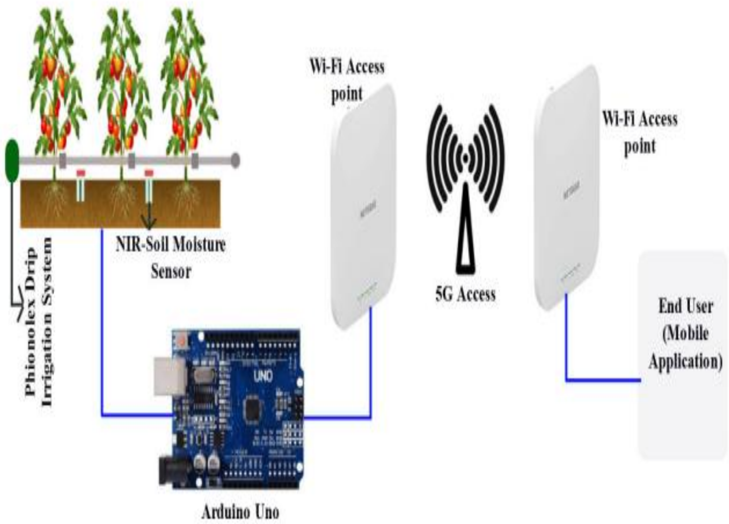

Figure 02: Smart irrigation system

The system in **Figure 2** above consists of three main components:

Arduino Uno Microcontroller, NIR-Soil Moisture Sensor, Pinolex Drip Automatic Water Controller.

The general principle of the system:

NIR-Soil Moisture Sensor: Observes the moisture of the soil and then sends the information to the microcontroller (Arduino Uno), It’s also connected to a Wi-Fi access point, which helps send all the data to a mobile app using 5G technology. On the other hand, this 5G network helps to save data from the NIR-Soil Moisture Sensor into the cloud service and send it to the Mobile App. From the mobile App, this system is smartly controlled(Singh et al., 2023).

- Below **figure 3** shows the site of experimentation of this system

Figure 03: Site of Experience *(Singh et al., 2023)*

Limit of this system:

- Limited support for all climates in the irrigation system (not performed in every environmental climate, for instance sensor)

- Limited Scalability (Inability of the system to cover a large area so that the use of water can be done efficiently)

- NIR sensors **only measure surface moisture**

- Limited to only one type of crop (Tomato)

I.6. Techniques of Irrigation Used in Burkina Faso

In Ouagadougou, various techniques are used for irrigation and to enhance agricultural productivity, particularly in the face of climate change variability. Those techniques are:

Supplemental irrigation, Manual (Watering can), Drip Irrigation, sprinkler irrigation, irrigation laser spray, etc.

- **Irrigation Watering can**

Irrigation by watering can refers to the use of a handheld container designed to water plants in order to nurture them. In these methods, we target watering, ensuring that water reaches the plant roots effectively. To avoid water spillage, we equip some watering cans with extension pipes that deliver water directly to the base of plants (William, 2008). This empirical method requires the presence of a human being at every moment when plants are under water stress.

This method involves, most of the time, a lot of water waste, and farmers stop watering their farms based on observation of the soil. This means that before stopping, they quantify it through observations. From this method, people are not using water efficiently because they rely solely on observation to determine whether plants are receiving enough water or not. This can lead to other problems, such as some crops receiving excessive water while others do not, as they do not measure the exact amount of water needed. Watering cans are effective for small-scale irrigation, but larger agricultural systems may require more advanced irrigation technologies to manage water distribution efficiently (Guofa, 2020).

Below is a picture of the Watering can:

Figure 04: Illustration Watering Can image[5]

- **Supplemental irrigation**

Processing involves providing additional water to the crop during dry periods. This activity is crucial for maintaining crop yields in agriculture that is mainly based on rainfall (rainfed agriculture). It allows for filling some gaps so that the plant can grow and improve crop yield (Fossi et al., 2012).

Studies made by Economic analysis and food security contribution of supplemental irrigation and farm ponds: evidence from northern Burkina Faso (2022) show that supplemental irrigation has significantly increased crop yields, and allowed people to meet their cereal needs as well as generate additional income for farmers.

- **Drip irrigation**

As defined above, drip irrigation is also one of the tremendous techniques used in Ouagadougou for irrigation purposes. This technique has become a critical agricultural innovation aimed at enhancing water efficiency and crop yields, particularly in the semi-arid Sahel region (Müller, 2015). Practicing these techniques leads to significant save water and improved plants.

Figure 05: Illustration Drip irrigation[6]

- **Sprinkler irrigation**

Sprinkler irrigation in Ouagadougou plays an essential role in improving crop yields. Particularly in the context of climate variability and water scarcity. Combined with acaricides (a process to combat small external parasites such as spiders) has been effective in managing pests and improving crop yields, especially in tomato production (Drabo et al., 2022). On another hand, the integrated approach reported production levels reaching approximately 14,875 kg/ha (Drabo et al., 2022).

This technique is essential for securing crop production against dry spells, which are frequent in Sahelian climates ("Economic analysis and food security contribution of supplemental irrigation and farm ponds: evidence from northern Burkina Faso", 2022).

Even though It has some benefits, there are still a lot of challenges when it comes to setup because of the lack of training of farmers (Fossi et al., 2012).

Figure 06*:* Illustration Sprinkler Irrigation

- **Irrigation laser spray**

Among the tremendous types of irrigation used in Burkina Faso, Laser spray is also widely used for irrigation needs. This method is an innovative paradigm to enhance agricultural productivity.

The Laser Spray Irrigation System (LSIS) **replicates** light rainfall with low pressure. The lateral pipes have tiny laser-drilled holes that release water in the form of fine sprays. This technique can reduce environmental impact and improve pesticide application accuracy (Hui et al., 2014).

The laser spray system operates with a pressure of 0.17 bar, which means it does not require high pressure to function properly. Furthermore, this system applies an average water quantity of 22.3 mm per hour. Additionally, the uniformity coefficient of this system is evaluated at 92.4%, which means that this system almost ensures the uniform distribution of water over a given study area(Omara, 2024).

Figure 07: Laser Spray Irrigation[8]

Despite the enormous potential offered by each type of irrigation used in Burkina Faso, such as laser spray, sprinkler, and drip irrigation, improvements are still needed at every level.

- These techniques do not consider the soil moisture level, which could result in losses or reduced crop yields.
- Moreover, these methods are not often autonomous, as they require significant human labor.
- Additionally, they lack remote control systems, which could allow for data analysis to predict the exact amount of water needed for crops.
- Finally, they don't take into account of exact amount of water each type of culture needs for better growth.

I.7. Assessment of crop irrigation water requirements

Crop irrigation water requirement is one of the big challenges in agricultural fields, especially for farmers who have fewer skills about the exact quantity of water that each crop needs for growth. The exact quantity of water that each crop needs may vary from one to another.

Crop irrigation water requirement (CIWR) It is the additional amount of water, provided through irrigation, that a crop needs to bridge the gap between its total water requirements (CWR) and the water naturally supplied by effective precipitation (Pef). It's usually measured in millimeters per day, per month, or per year (1 mm = 10 m^3/ha)[9]

- Crop Water Requirement (CWR) is defined as the amount of water a plant needs to grow properly.
- Effective precipitation (Pef) refers to the amount of rainfall that is available for plant use and contributes to meeting their water requirements. For example, if part of the rainwater evaporates or runs off without soaking into the soil, that part is not considered "effective."

From that definition above, the estimation of CIWR is derived from the equation:

$$\mathbf{CIWR = CWR - Pef} \quad (1)$$

To estimate CWR, we need to know two other variables: crop coefficient (Kc) and the potential evapotranspiration (ETo).

The formula for calculation of CWR:

$$\mathbf{CWR = ET_O * Kc} \quad (2)$$

- **Potential Evapotranspiration (ET_o).**

ET_o is a pivotal component of the hydrological cycle and influences agricultural and water management. Quantifying it can enhance us to efficiently reduce water waste for agricultural practices. When we estimate Eto, it allows for understanding water dynamics mostly in the regions where meteorological data are limited(Oliveira Da Silva et al., 2022).

Recent studies using machine learning and regression models to improve Eto predictions have shown greater accuracy compared to traditional methods (Sarkar et al., 2022).

- **Crop coefficient Kc**

Kc is as also a parameter used for CWR estimation, which embeds crop transpiration and soil evaporation. Its values are evaluated based on each stage of plant growth. Generally, split into four, namely respectively initial stage, development stage, mid-season stage, and late-season stage(Nagy et al., 2024).

The initial stage: Period from sowing until the crop covers about 10% of the ground.

The crop development stage: Period from end of initial stage and lasts until the full ground cover has been reached (ground cover 70%–80%); it does not necessarily mean that the crop has reached its maximum height.

The midseason stage: The midseason stage is the period starting right after the development stage and continuing until maturity. It includes flowering and grain formation

The late season stage: The late season stage starts once the midseason stage ends and continues up to the day of harvest. Finally, the formula of CIWR is:

$$\mathbf{CWR = ET_O * Kc - Pef} \quad (3)$$

✓ **Evaluating Crop Water Needs: Case Study on Tomato and Onion**

❖ **Tomato**

Tomatoes rank among the top vegetable crops cultivated globally, and they are also widely grown in Burkina Faso. It helps farmers to support their nutritional needs and generate income so that people can use it for other purposes (Ouattara & KONATE, 2024). The first harvest is possible 45-55 days after flowering or 90-120 days after sowing(Ouattara & KONATE, 2024)

The estimated consumption from the agricultural statistical dashboard of tomatoes in Burkina Faso was 1,184,000 metric tons in 2019, which equates to a per capita consumption of 56 kg per year or 153 g per day (Ouattara & KONATE, 2024). Tomatoes contribute to a healthy and balanced diet; they are rich in minerals, vitamins, essential amino acids, and even contain high amounts of vitamin B and C.

The tomato plant, given its importance, must adhere to certain conditions, notably soil moisture, for better plant growth and for better yield.

See below in Table 1, the range of humidity at which tomato crops were experimented with during different stages of growth.

Table 1: Different water treatment schemes of the irrigation regime of tomatoes(Wang, 2018)

Treatment	Seedling stage (%)	Blooming and fruiting stage (%)	Prime fruiting stage (%)	Late fruiting stage (%)
1	80~85	80~85	80~85	80~85
2	50~55	75~80	80~85	75~80
3	60~65	75~80	80~85	75~80
4	70~75	75~80	80~85	75~80
5	70~75	50~55	80~85	75~80
6	70~75	60~65	80~85	75~80
7	70~75	70~75	80~85	75~80
8	70~75	75~80	50~55	75~80
9	70~75	75~80	60~65	75~80
10	70~75	75~80	70~75	75~80
11	70~75	75~80	80~85	50~55
12	70~75	75~80	80~85	60~65
13	70~75	75~80	80~85	70~75

The result below shows the outcome of testing different water treatment schemes in a solar greenhouse at different stages. It shows that when the range of soil humidity was controlled within **70%~75%, 60%~65%, 80%~85%, and 75%~80%** of the fields, respectively, in different developing stages, the tomato crop yield is the highest, which can reach 54050. 27kg/hm^2(Wang, 2018). Another Study was conducted, and the soil moisture needed for planting tomatoes is between **60% to 80%,** with a temperature range between 24 to 28 degrees Celsius(Nurhasanah et al., 2021).

A watering device for tomatoes using a soil moisture sensor was implemented by (Djahi & Pollo, 2018) and the suitable range of soil humidity is between **70 to 80** %.

- **Onion**

In Burkina Faso, onion accounts for more than 30% of vegetable production, meaning that it is widely cultivated by farmers, allowing them to feed themselves and generate income. This plant's growing period and harvest can extend from 90 to 120 days, approximately from 3 to 4 months(Growing Onions in Home Gardens, 2013).

The onion crop, compared to other vegetable crops, is more resilient and can even support small drought periods. On the other hand, it contributes to establishing a balance between human health and consumption. However, regarding plants, certain water conditions must be met to optimize their yield and avoid water waste.

According to (Sumaoy et al., 2024). The range of humidity that the onion plant should have for better growth and, ultimately, a good yield is between **60% and 70%.**

A significant reduction in bulb size and mass occurs when soil moisture drops to **50%** of field capacity, indicating that this is a critical threshold for onion production(Lobell & Field, 2007).

Another study has been conducted for different thresholds of 100%, 75%, and 50%, and the results show that onions perform best at **75%** of field capacity**.**

To achieve optimum crop yield for onions, the relative humidity of the soil is maintained between **60% and 80%** (Liu, 2019).

I.8. Some efficiency requirements for an irrigation system addressing gardening water waste and vegetable crop production

For efficient requirements, it is crucial to use advanced irrigation technologies and optimize water use for crop growth and maximize crop yield. The implementation of soil moisture-controlled systems by using sensors and monitoring the quantity of water in the soil, and triggering irrigation when needed, can avoid over-irrigation and enhance plant productivity(Olusakin et al., 2024).

Saving water and then using it for irrigation systems with real-time control and monitoring, creating a balance between the needed water and water that is available (supply and demand), will help to reduce water waste (Yang Li, 2018)

Create a mobile-friendly web app that displays soil moisture levels and sends alerts when a problem is detected.

Renewable energy, such as solar panels, can be used to power the irrigation system and make it affordable for the user.

Water use efficiency should minimize losses from runoff, and select a suitable crop variety for local conditions(de Pascale et al., 2011).

- **Conclusion**

This literature review reveals that while smart irrigation systems offer valuable tools for agriculture, they still face limitations in real-world applications. Similarly, traditional irrigation methods, though practical, often fall short in efficiency and adaptability, particularly in regions like Ouagadougou, where water scarcity and climate challenges demand smarter solutions.

To bridge these gaps, we propose a smart irrigation system that can be integrated with both traditional and non-traditional methods, aiming to enhance water use efficiency while preserving the environment. Based on what the literature review reveals, for the next chapter, we will present those materials and tools for the implementation of the smart system, addressing or tackling water waste in vegetable crops.

CHAPTER II: MATERIALS AND METHODS

The second Chapter of this work presents the materials and methods that were employed to develop a smart system designed to reduce water waste and improve vegetable crop production

II.1 Study Area

Burkina Faso is located at the very center of West Africa. It covers an area of around 274,222 km^2, It shares its borders with Mali in the north and northwest, Niger in the east, Benin in the southeast, to the south, you'll find Togo and Ghana, with Côte d'Ivoire positioned to the southwest. Burkina is located between 9º20 and 15º50 north latitude, 5º20 west longitude, and 2º30 east longitude(Baki et al., 2022).

Ouagadougou is the capital of Burkina Faso and is found close to the center of the country. It has a semi-arid climate. The weather is split into two distinct seasons: a dry season from November to April, with an average of less than 100 mm of precipitation, and a wet season occurs mainly from May to October, with an average annual total of around 700 mm (Ouarma et al., 2020). Humidity levels in Ouagadougou have shown a decline, particularly during the dry season, with a significant decrease in the duration of wet periods affecting agricultural management practices (Bambara et al., 2019). In Ouagadougou, vegetable agriculture practices are characterized by a mix of traditional methods and modern challenges, especially in water use.

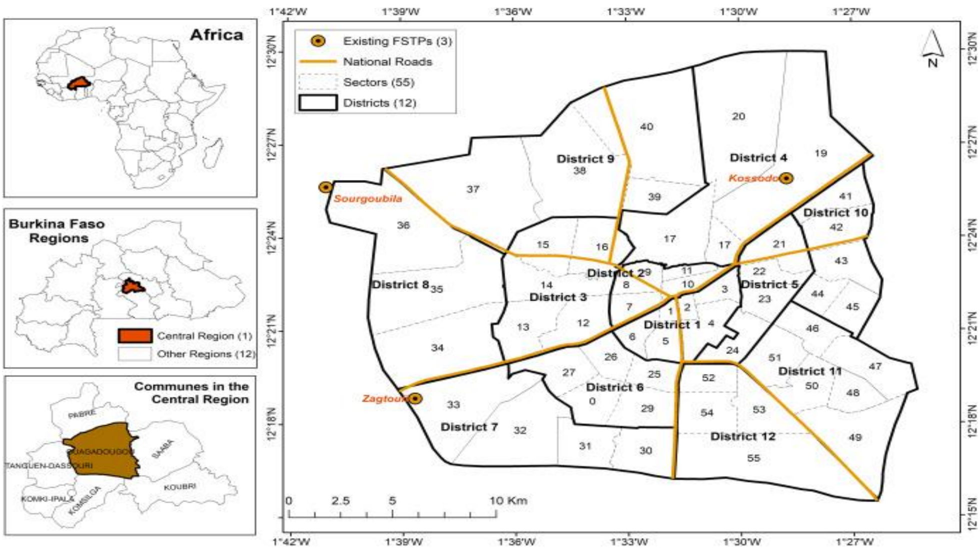

Figure 08: Position of Ouagadougou on the map (Zoungrana et al., 2023)

II.2 Data Collection

A survey was carried out to collect data in order to assess the actual performance of the types of irrigation systems used in Ouagadougou. The goal of this survey was to understand the different irrigation systems in use, which would help achieve the different objectives of this thesis.

The survey focused on two main sources:

- The Ministry of Agriculture of Burkina Faso (Ouagadougou)
- Experts based on knowledge, involved in the vegetable crop, were approached.

Regarding the selection of those experts based on their expertise**,** during our visit to the Ministry of Agriculture in Ouagadougou, we were provided with a list of key thematic areas and contacts of specialists involved in market gardening in the region. This list was instrumental in identifying individuals with in-depth knowledge and practical experience in the field. Using the information provided, we were able to meet with these experts and engage in discussions about their approaches to vegetable crop production, particularly focusing on the methods they employ and the types of irrigation systems currently used in Ouagadougou. These exchanges were crucial for understanding the local practices and challenges related to irrigation management in market gardening. The interviews were conducted in French, and a sample of the questions asked can be found in **Annex I**.

II.3 Materials and Methods

For this study, many materials/tools have been used to implement this smart system, which reduces water waste and improves vegetable crop watering.

II.3.1 Materials

- **Arduino Integrated Development Environment (IDE**) is a program that enables users:

To write and upload code to microcontrollers such as Arduino board, ESP32, ESP8266, Raspberry Pi, and cetera[10]. The programming language that this software supports is either C or C++. This software can be performed in several types of exploitation systems such as Windows, Mac OS X, and Linux[11].

Here is what the software looks like

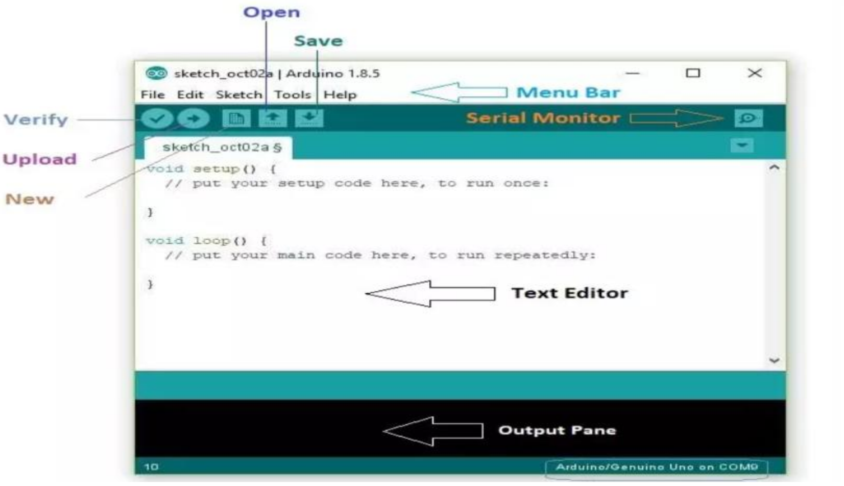

Figure 09: Arduino Board Software[12]

- **Mendeley Software** is a free reference manager that can help you store, organize, note, share, and cite references and research data. It also enhances to automatically generates bibliographies, collaborates easily with other researchers online, easily imports papers from other research software, finds relevant papers based on what you're reading, and accesses your papers from anywhere online.
- **3D Printer,** it's a machine that makes real, three-dimensional objects based on a digital design.
- **Proteus** is software and widely used for the simulation of electronic components that allow us to design electronic circuits, to simulate the behavior of the component, program microcontrollers (Arduino, EPS32 …), and virtually test a circuit before building it in real life.
- **Microsoft Word on Windows** was used to write the report of this thesis.

➢ **Electronic components used to design the smart irrigation system**

❖ **ESP32 and a Capacitive soil moisture sensor**

The ES32 is a versatile microcontroller and powerful platform that is widely utilized in many applications. Its embedding of WIFI and Bluetooth allows for sharing data in real time and remote control, which is sustainable (Gagan et al., 2024).It's able to read inputs (humidity sensor, a finger on a button, etc.) and turn them into an output (publishing data online). We use ESP32 because it has a huge capacity to contain our sensor information and low cost. Capacitive Soil moisture sensors measure the amount of moisture in the soil. Depending on the digital value that it will produce, let us know whether the soil is dry or humid. The one we used in this study indicates that a high value means the soil is humid. Here is a figure of ESP2 and the soil moisture sensor.

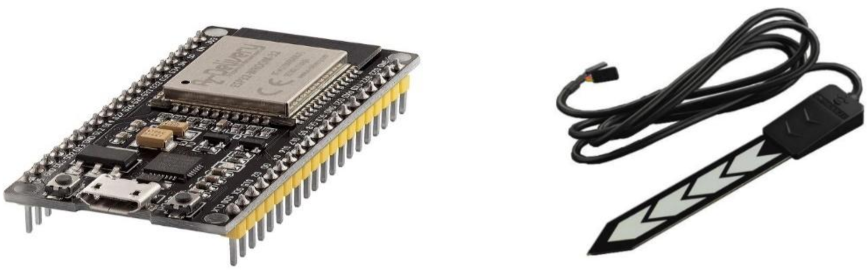

Figure 10: ESP32 Microcontroller and Capacitive Soil Moisture sensor[13]

- ❖ **Liquid Crystal Display (LCD), Tension Booster (MT3608), and The Global Positioning System (GPS)**

LCD is a screen commonly used to display information from sensors or a microcontroller (ESP32). We used to display soil moisture information of two types of crops (Onion and Tomato) as well as GPS coordinates so that we can locate our system.

Tension Booster is a device that boosts the tension from the lower output to the higher output, and we used it to boost the battery of our system to power our microcontroller. The **GPS** module is used to get the exact location of the system. See Figure 13 of the screen display.

Figure 11: LCD, MT3608, and GPS

- **Buzzer, LED, and Push-button**

A buzzer is an electronic component that produces a sound or alarm when powered. In General, it has two pins: a positive (+) pin and a negative (-) pin. We use it to emit an audible signal in two cases: when the plant needs water and when the plant receives more water than it needs. At the same time, two LEDs of different colors (red and green) were used to identify the problem facing the plant, whether it was too wet or too dry.

Push button is a simple mechanical switch that lets someone control an electrical circuit by pressing it, triggering an internal part to either connect or disconnect the circuit. In this work it allows the user to select the type of crop as well as confirm the selection. See below the Figure 12 of those electronic components.

Figure 12: Buzzer and LED, and Push Button

- **Solenoid valve normally closes, Panel Solar, battery lithium, and Charger controller 6/12V.**

A Solenoid valve is a unit control that allows or blocks fluid flow depending on its electrical activation. It is used to automatically control fluid flow. It operates with 12 volts. When you turn it on, it makes a magnetic pull that moves a small piece against a spring. Once the power is cut, the spring pushes the plunger or armature back to its starting position action[15]. The one that we used is normally closed, because we don't want our water to flow once the system is powered, without taking into account the soil moisture content.

To make our system autonomous, meaning it operates without an external power source. We used a solar panel and a lithium battery, along with a charge controller, in this study. The solar panel captures sunlight, converts it into direct current (DC), and sends it to the battery through the charge controller, which then powers the solenoid. See below the Figure of those electronics components

Figure 13: Solenoid valve 12 V, Panel Solar, Battery Lithium and charger controller

- ❖ **Relay Module**

A relay module is an electrical component that acts as a switch that can control high-voltage devices using low-voltage signals, from a microcontroller such as ESP32, ESP8266, and even smartphones. It can receive a command and switch regardless (Yunardi et al., 2022).

The relay has two groups of pins Figure 19**,** One is taking the low voltage group, and the other high voltage group.

Low voltage group:

GND pin: connect to GND
VCC pin: connect to the VCC
IN (SIG) pin: gets control signals from the microcontroller.

High voltage group:

COM pin: common pin, it is used in both normally open and closed.
NO pin: pin used for normally open mode.
NC pin: It is used for the normally closed mode.

For our system, it is used to switch the solenoid valve depending on the soil moisture value that the microcontroller will record. See Figure 14 of the relay module.

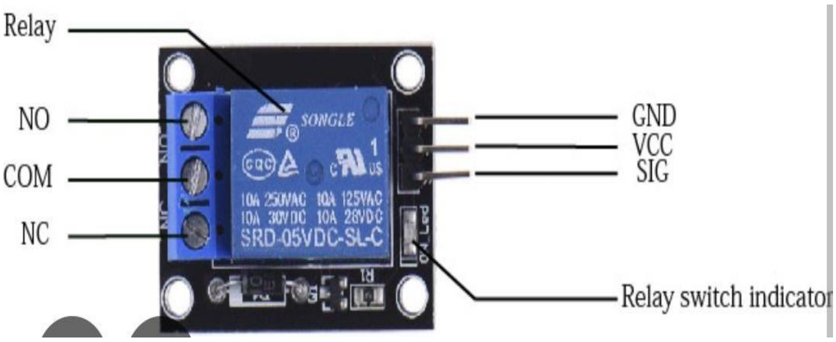

Figure 14: Relay module

❖ **Water flow measurement device**

The water flow meter is a device used to measure the flow rate of liquids and gases (water, oil, cetera) that pass from one point to another(Гавриловић & Рад, 2024). It helps to watch and control how much water is flowing accurately. For our system, the flow meter has been used to assess the amount of water that passes through the pipe or from our water source. The rate of flow of water is measured as liters per hour or minute. Below is Figure 15 of the water flow

Figure 15: Water flow meter

❖ **Printed Circuit Board (PCB)**

A PCB, or printed circuit board, is designed to connect and support electronic components via conductive tracks electrically. It is widely utilized for all electrical components capable of conducting current. This versatile component simplifies the assembly and wiring of electronics, reduces space, enhances reliability, and facilitates mass production. To build our system with optimal space efficiency and reliability, we utilized a PCB. Below is the figure for the PCB

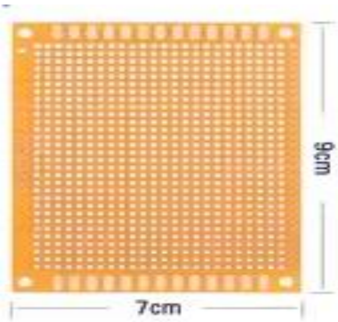

Figure 16: PCB

II.3.2. Methods

To achieve the three (03) specific objectives of this thesis, a structured methodological approach was adopted, as outlined below:

- **Survey on agricultural practices**
  An investigation was conducted on vegetable farming practices across various areas in Ouagadougou. A total of fifteen (15) farmers were approached, and their responses were collected to gain insights into their irrigation methods and challenges related to water use.

- **Statistical analysis of survey results**
  The collected data were statistically analyzed to evaluate the performance of existing irrigation methods and identify common inefficiencies. (**Specific Objective 1)**.

- **Definition of efficiency requirements**
  Drawing from both the general literature and the empirical data from the surveyed farmers, appropriate efficiency requirements for irrigation systems were formulated. These requirements were aimed at minimizing water waste and enhancing vegetable crop production in the context of Ouagadougou. (**Specific Objective 2)**.

- **Development of a smart irrigation system**
  Based on the defined efficiency requirements, a user-friendly and intelligent irrigation system was designed and developed. This system integrates smart technologies to promote efficient water use in vegetable crop irrigation (**Specific Objective 3)**.

To build the smart irrigation system, I first did a simulation with Proteus software by adding all the needed parts, such as libraries. Then, I wrote the program using Arduino

IDE, uploaded it to the microcontroller, and connected the microcontroller to the electronic parts. Once everything was working correctly, I used SolidWorks software to design the holding box for the system, and then printed it using the 3D printer available at WASCAL's competence center. Finally, I assembled all the components inside the box.

These steps are illustrated in the methodology process chart shown in Figure 17 below:

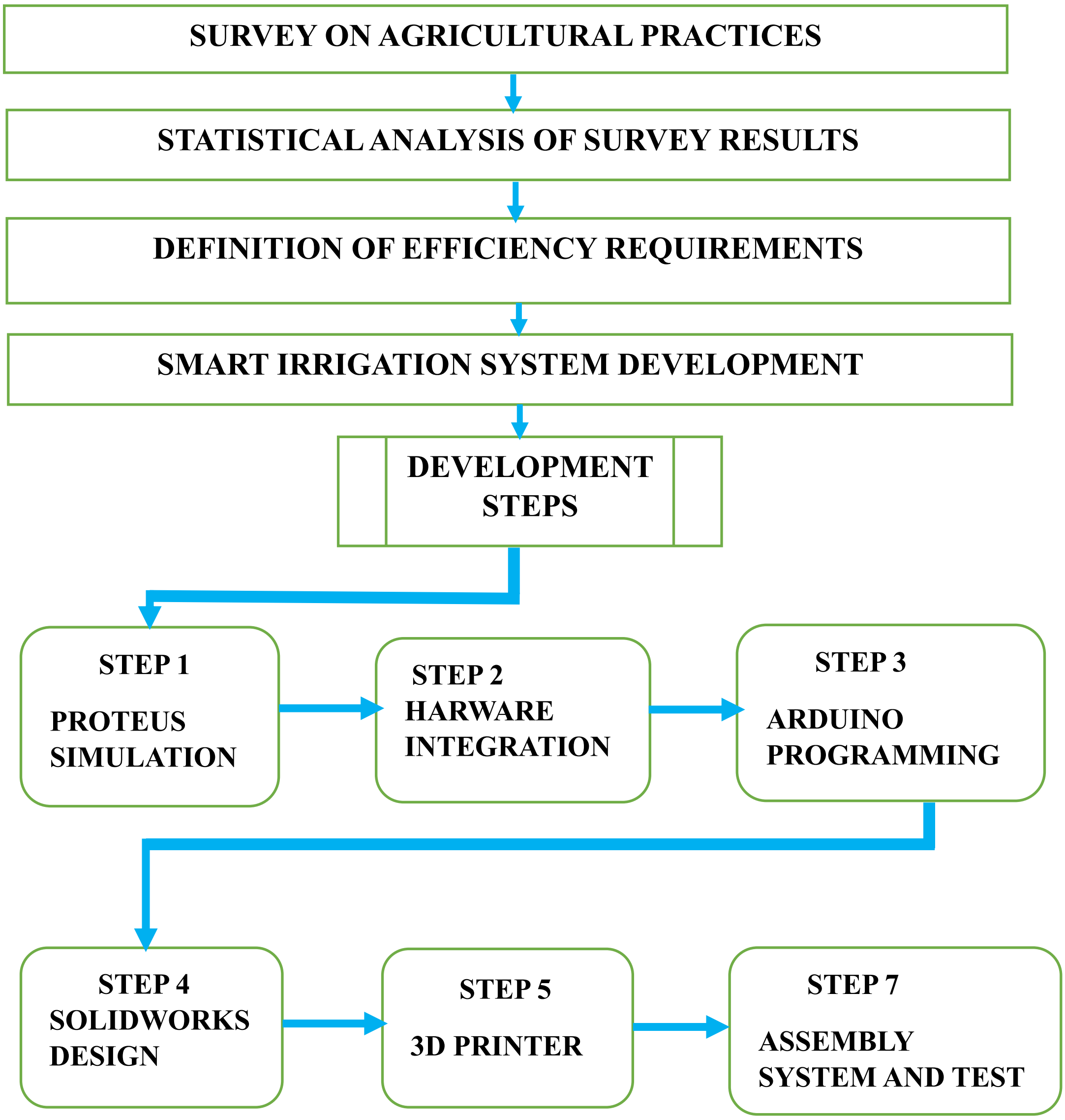

Figure 17: Flow Chart of methodology process

II.3. Development of a smart system for efficient water use in vegetable crop watering

This part concerns the third objective of our project, which is to design a smart system for efficient water use in vegetable crop irrigation. To achieve this, the implementation steps are explained below. As shown in the sequence diagram, our system is divided into two parts. The first is what we call **Smart Agric (soil humidity reading sensor)**, which allows the user to measure the soil moisture of two types of crops, such as **tomatoes and onions**. The second part of the system is called WASCAL Water Trigger. It receives the soil moisture information of the type of crops and then triggers water accordingly to the threshold that was defined based on the literature. An app was implemented to visualize and gather the soil humidity information to make a decision

The **Proteus** software was used to simulate the first part of our system.

II.3.1. Proteus Design

For our system, we first used Proteus software to simulate the design by adding the libraries for each part, as shown in the picture below. We established connections between the microcontroller and several electronic components, including an LED, a GPS, a push button, a buzzer, resistors, a capacitive soil moisture sensor, and an LCD.

For the microcontroller, both digital and analog pins of the ESP32 were utilized as follows:

- The **RX** and **TX** pins for the GPS module are connected to pins **16** (RX) and **17** (TX) of the ESP32 board via **Serial2** communication.
- The **capacitive soil moisture sensor** is connected to analog pin **32** of the ESP32.
- The **buzzer** is connected to digital pin **5** of the ESP32.
- The **Menu**, **Next**, and **Select** buttons are connected to pins **15**, **13**, and **14** of the ESP32, respectively.
- The **red** and **green LEDs** are connected to digital pins **25** and **26** of the ESP32, respectively.

After that, we compile the code from the Arduino IDE and then upload it to the Proteus to start the simulation.

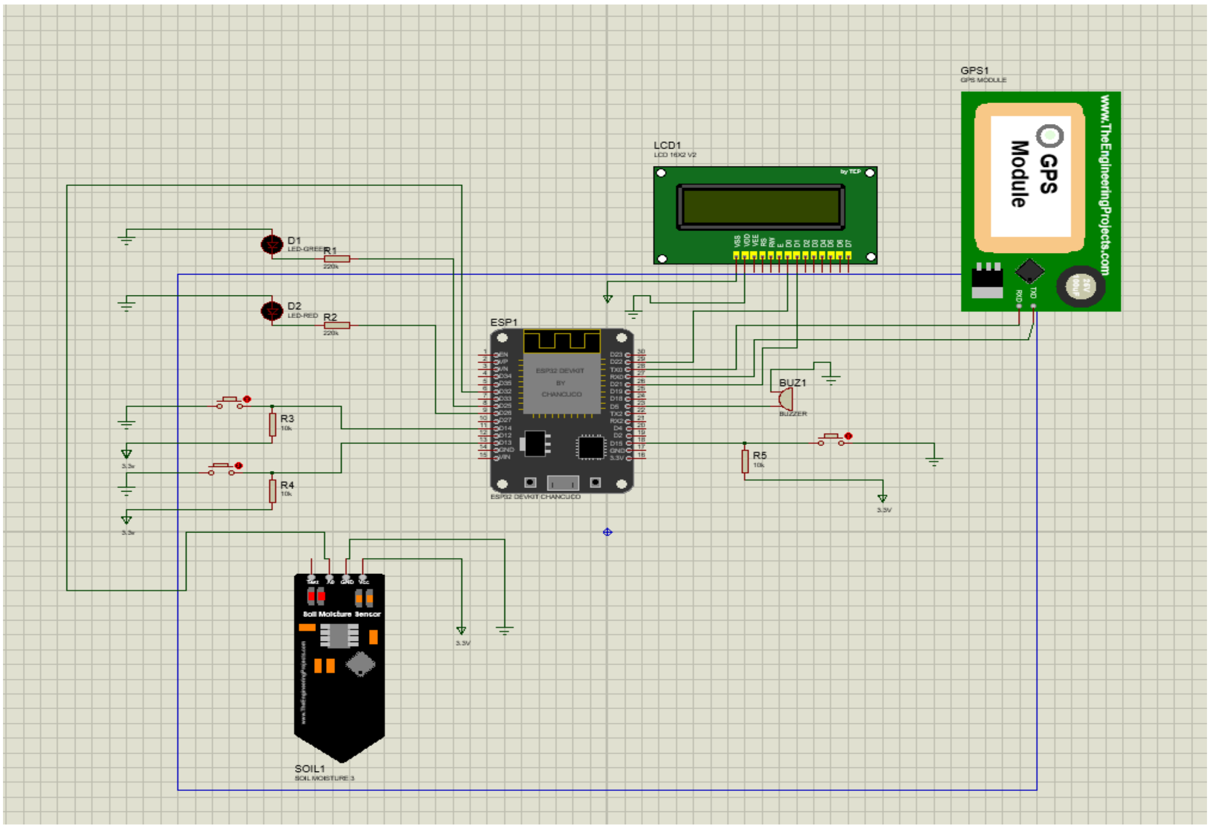

Figure 18: Proteus Design of the smart Agric simulation

After using Proteus for this simulation, we use those materials to implement the prototype. Below is the figure for that one.

Figure 19: Smart Agric prototype

II.3.2 Design of the second part of the smart irrigation system (Water trigger)

Concerning the second part of our system, "**Water trigger**", we used a breadboard for quick circuit prototyping. Several electronic components were used, including an ESP32 microcontroller, a 6V solar panel, a charger controller, a 6V battery, a 12V solenoid valve, a flow meter, a relay module, and a voltage booster.

The connection between different electronic components is as follows:

Power Supply Setup

- **Solar Panel (6V) → Charger Controller**
- **Charger Controller → 6V Battery** (for charging and powering)
- **Charger Controller Output** → to power other components:

Voltage Booster

- **Input**: Connected to 6V Battery output
- **Output**: Boosts to 12V
- **12V Output** → Powers **12V Solenoid Valve**

Solenoid Valve Control (via Relay)

- **Relay VCC/GND** → 5V and GND from ESP32
- **Relay IN pin** → GPIO from ESP32 (to control it)
- **Relay COM** → Voltage Booster (+) 12V output
- **Relay NO (Normally Open) → Solenoid Valve +**
- **Solenoid Valve − → Voltage Booster Ground**

Flow Meter (Hall Effect Sensor)

- **VCC** → 5V from ESP32 or regulator
- **GND** → Common Ground
- **Signal (OUT)** → GPIO on ESP32

After the connection between different elements listed above, for the second part of the system (**Fig. 20**), an Arduino program was implemented and uploaded to the Arduino Microcontroller.

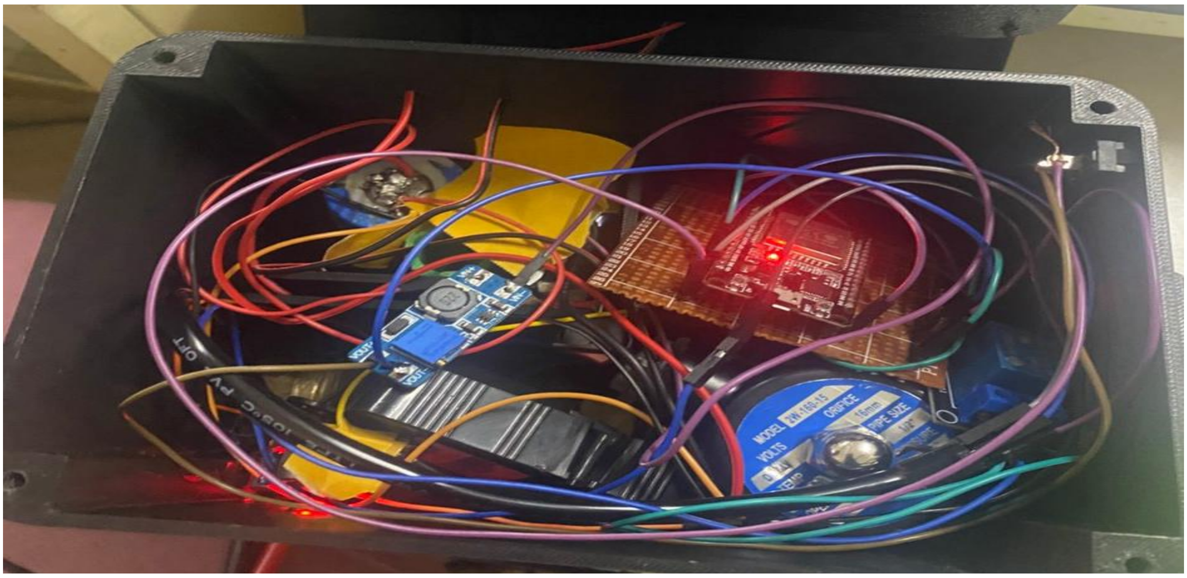

Figure 20: Water Trigger Holder

II.3.3 Mobile Application Development Using Flutter

In this project, a mobile application was developed using **Flutter** with **Visual Studio Code**. The purpose of the application is to receive and display data that is sent from the ESP32 microcontroller to **Firebase**.

To build this application, a real-time database was used to collect the data from the sensors connected to the ESP32. The Flutter app communicates with the Firebase database using specific protocols to retrieve and display this data.

The mobile app includes several useful features:

- It allows the user to monitor **humidity levels in real time**.
- It includes a **user authentication system** to control access.
- It shows the **status of the irrigation valve** (open or closed).
- It displays the **GPS coordinates** of the system. This mobile application helps users interact with the irrigation system easily and remotely.

Below you'll find our Firebase status along with the configuration we've established to receive data from the microcontroller.

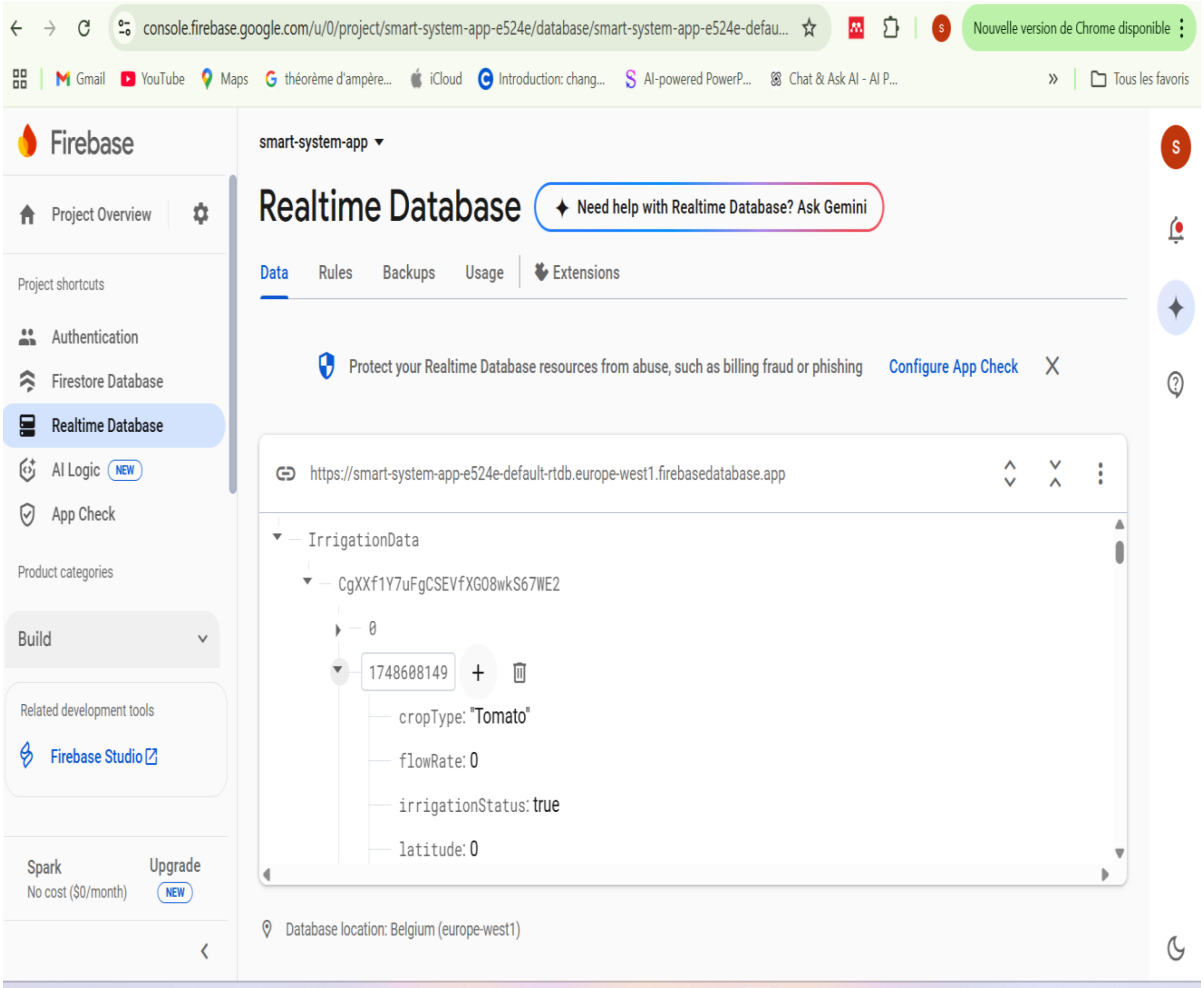

Figure 21: Firebase Real-time data

II.3.4 Description of the operating principle of the smart irrigation system for reducing watering waste on the vegetable crop

To describe all the functionality of the smart irrigation system well, a Diagram of the sequence (Fig) was used to design a Unified Modeling Language (UML). UML is a set of simple pictures and diagrams that help people who make computer programs. These pictures help them: Plan what they want to build, show their ideas to others, build their software correctly, and keep records of how their program work

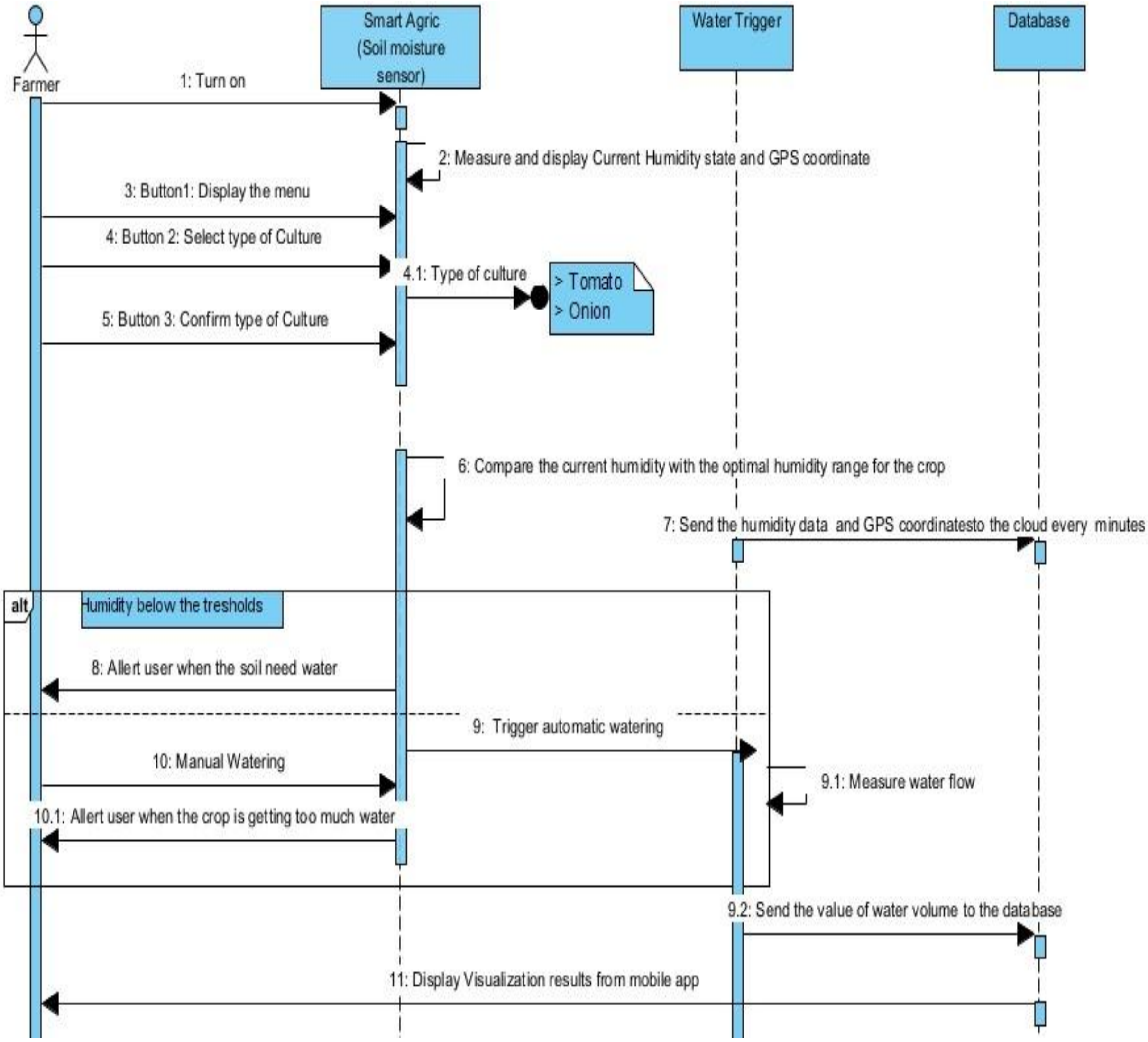

Figure 22: Description of the operation principle of the smart system

Conclusion

This chapter has provided a detailed overview of the methodology adopted and the materials used in the development of the smart irrigation system. It outlined each step taken to design and implement a solution capable of minimizing water wastage while improving the productivity of vegetable crops. The integration of various components, including sensors and microcontrollers, was described, along with the use of Firebase as a real-time database for storing humidity readings and GPS coordinates collected from the field. This work will allow an accurate monitoring so that water can be managed efficiently. In the next chapter, we will present and analyze the results obtained from the system implementation, drawing insights from the data gathered throughout the previous phases of the study.

CHAPTER III: RESULTS AND DISCUSSION

This Chapter has presented the results obtained from the implementation of the smart system as well as the results we obtained from the survey.

III.1 RESULTS

III.1.1 Descriptive Analysis of Irrigation Practices in Ouagadougou

Descriptive Statistics

Table 2 below shows the results of the survey that was conducted in the field of those who are practicing vegetable crop farming.

Table 2: Type of irrigation currently used in Ouagadougou

Irrigation Type	Percentages of the results from expert-based knowledge %
Laser Spray	20
Sprinkler	26.67
Drip Irrigation	13.33
Watering Can	40

The survey results show that various irrigation techniques are currently used in Ouagadougou, namely laser spray, drip irrigation, sprinkler irrigation, and watering can, with respective usage rates of 20%, 13.33%, 26.67%, and 40%.

This finding indicates that the most commonly used method of irrigation in Ouagadougou for vegetable crop watering is **Watering Can**, accounting for 40% of respondents. This means, traditional methods and manual methods are widely used due to their low cost and accessibility of those systems. This finding is in agreement with the study by Ouedraogo et al., (2019) , which revealed that the watering can method is widely used due to financial constraints.

For more advanced systems, such as drip irrigation systems, are less common, accounting for only 13.33%. This could be financial constraints, and lack of awareness, or limited access to technology.

Systems such as sprinklers (26.67%) and laser spray (20%) are used moderately, which shows that farmers are beginning to take an interest in them. These observations highlight a potential opportunity for the introduction and promotion of smart irrigation technologies, especially if they are affordable, easy to use, and tailored to local conditions

III.1.2 Irrigation practices and water use by farmers

From the survey results, a table was created to present the water usage by each type of irrigation method. See Table 3 below for Irrigation Practices and Water Use by Farmers.

Table 3: Irrigation Practices and Water Use by Farmers

Irrigation Method	Watering Frequency	% of Farmers	Water Quantity
Laser Spray	Every two days	75%	Not measurable
	Once per day (30 minutes)	15%	Not measurable
Sprinkler	Once every day	50%	Not measurable
	Every two days	25 %	Not measurable
	Twice per day	25 %	Not measurable
Drip Irrigation	Once every day (avg. 30 min)	90%	Not measurable
	Every two days	10%	Not measurable
Watering Can	Once every day	80%	100 L per plot (10 cans of 10L each)
	Twice per day	20%	100 L per plot (10 cans of 10L each)

In addition to identifying the types of irrigation methods used, the survey also explored the frequency and estimated quantity of water applied by farmers using each technique. For the Watering Can method (manual ones), 80% of the farmers are watering once daily, while the remaining 20% are watering twice daily. The amount of water used for watering can be estimated by 10 watering cans per plot, which is approximately 100 liters, because each can contains 10 liters.

For the Drip irrigation methods, 90 % of the farmers are watering each day within a certain period, but the average of that is 30 minutes, and the remaining 10% of the farmers are watering each two days within a certain period as well. The amount of water that this method involves is not quantifiable because they don't have a device to measure the quantity of water; they just rely on observation

For the Sprinkler method, 50% of the farmers are watering their farm each day within a certain period, 25% every two days, and the remaining 25% of the farmers are watering their farm twice a day within a certain period of the day. The quantity of water they use is not measurable because their system cannot record this data.

In the last method, which is the laser spray method, 75% of the farmers water their farm every two days, and the remaining 15 % of farmers water their farm once per day within 30 minutes. They don't have any way to quantify the amount of water they use during the irrigation process.

III.1.3 Percentage of farmers based on the feature of a smart system

The plot below shows a general visualization of smart irrigation system should have for the implementation. We see the expectations of farmers who are practicing vegetable crop production

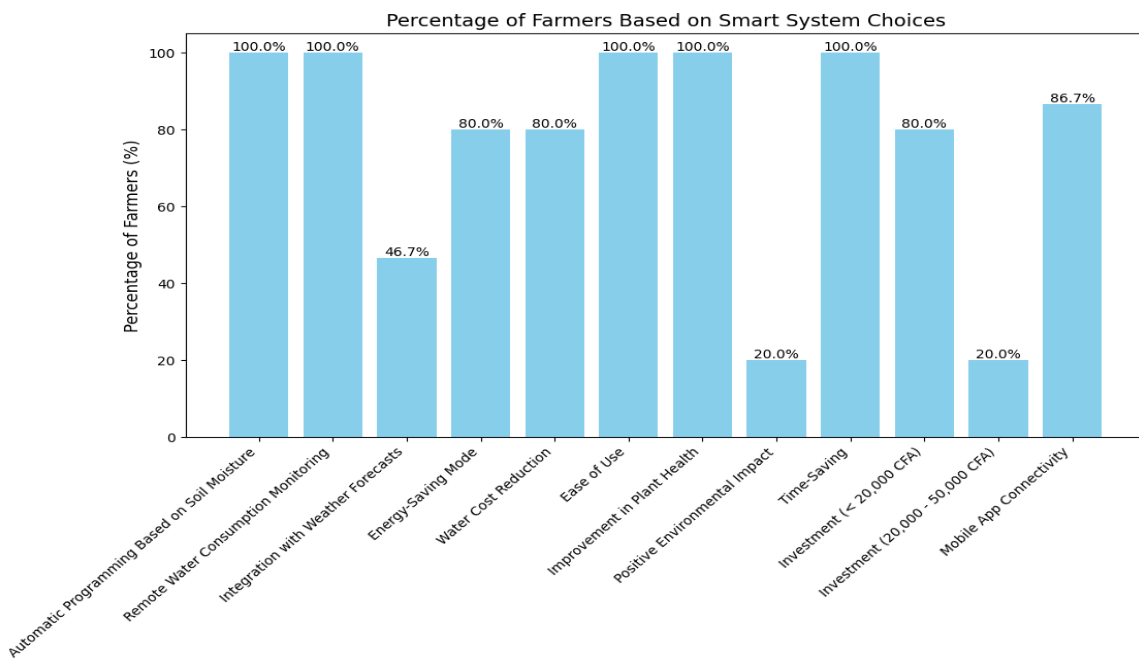

Figure 23: Visualization of features that a smart system should have

The bar chart below (Figure 23) illustrates the percentage of interviewed farmers who expect specific features to be included in a smart irrigation system for reducing water waste in the vegetable crops.

As illustrated from the bar chart, 100% of those farmers are expecting to have a system which are:

- Automatic Programming Based on Soil Moisture
- Remote Water Consumption Monitoring
- Ease of Use
- Improvement in Plant Health
- Time-Saving

80–87% of farmers are expecting to have:

- Mobile App Connectivity
- Energy-Saving Mode
- Water Cost Reduction
- Investment (< 20,000 CFA)

46.7% want a system integration with Weather Forecasts

20 % expected a system with a Positive Environmental Impact and Investment (20,000–50,000 CFA)

These results reveal that farmers prefer to focus on a smart system that offers immediate service and ease of use, particularly features that simplify system operation while improving crop health, reducing labor, and minimizing water waste. The integration of a mobile device for system monitoring shows that stakeholders in the vegetable farming sector are seeking a solution that is both user-friendly and affordable. The fact that few individuals are willing to invest more than 20,000 FCFA indicates a preference for a low-cost system.

III.1.4 Proposition of the efficiency requirement for an irrigation system addressing gardening water waste and crop production.

The system we implemented is based on requirements derived from both farmer feedback and a review of relevant literature. From the survey conducted in Ouagadougou, we observed that most farmers rely on visual observation to determine whether their fields have received sufficient water. Furthermore, existing systems such as sprinklers, drip irrigation, and laser spray methods do not take soil moisture levels into account before irrigation, leading to significant water waste.

Therefore, we propose the following:

- ✓ Easy to use

From the survey, farmers need a versatile system that is affordable and easy to use

- ✓ Use of Soil Moisture Sensors

Implement a soil moisture-based control system that triggers irrigation only when necessary, avoiding over-irrigation and enhancing plant productivity

- ✓ Rechargeable

When the Smart Agric system is discharged, it can be recharged using a solar panel, a USB cable, or other available power sources

- ✓ Integration of Renewable Energy Sources

Power the irrigation system with renewable energy, such as solar panels, to ensure affordability and sustainability for end users.

- ✓ Measure the quantity of water used

Measuring the amount of water used helps determine the exact water requirements of the crops and allows for the identification of issues in the irrigation process.

- ✓ GPS Coordinates

GPS coordinates allow the system to record the exact location of the farm, which is useful for mapping, monitoring multiple fields, and integrating with weather forecast data for location-specific irrigation decisions

- ✓ Mobile/Web Interface for Visualization

Develop a web or mobile application to visualize soil moisture data and send notifications when irregularities or issues are detected in the system.

- ✓ The optimal range of tomato and Onion for our system, based on the literature, will be respectively between **60 to 80 and 60 to 70.**

III.1.5 Development of smart irrigation systems for reducing gardening water waste and improving crop production.

- First part **"Smart Agric (reading humidity sensor)"**

The Smart Agric device consists of an ESP32 microcontroller integrated with GPS, an LCD I2C screen, LEDs, resistors, a push button, a buzzer, a lithium battery, and a rechargeable battery. See below the figure of the system

Figure 24: Smart Agric system

Smart Agric was developed to execute multiple functions:

- It measures soil moisture for two vegetable crops (tomato and onion) to enhance irrigation practices for local farmers who traditionally use watering cans and visual observation. This system helps farmers determine the optimal water quantity needed for better growth and improved yields.

- The device has two LEDs and a buzzer. When the soil is too dry, the buzzer makes a sound and the red light turns on. When humidity exceeds the optimal range, the buzzer also sounds, but the green LED activates instead. No alerts occur when humidity remains within the optimal range.

- It records GPS coordinates at each soil moisture measurement location with a precision of 4 meters.

- The system wirelessly communicates with the Wascal water trigger system, transmitting soil humidity data and GPS coordinates. In open field conditions, this wireless communication has an effective range of up to 722 meters.

- The device utilizes a lithium battery with a rechargeable mode, allowing users to recharge from various power sources, including power banks, USB cables, and other standard charging methods, when the system's power is depleted.

- Second part **"WASCAL WATER TRIGGER"**

The second part of the system includes an ESP32 microcontroller, a solenoid valve, a solar panel, a 6V battery, a booster converter, a water flow sensor, and a charge controller. See figure 25 below

Figure 25: Wascal Watter Trigger

This system was designed to perform several important tasks:

- **Wireless Communication**: The system uses the ESP-NOW protocol to communicate wirelessly with the Smart Agric (figure 30) system and get data.

- **Automatic Watering Control**: The system receives soil humidity readings from each selected crop (tomato and onion) along with their GPS coordinates. It then controls watering by comparing the current soil humidity with the optimal level for the selected crop type. When the soil becomes too dry, the system automatically turns on the water. When the soil has enough water, the system stops watering. It waits until the soil dries and reaches the **critical minimum level** before starting again. This automatic watering process helps farmers use water efficiently and ensures crops receive water exactly when they need it.

- **Water volume**: The system, once it turns on, starts to record the exact amount of water that is passing through the solenoid valve. After that, those values are directly sent to Firebase, where we can retrieve them from the app in real time. This will help farmers understand the water consumption patterns that crops need for optimal growth.

  Data Storage and Remote Access: The system sends data like humidity and GPS location to Firebase using Wi-Fi. This lets farmers see their crop information on a mobile app from anywhere in the world.

Mobile Application Development: User Interface for Remote Irrigation Control and Data Visualization

For Remote control and data visualization, we built a mobile app using Flutter, and below is a picture of the app.

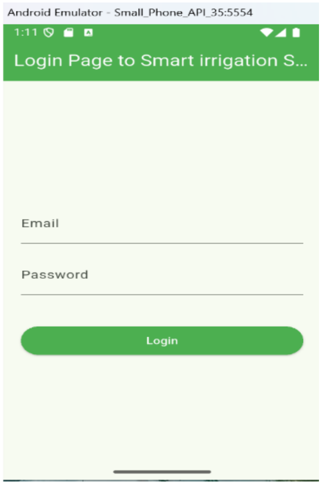

Figure 26: App Interface for authentication

This app was built using Flutter. It retrieves data (humidity along with GPS coordinates) from the Firebase and displays it. To access the main interface, the user must enter coordinates that have been configured in Firebase, and then they can access the main dashboard, where they can view real-time sensor readings as well as GPS coordinates. The main interface provides access to numerous features, such as visualizing humidity readings from sensors, monitoring water volume in real time, viewing the location where data is being recorded, and checking the crop type and solenoid valve status. However, through the app, we can turn the water trigger system on or off. Below is a figure of the main interface of the app was built using Flutter.

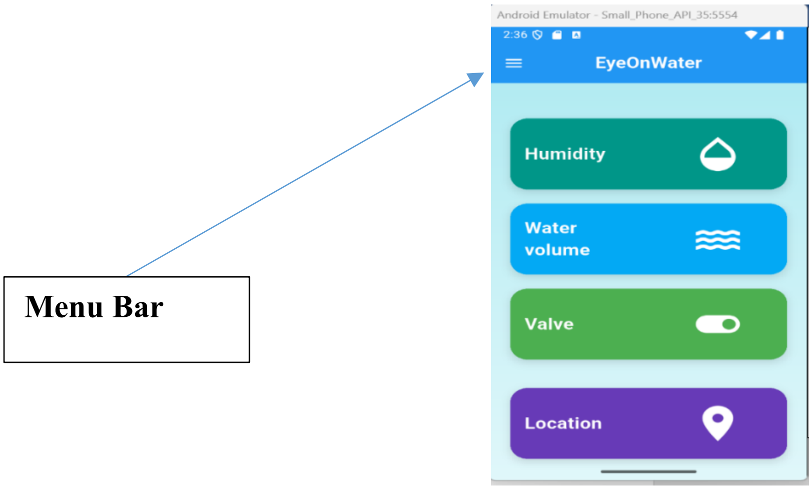

Figure 27: Main Interface of the app

When the user clicks on the **menu bar**, the app automatically displays three options. First, it retrieves all the data that has been sent to Firebase (data history). Second, it provides charts to visualize the daily average of humidity and water volume usage (chart). The third option allows the user to log out of the app (log out). These features help farmers truly control the system, and based on these results, they can estimate the exact amount of water their crops will need. With this information, they can efficiently irrigate their crops even without real-time humidity readings. See Figure 28 below.

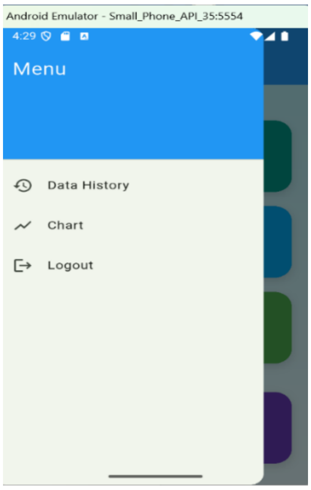

Figure 28: Menu Bar

When the **Data History** option is selected, the interface displays all the data that has been sent to Firebase, including information such as soil humidity, type of crops, and volume of water. The image below presents an example of the data recorded during the development phase of the application. (Figure 29)

Figure 29: History Data

When the **Chart** option is selected, the interface displays the trend of Water volume use, as well as the trend of humidity (Figure 30).

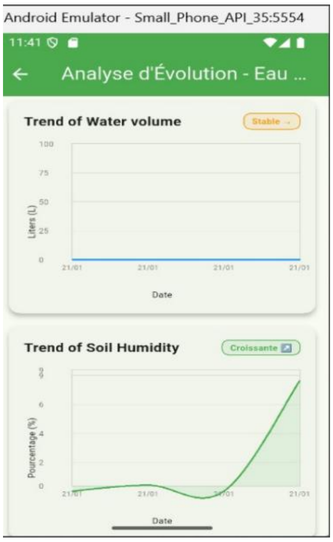

Figure 30: Chart of a trend of selecting crop and water use

On the **EyeOnWater** screen (Figure 27), four widgets are displayed. The first widget shows the real-time trend of the humidity level for the selected crop. It also provides the numerical value of soil moisture, which helps determine the amount of water present in the soil at a specific moment.

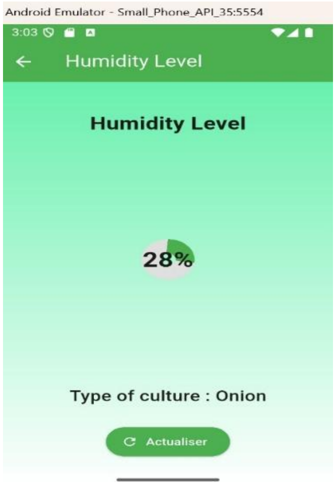

Figure 31: Humidity level

The humidity level displayed is retrieved from Firebase, which receives data from the smart agriculture system via Wi-Fi every minute.

The second widget shows the volume of water used, providing insights into irrigation patterns and helping monitor water consumption.

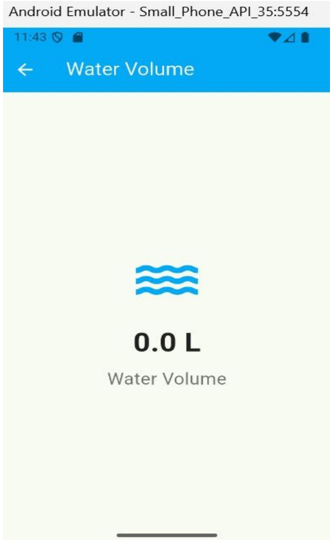

Figure 32: Water Volume display

The third widget displays the state of the solenoid valve. It includes a feature that indicates whether the valve is operating in on mode or off. That allows us to see if the system is watering the crop or not.

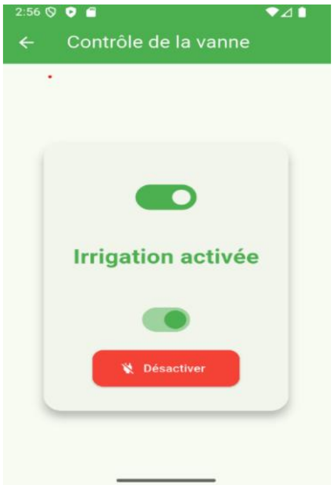

Figure 33: Control valve

The fourth widget provides the geolocation of the monitoring point along with the name of the selected crop. The image below shows the location where the system was first developed. It clearly shows the Ouaga 2000 bridge, where the WASCAL Competence Center is located.

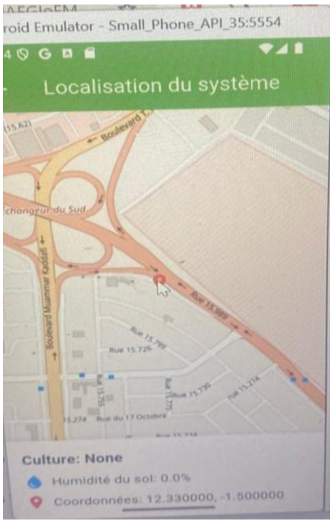

Figure 34: Location of the system along with the crop

❖ **Experimental Testing of the Smart System**

After developing the smart irrigation system to reduce water waste and improve crop production, we conducted an experimental test to validate its functionality in real-world conditions. The test was carried out in front of the WASCAL building, where our laboratory work took place. This location was selected to simulate a realistic deployment environment and to assess the system's responsiveness and reliability. As shown in the figure below, the system successfully activated, and water flowed through the water trigger as intended, confirming the effectiveness of the prototype. Due to the limited time available for implementation, we were unable to conduct long-term experiments in actual market gardening settings. However, we plan to carry out extended field testing after the presentation of the system to further evaluate its performance and adaptability under real agricultural conditions.

Figure 35: Experimental Test of the Smart Irrigation System Demonstrating Water Flow through the Trigger

- **Proposition of humidity sensor deployment**

For our proposed system, in case we want to use it over a large area, the best way to position those capacitive soil moisture sensors in the fields to maximize water use efficiency is as follows:

For homogeneous soil (No matter where you take a sample from, it will have **almost the same physical and chemical properties, such as texture, density, and permeability)**, we can place one sensor for every 1 acre (0.50 hectares) to use water efficiently. For 1 hectare, we are going to have two sensors placed diagonally and one in the middle of the field, which will get the soil moisture value of each and then calculate the average and trigger watering for the whole field when the soil needs it. Figure 36 below shows an example of that.

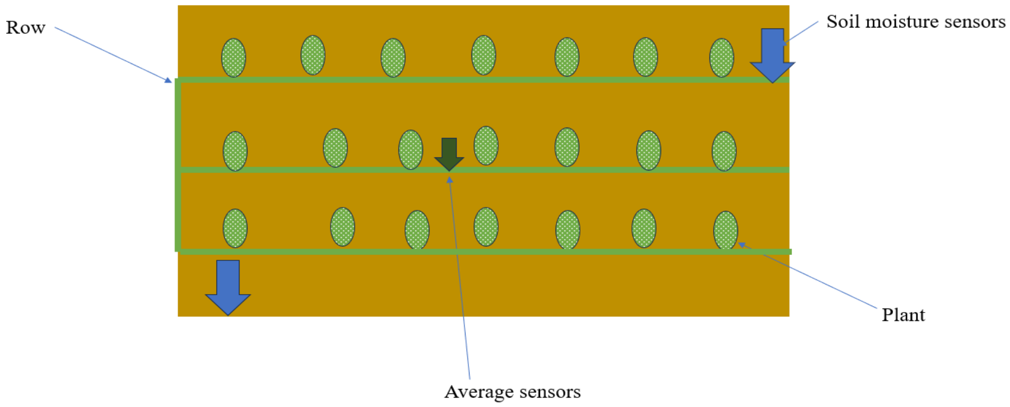

Figure 36: Proposed system for 1 hectare

For the **non-homogeneous soil (the characteristics of soil are not the same everywhere)**, we could use X methods(Permal et al., 2021) (good for non-homogeneous soil and aim to locate soil where the need for water is urgent), and to get more information about the humidity of the soil for better irrigation of the crops. Those sensors should be placed as shown in the following figure. For this method, we will use six sensors. One sensor will calculate the average of the remaining five sensors and send the data to the microcontroller ESP32, which will then trigger the water when needed.

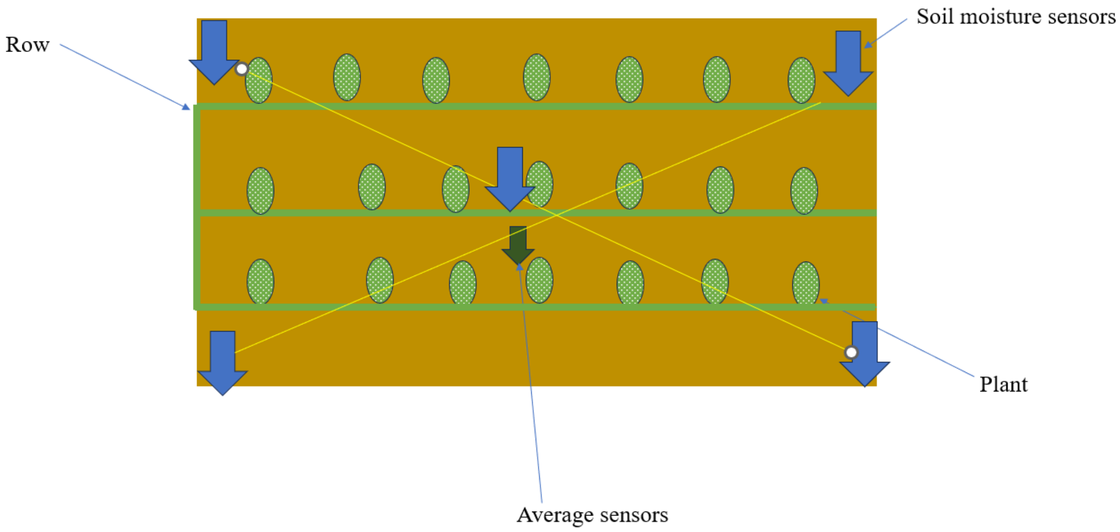

Figure 37: Proposed system for 1 hectare of non-homogeneous field

Overview of the Smart System in the Field: A Case Example with Drip Irrigation.

The figure below illustrates how the proposed smart irrigation system can be practically implemented in an agricultural field, where it is integrated with a drip irrigation setup to enable efficient and automated water distribution.

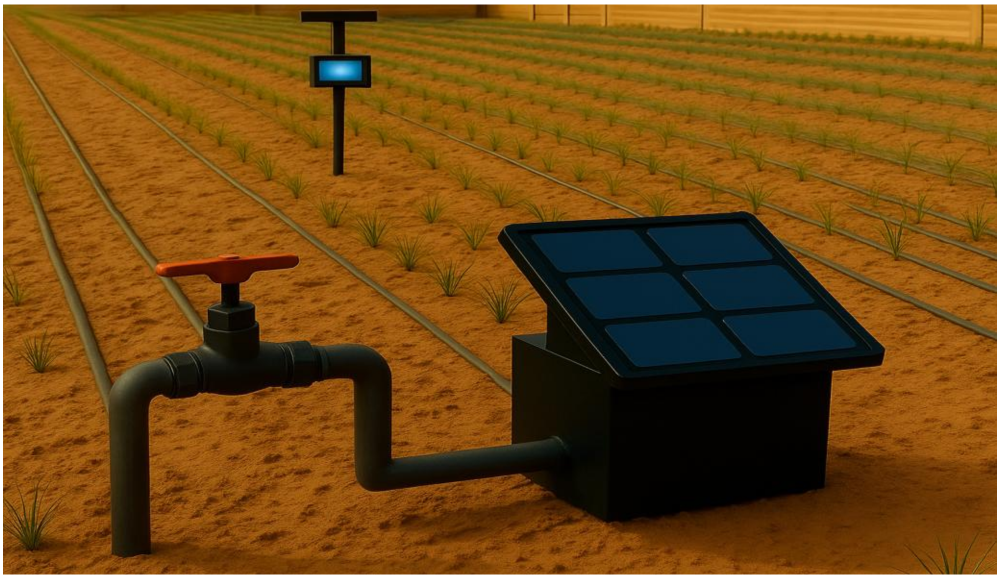

Figure 38: Illustration of the field deployment of a smart system

III.2 DISCUSSION

The implementation of the smart irrigation system for onion and tomato cultivation in Ouagadougou marks a significant step toward improving water use efficiency and addressing agricultural challenges under the pressure of climate variability. Burkina Faso, like many countries in the Sahel region, faces chronic water scarcity, increased evapotranspiration, and unreliable rainfall due to climate change (Leal Filho et al., 2022; IPCC, 2021). This context necessitates the adoption of adaptive technologies that optimize water use while maintaining crop productivity. The system developed in this study responds to this need through the use of Internet of Things (IoT) technologies, ESP32 microcontrollers, capacitive soil moisture sensors, flow meters, and Firebase cloud data services, combined with a solar-powered architecture suitable for resource-constrained environments.

Survey results showed that the majority of farmers still rely on traditional watering methods, especially the use of watering cans, with 40% of respondents using this method. This approach is not only labor-intensive but also inefficient, as farmers tend to water based on visual estimation, often leading to excessive or inadequate irrigation. This aligns with findings from Adejumo and Oni (2021), who reported that traditional irrigation methods result in up to 60% water loss in sub-Saharan agricultural systems. In contrast, the smart system developed in this study enabled real-time monitoring of soil moisture and automated irrigation decisions, reducing unnecessary water use and providing timely water delivery based on actual plant needs a concept supported by studies such as Jones (2004) and Kifle et al. (2023), which emphasize the benefits of data-driven irrigation scheduling.

In the small experimental test conducted in this study, the system functioned efficiently across several watering cycles, maintaining soil moisture within optimal thresholds for tomato (60–80%) and onion (60–70%) as defined in the literature (Wang, 2018; Nurhasanah et al., 2021; Liu, 2019), and it stopped once moisture returned to the optimal range. While no quantitative water-saving results were formally recorded, this initial verification supports previous studies that demonstrate how automated irrigation based on sensor feedback can significantly improve the precision and timing of watering (Ihuoma & Madramootoo, 2017; Jones, 2004). These findings are in line with previous research conducted by Ihuoma and Madramootoo (2017), who reported that smart irrigation systems can reduce water use by 30–50% while improving crop yields in smallholder systems.

The wireless communication between the Senor system unit and the Water Trigger component worked over a 700-meter distance using ESP-NOW protocol, validating that such low-power communication is feasible in semi-urban and peri-urban agricultural zones. Unlike some smart irrigation systems that rely on GSM or 5G (Singh et al., 2023), this design avoids subscription fees and infrastructure dependencies, making it suitable for farmers in regions with weak network coverage. Furthermore, the use of solar panels aligns with findings by Mdemu et al. (2020) and Burney et al. (2010), who advocate solar-powered irrigation as a cost-effective and sustainable solution for off-grid areas.

The mobile application interface developed using Flutter enabled farmers to monitor real-time moisture levels, water usage, GPS coordinates, and irrigation status. The mobile-first approach addresses digital inclusion, especially as smartphone penetration increases in Africa (GSMA, 2023). Farmers surveyed expressed a desire for mobile connectivity, and similar findings were reported by Tazhina and Parker (2020), who highlighted that user-friendly interfaces are essential for technology acceptance among smallholders.

The limitations relate to user training and digital literacy. Although the app was designed to be intuitive, farmers unfamiliar with digital tools may require initial support. This reinforces the recommendations of Karamage et al. (2017), who stress that technological interventions must be accompanied by capacity-building programs to ensure adoption and long-term sustainability.

In conclusion, this study demonstrates that a well-designed, context-aware smart irrigation system can substantially reduce water waste and improve agricultural productivity in urban and peri-urban Burkina Faso. The system's performance in experimental tests, alignment with the literature, and positive reception by local stakeholders highlight its potential for wider deployment. As climate change continues to threaten food and water security in West Africa, such technologies offer a pathway toward sustainable, climate-resilient agriculture.

Conclusion

This chapter showed that most farmers still use manual watering methods, which waste a lot of water. Few farmers use modern systems, and those who do still rely on visual checks. The smart irrigation system we developed can solve these problems by automating watering based on soil moisture and helping farmers monitor their fields easily. The experimental tests proved the system works well and can help save water and improve crop production. Further tests in real farms will confirm its full benefits.

GENERAL CONCLUSION AND PERSPECTIVE

This study makes an important contribution by addressing the challenge of inefficient water use in vegetable crop irrigation in Ouagadougou.

First, the irrigation techniques currently used in the area have clear deficiencies in their implementation. Our survey showed that traditional methods, especially the use of watering cans, remain widespread. These outdated practices persist mainly due to limited access to modern technologies and a lack of awareness, causing significant water waste and reducing productivity. Even farmers who use more advanced irrigation methods like sprinklers, drip, and laser spray rely mostly on visual estimation rather than precise measurement of water needs, which leads to inefficient watering.

Second, efficient requirements were proposed to improve vegetable crop watering and reduce water waste effectively. Drawing from survey insights and a comprehensive literature review, specific technical and functional requirements were identified. These requirements include accurate soil moisture sensing, precise field localization using GPS, and a mobile application interface for real-time monitoring of soil conditions and water usage.

Finally, a smart irrigation system was developed and implemented based on these requirements to reduce gardening water waste while improving vegetable crop irrigation. The system integrates a soil moisture sensor, a GPS module, and a Flutter-developed mobile app to enable automated, need-based irrigation. By analyzing soil moisture levels before activating watering, the system aligns irrigation with the actual needs of crops like tomatoes and onions. The GPS module ensures accurate field mapping, and the mobile app provides users with easy access to real-time data on soil moisture and water consumption.

Overall, the results demonstrate that the proposed smart irrigation system offers a practical, scalable, and sustainable solution for urban agriculture in Ouagadougou. By reducing water waste and enabling informed decision-making, this work supports improved water management and contributes to the broader goals of sustainable agriculture and resource optimization in the region

In order to improve the system, further work can be done, such as:

- Experimentation with the smart irrigation system in real conditions
- Use of GSM techniques to send the data (on when the irrigation starts and how it stops) to the farmer to help him monitor the system
- Use of DHT22 sensor to embed with the system to give more precision on humidity, as well as an idea about the temperature
- Use of technology Lora for long-distance transmission instead of ESP-NOW communication.
- Print a PCB
- Use of a Solar panel to power the smart Agric system (reading soil moisture sensor)

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Annex:

Survey on Smart Irrigation System for Reducing Water Waste and Improving Vegetable Crop in Ouagadougou

Understanding Current Irrigation Practices

This section aims to understand the current irrigation methods used for vegetable crops in Ouagadougou, as well as to identify the challenges faced with existing systems.

1. What type of irrigation system do we currently use in Ouagadougou for vegetable crops?

- [ ] Drip irrigation
- [ ] Sprinkler irrigation
- [ ] Manual watering (details)
- [ ] Other (please specify): ___________

2. How often do you water your vegetable crop?

- [ ] Daily
- [ ] Every two days
- [ ] Weekly
- [ ] Other (please specify): ___________

3. How much water (approximately) do you use for gardening each time you water?

- [ ] Less than 10 liters
- [ ] 10-30 liters
- [ ] 30-50 liters
- [ ] More than 50 liters
- [ ] Non quantifiable

4. Do you face any challenges with the current irrigation system in your garden(equipment)?

- [ ] Yes
- [ ] No
- If yes, please specify: ___________

5. How do you assess if your plants are getting enough water?

- [ ] By soil moisture
- [ ] By plant appearance
- [ ] By a specific tool/instrument (please specify): ___________
- [ ] I do not have a specific method

6. Are you aware of water wastage during irrigation?

- [ ] Yes
- [ ] No
- [ ] Not sure

Assessing Efficiency Requirements for Smart Irrigation

This section assesses the importance of water conservation and the potential features of a smart irrigation system.

1. Would you be interested in using a smart irrigation system that automatically adjusts watering based on soil moisture?

- [ ] Yes
- [ ] No
- [ ] Maybe

2. What features would you find most useful in a smart irrigation system? (Select all that apply)

- [ ] Automatic scheduling based on soil moisture
- [ ] Integration with weather forecasts
- [ ] Mobile app control
- [ ] Remote monitoring of water usage
- [ ] Alerts for water usage efficiency
- [ ] Energy-saving mode

3. What is the maximum amount you would be willing to spend on a smart irrigation system for your garden?

- [ ] Less than 20,000 CFA
- [ ] 20,000 - 50,000 CFA
- [ ] 50,000 - 100,000 CFA
- [ ] More than 100,000 CFA

- Over

4. What type of connectivity would you prefer for controlling your smart irrigation system?

- [ ] Mobile app (via internet)
- [ ] Bluetooth control
- [ ] GSM Protocol

5. What are the key factors that would encourage you to adopt a smart irrigation system? (Select all that apply)

- [ ] Cost savings on water
- [ ] Ease of use
- [ ] Better plant health and growth
- [ ] Environmental impact
- [ ] Saving time

User Feedback For Developing a Smart Irrigation System

This section focuses on collecting feedback regarding the design and usability of the proposed smart irrigation system.

1. Would you find it helpful if the system could detect soil moisture levels and adjust watering automatically?

- [ ] Yes
- [ ] No
- [ ] Maybe

2. Would you prefer the system to send notifications when it's time to water the garden or when there's a potential issue?

- [ ] Yes
- [ ] No
- [ ] Maybe

3. How much time are you willing to spend learning how to use a new irrigation system?

- [ ] Less than 1 hour
- [ ] 1-2 hours
- [ ] More than 2 hours

4. Would you like the option to set different watering schedules for different plants in your vegetable crops?

- [ ] Yes
- [ ] No
- [ ] Maybe

5. Do you think a smart irrigation system could help improve the quality and growth of your vegetable crops?

- [ ] Yes
- [ ] No
- [ ] Maybe

6. What additional features or improvements would you suggest for a smart irrigation system in your area?

- ___________
- ___________

Code source development

```cpp
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <TinyGPS++.h>
#include <esp_now.h>
#include <WiFi.h>

// Définir les broches
#define RXD2 16
#define TXD2 17
#define BUZZER_PIN 5
#define SOIL_SENSOR_PIN 32
#define MENU_BUTTON 15
#define NEXT_BUTTON 13
#define SELECT_BUTTON 14
#define RED_LED_PIN 25
#define GREEN_LED_PIN 26

#define GPS_BAUD 9600

// Structure à envoyer
typedef struct struct_message {
  float soil_humidity;
  float latitude;
  float longitude;
  int selecteOption; // 1: tomate, 2: oignon
} struct_message;

struct_message myData;
esp_now_peer_info_t peerInfo;
uint8_t receiverMacAddress[] = {0x08, 0xA6, 0xF7, 0xA1, 0xDE, 0xA0};

// Initialisations
TinyGPSPlus gps;
HardwareSerial gpsSerial(2);
LiquidCrystal_I2C lcd(0x27, 16, 2);

// Variables
float soil_percent = 0;
int selectedOption = 0;
bool alreadyBipped = false;
bool dataSent = false; // Nouvelle variable pour suivre l'état de l'envoi des données

// Seuils d'humidité
const float TOMATO_MIN = 60.0, TOMATO_MAX = 80.0;
const float ONION_MIN = 60.0, ONION_MAX = 70.0;

// Bip de notification
void bipTroisFois() {
  for (int i = 0; i < 3; i++) {
    digitalWrite(BUZZER_PIN, HIGH);
    delay(200);
    digitalWrite(BUZZER_PIN, LOW);
    delay(200);
  }
}

// Callback d'envoi
void OnDataSent(const uint8_t *mac_addr, esp_now_send_status_t status) {
  if (status == ESP_NOW_SEND_SUCCESS) {
    Serial.println("Données envoyées avec succès");
    if (!dataSent) {
      bipTroisFois(); // Biper trois fois une seule fois
      dataSent = true; // Marquer que les données ont été envoyées
    }
  } else {
    Serial.println("Échec d'envoi");
  }
}

void setup() {
  Serial.begin(115200);
  WiFi.mode(WIFI_STA);

  if (esp_now_init() != ESP_OK) {
    Serial.println("Erreur d'initialisation ESP-NOW");
    return;
  }

  esp_now_register_send_cb(OnDataSent);

  memcpy(peerInfo.peer_addr, receiverMacAddress, 6);
  peerInfo.channel = 0;
  peerInfo.encrypt = false;

  if (esp_now_add_peer(&peerInfo) != ESP_OK) {
    Serial.println("Erreur ajout peer");
    return;
  }

  gpsSerial.begin(GPS_BAUD, SERIAL_8N1, RXD2, TXD2);
  lcd.init();
  lcd.backlight();

  pinMode(BUZZER_PIN, OUTPUT);
  pinMode(MENU_BUTTON, INPUT);
  pinMode(NEXT_BUTTON, INPUT);
  pinMode(SELECT_BUTTON, INPUT);
  pinMode(RED_LED_PIN, OUTPUT);
  pinMode(GREEN_LED_PIN, OUTPUT);
}
```

```
void loop() {
  int soilValue = analogRead(SOIL_SENSOR_PIN);
  soil_percent = 100 - (soilValue * 100.0 / 3723);
  if (soil_percent < 0) soil_percent = 0;

  while (gpsSerial.available() > 0) {
    gps.encode(gpsSerial.read());
  }

  float latitude = gps.location.isValid() ? gps.location.lat() : 0.0;
  float longitude = gps.location.isValid() ? gps.location.lng() : 0.0;

  if (digitalRead(MENU_BUTTON) == LOW) {
    displayMenu();
    return;
  }

  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Soil Hdty: ");
  lcd.print(soil_percent, 0);
  lcd.print("%");

  lcd.setCursor(0, 1);
  lcd.print("Lat:");
  lcd.print(latitude, 1);
  lcd.print(",Ln:");
  lcd.print(longitude, 1);

  // Envoi des données
  myData.soil_humidity = soil_percent;
  myData.latitude = latitude;
  myData.longitude = longitude;
  myData.selecteOption = selectedOption;
  esp_now_send(receiverMacAddress, (uint8_t *) &myData,
sizeof(myData));
  // Après l'envoi, désactiver tous les autres bips
  if (dataSent) {
    // Ne pas faire de bip supplémentaire une fois les données envoyées
    alreadyBipped = true;
  }

  if (selectedOption == 1) {
    handleWatering(TOMATO_MIN, TOMATO_MAX);
  } else if (selectedOption == 2) {
    handleWatering(ONION_MIN, ONION_MAX);
  }

  delay(1000);
}

void displayMenu() {
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("1. Tomato");
  lcd.setCursor(0, 1);
  lcd.print("2. Onion");

  while (true) {
    if (digitalRead(NEXT_BUTTON) == LOW) {
      selectedOption = (selectedOption == 1) ? 2 : 1;
      lcd.clear();
      lcd.setCursor(0, 0);
      lcd.print("1. Tomato");
      lcd.setCursor(0, 1);
      lcd.print("2. Onion");
      lcd.setCursor(0, selectedOption - 1);
      lcd.print(">");
      digitalWrite(BUZZER_PIN, LOW);
      delay(150);
      digitalWrite(BUZZER_PIN, LOW);
      delay(300);
    }

    if (digitalRead(SELECT_BUTTON) == LOW) {
      confirmSelection();
      return;
    }
  }
}

void confirmSelection() {
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Selected: ");
  lcd.print(selectedOption == 1 ? "Tomato" : "Onion");
  digitalWrite(BUZZER_PIN, HIGH);
  delay(300);
  digitalWrite(BUZZER_PIN, LOW);
  delay(300);
}

void handleWatering(float minThreshold, float maxThreshold) {
  if (soil_percent < minThreshold && !alreadyBipped) {
    digitalWrite(RED_LED_PIN, HIGH);
    digitalWrite(GREEN_LED_PIN, LOW);
    digitalWrite(BUZZER_PIN, HIGH);
    delay(100);
    digitalWrite(BUZZER_PIN, LOW);
  } else if (soil_percent > maxThreshold) {
    digitalWrite(RED_LED_PIN, LOW);
    digitalWrite(GREEN_LED_PIN, HIGH);
    digitalWrite(BUZZER_PIN, HIGH);
    delay(100);
    digitalWrite(BUZZER_PIN, LOW);
  } else {
    digitalWrite(RED_LED_PIN, LOW);
    digitalWrite(GREEN_LED_PIN, LOW);
  }
}

// ✅ TA fonction ajoutée à la fin :
void resetToMenu() {
  selectedOption = 0;
}
```