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THESIS TITLE

INTELLIGENT SYSTEM FOR MONITORING ENVIRONMENTAL CONDITIONS IN GREENHOUSES

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Dedications

By the grace of Allah, the Most Merciful, the Most Compassionate, whose infinite wisdom guided me through every challenge and inspired this work.

To my beloved family, whose prayers and sacrifices were my steadfast support, and to my mentors, whose knowledge illuminated my path.

May this research serve as a humble contribution to humanity, reflecting the divine balance between technology and nature.

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Finally, I acknowledge all those who contributed directly or indirectly to this work. Your kindness and inspiration have left an indelible mark on this journey.

Abstract:

Greenhouse agriculture is essential for addressing global food security and adapting to shifting climatic conditions. However, traditional methods of environmental monitoring often struggle to balance precision and responsiveness, leading to suboptimal crop growth and resource inefficiencies. This thesis proposes an Smart IoT-based system designed to revolutionize greenhouse management through real-time monitoring and remote control of critical environmental parameters.

The system employs a layered IoT architecture that merges edge computing for immediate decision-making with platforms for holistic oversight. By continuously tracking variables such as air temperature, humidity, soil moisture, and light intensity, the framework dynamically adjusts irrigation, ventilation, and lighting systems to maintain ideal growing conditions. A centralized dashboard provides farmers with intuitive access to real-time data, enabling proactive adjustments and reducing reliance on manual interventions.

Focusing on precision and adaptability, the design emphasizes seamless integration of sensor networks. While the theoretical framework prioritizes universal applicability, its modular structure allows customization for diverse crops and regional challenges, such as water scarcity or extreme weather patterns. Future extensions could incorporate predictive modeling to anticipate environmental shifts, further enhancing resilience.

This work underscores the transformative potential of IoT in modern agriculture, offering a pathway to sustainable practices, reduced resource waste, and enhanced crop yields. By bridging technological innovation with ecological stewardship, the system contributes to a future where greenhouses operate as self-regulating ecosystems, advancing food security while mitigating environmental strain.

Key words: Environmental monitoring, greenhouse, climate control, sensors, actuators, embedded systems, automation, alerts, sustainable agriculture, IoT.

Résumé :

L'agriculture sous serre est essentielle pour répondre aux enjeux de sécurité alimentaire mondiale et s'adapter aux conditions climatiques changeantes. Cependant, les méthodes traditionnelles de surveillance environnementale peinent souvent à concilier précision et réactivité, conduisant à une croissance sous-optimale des cultures et à des inefficacités dans l'utilisation des ressources. Cette thèse propose un système intelligent basé sur l'IoT conçu pour révolutionner la gestion des serres grâce au suivi en temps réel et au contrôle à distance des paramètres environnementaux critiques.

Le système utilise une architecture IoT en couches qui combine l'informatique en périphérie pour la prise de décision immédiate avec des plateformes pour une supervision globale. En suivant continuellement des variables telles que la température de l'air, l'humidité, l'humidité du sol et l'intensité lumineuse, le cadre ajuste dynamiquement les systèmes d'irrigation, de ventilation et d'éclairage pour maintenir des conditions de croissance idéales. Un tableau de bord centralisé fournit aux agriculteurs un accès intuitif aux données en temps réel, permettant des ajustements proactifs et réduisant la dépendance aux interventions manuelles.

En mettant l'accent sur la précision et l'adaptabilité, la conception privilégie une intégration transparente des réseaux de capteurs. Bien que le cadre théorique priorise une applicabilité universelle, sa structure modulaire permet une personnalisation pour diverses cultures et défis régionaux, tels que la pénurie d'eau ou les conditions météorologiques extrêmes. Des extensions futures pourraient incorporer une modélisation prédictive pour anticiper les changements environnementaux, renforçant ainsi la résilience.

Ce travail souligne le potentiel transformateur de l'IoT dans l'agriculture moderne, offrant une voie vers des pratiques durables, une réduction du gaspillage des ressources et des rendements agricoles améliorés. En combinant innovation technologique et gestion écologique, le système contribue à un avenir où les serres fonctionnent comme des écosystèmes autorégulés, améliorant la sécurité alimentaire tout en atténuant les pressions environnementales.

Mots clés : Surveillance environnementale, serre, contrôle climatique, capteurs, actionneurs, systèmes embarqués, alertes, agriculture durable, IoT.

ملخص:

تُعد الزراعة في البيوت المحمية أمرًا بالغ الأهمية لمواجهة تحديات الأمن الغذائي العالمي والتكيف مع الظروف المناخية المتغيرة. ومع ذلك، غالبًا ما تعجز أساليب الرصد البيئي التقليدية عن تحقيق التوازن بين الدقة والاستجابة، مما يؤدي إلى نمو غير مثالي للمحاصيل وعدم كفاءة في استخدام الموارد. تقترح هذه الأطروحة نظامًا قائمًا على إنترنت الأشياء، مُصممًا لإحداث ثورة في إدارة البيوت المحمية من خلال المراقبة الآنية والتحكم عن بُعد في المعايير البيئية المهمة .

يستخدم النظام بنية إنترنت الأشياء متعددة الطبقات، تجمع بين الحوسبة الطرفية لاتخاذ القرارات الفورية ومنصات المراقبة الشاملة. من خلال المراقبة المستمرة لمتغيرات مثل درجة حرارة الهواء والرطوبة ورطوبة التربة وشدة الضوء، يُعدّل الإطار أنظمة الري والتهوية والإضاءة ديناميكيًا للحفاظ على ظروف نمو مثالية. تُتيح لوحة معلومات مركزية للمزارعين وصولاً سهلاً إلى البيانات في الوقت الفعلي، مما يُمكّنهم من إجراء تعديلات استباقية وتقليل الاعتماد على التدخل اليدوي.

مع التركيز على الدقة والقدرة على التكيف، يُعطي التصميم الأولوية للتكامل السلس لشبكات الاستشعار. وبينما يُولي الإطار النظري الأولوية للتطبيق الشامل، فإن هيكله المعياري يسمح بالتخصيص ليناسب مختلف المحاصيل والتحديات الإقليمية، مثل ندرة المياه أو الظروف الجوية القاسية. ويمكن أن تتضمن التوسعات المستقبلية نمذجة تنبؤية لتوقع التغيرات البيئية، مما يعزز المرونة.

يُسلّط هذا العمل الضوء على الإمكانات التحويلية لإنترنت الأشياء في الزراعة الحديثة، مُمهّدًا الطريق نحو ممارسات مستدامة، وتقليل هدر الموارد، وتحسين إنتاجية المحاصيل. ومن خلال الجمع بين الابتكار التكنولوجي والإدارة البيئية، يُسهم النظام في بناء مستقبل تعمل فيه الدفيئات الزراعية كنظم بيئية ذاتية التنظيم، مما يُحسّن الأمن الغذائي ويُخفّف الضغوط البيئية.

الكلمات المفتاحية: مراقبة البيئة، البيوت الزجاجية، التحكم في المناخ، أجهزة الاستشعار، المحركات، الأنظمة المضمنة، التنبيهات، الزراعة المستدامة، إنترنت الأشياء.

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List of acronyms

Acronym	Meaning
IOT	Internet Of Things
AEC-Q101	Automotive Electronics Council Qualification Standard
CO	Carbon Dioxide
DHT11	Digital Humidity & Temperature Sensor
DS18B20	Digital Temperature Sensor
FR4	Flame Retardant 4
GFSK	Gaussian Frequency-Shift Keying
HASL	Hot Air Solder Leveling
ISM	Industrial, Scientific, Medical Band
L/H	Liters Per Hour
MQ-135	Air Quality Sensor)
NTC	Negative Temperature Coefficient
PG13.5	Thread Connection Standard
PPM	Parts Per Million
Pt100	Platinum Resistance Thermometer (100)
RH	Relative Humidity
SMD	Surface-Mount Device
TEMT6000	Ambient Light Phototransistor
YF-S201	Water Flow Sensor Model
NRF24L01	2.4GHz Wireless Transceiver Module
API	Application Programming Interface
CSS	Cascading Style Sheets
HTML	HyperText Markup Language
HTTP	HyperText Transfer Protocol
IDE	Integrated Development Environment
REST	Representational State Transfer
SPI	Serial Peripheral Interface
TCP	Transmission Control Protocol
W3C	World Wide Web Consortium
ARM	Advanced RISC Machine Architecture
PCB	Printed Circuit Board
SoC	System on Chip
VS Code	Visual Studio Code

General introduction

Modern agriculture stands at the forefront of global challenges, tasked with feeding a growing population while adapting to climate change and resource scarcity. Greenhouses, as controlled environments, play a pivotal role in this mission, enabling year-round crop production and mitigating the impacts of erratic weather. In regions like Algeria, where arid climates and water shortages threaten traditional farming, greenhouses offer a lifeline for food security and economic stability. However, managing these environments remains fraught with inefficiencies. Traditional methods rely heavily on manual monitoring of temperature, humidity, soil moisture, and light practices that are labor-intensive, error-prone, and incapable of responding dynamically to sudden environmental shifts. These limitations hinder productivity, escalate resource waste, and jeopardize crop yields, underscoring the urgent need for smarter, adaptive solutions.

The Internet of Things (IoT) emerges as a transformative force in this context. By integrating sensors, microcontrollers, and real-time data analytics, IoT enables precise, remote control of greenhouse conditions. Such systems empower farmers to optimize water use, regulate climate parameters, and preemptively address risks—revolutionizing how we grow food in a resource-constrained world. For Algeria, where agriculture consumes over 60% of freshwater resources and climate variability intensifies, IoT-driven greenhouses could unlock sustainable farming practices, reduce waste, and bolster resilience against environmental stressors.

This thesis addresses these challenges by proposing an IoT-based system designed to monitor and manage greenhouse environments in real time. The system leverages cutting-edge technologies, including sensors and actuators, to create a self-regulating ecosystem. By embedding intelligence at every layer, from data collection to user interaction, the project aims to democratize precision agriculture, making it accessible even for small-scale farmers.

This work is structured as follows :

– Chapter 1 : State of the Art examines advancements in modern agriculture, focusing on IoT-enabled greenhouse technologies, hydroponics, and automation trends. It critiques traditional practices and highlights innovations in environmental control systems.

– Chapter 2 :IoT-Based System Architecture details the design of an IoT-based system architecture for smart greenhouses,reviewing related work on IoT applications in greenhouse environments, and a proposed system architecture.

– Chapter 3: Implementation and Results explores the selection of hardware (Arduino, Raspberry Pi) and software (Thonny, Docker) tools and presents the deployment of a functional prototype, testing outcomes, and the development of a web-based dashboard for real-time monitoring.

Chapter 1
State of the Art

1.1 Introduction

The world's population is fast becoming so large, and the challenges related to agriculture, henceforth, will become more complex, requiring more efficient and sustainable production methods to meet food requirements. The advances in digital technologies, especially the Internet of Things (IoT) and embedded systems, open up tremendous possibilities for modernizing traditional agricultural practices. Smart agriculture, powered by advanced technology, should have promising solutions for improving resource management efficiency, increasing yields, and mitigating environmental impacts.

In this respect, intelligent greenhouses are becoming one of the pillars of modern agriculture. They allow accurate control of environmental parameters such as temperature, humidity, and light, ensuring optimal conditions for the growth of crops while minimizing the necessary inputs. Nevertheless, the development and deployment of such systems necessitate a deep comprehension of the technologies and the difficulties they present.

1.2 Modern agriculture

The concept of modern agriculture is well understood by many farmers, even if it's not always easy to define precisely. While most farming systems today don't fall completely into either the "modern" or "traditional" category, the differences between them still have a major impact on how agriculture is evolving worldwide.

In traditional farming systems, farmers focus on using the natural resources available to them as efficiently as possible. They rely on what the land, rainfall, seeds, and simple tools can provide. Their work follows a familiar cycle: prepare the soil, plant the seeds, protect the crops from pests and weeds, and finally, harvest. The success of these systems depends largely on natural soil fertility and climate conditions, meaning that productivity tends to grow slowly over time. Traditional farming often lacks access to modern tools and technologies, limiting its ability to scale or respond to changing conditions.

What really sets traditional and modern farming apart is how farmers see their role. In modern systems, farmers see themselves not just as workers of the land but as active managers of complex, technology-driven processes. They are open to adopting innovations, using data, and making informed decisions to optimize every part of their operation. This shift in mindset from working with nature to controlling and enhancing it is central to the transformation of agriculture.

Modern agriculture benefits from access to advanced technologies, scientific knowledge, better infrastructure, investment, market connections, and supportive government policies. These systems use machines, fertilizers, pesticides, and smart management techniques to increase yields, reduce labor, and improve overall profitability. It represents a step forward in the long history of farming, where science and mechanization have gradually taken the place of purely manual and traditional practices [40].

According to Encyclopedia Universalis, modern agriculture even marks a "mental mutation" a fundamental change in how farming is approached. It emphasizes productivity and competitiveness, often leading to the specialization of certain functions to meet the demands of national and international markets [34].

1.3 Modern agriculture in Greenhouses

1.3.1 Vertical farming

Vertical farming is among the most cutting-edge forms of contemporary agriculture made possible by agritech. Crops are cultivated in this technique in stacked layers, frequently under controlled conditions. In urban settings where land is scarce, this technology-driven farming approach is very helpful [49].

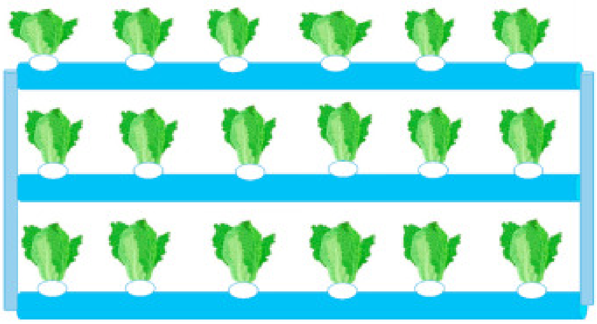


Figure 1.1: *Vertical Farming system [36].*

1.3.2 Hydroponics

The hydroponics farming technique requires no soil at all and consumes less soil. The procedure calls for using nutrients, such as a water solution rich in minerals, to develop robust plants without the usage of solid media. A subset of hydroculture is hydroponic farming, and the nutrients used in these systems are sourced from various sources. Using nutrients, such as a mineral-rich water solution, to grow robust plants without the use of solid media.[35]. Furthermore, we find different types of hydroponics systems such as:

- Wick System
- Deep Water Culture (DWC)
- Ebb and flow system (flood and drain)
- NFT (Nutrient Film Technique)

Figure 1.2: *Hydroponics cultivation of lettuce under shadenet [37].*

1.3.3 Aquaponics

A closed-loop system, aquaponics primarily depends on the mutually beneficial link between aquaculture and agriculture for fertilization. This agricultural technique blends hydroponics with traditional aquaculture [35].

1.3.4 Aeroponics

Growing plants without soil or a base component is known as aeroponics, which is a subset of hydroponics. This technique eliminates the need for soil or substrate by allowing the plant

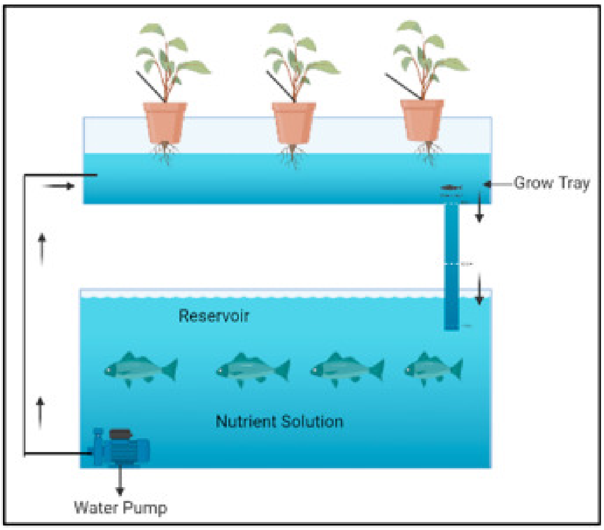


Figure 1.3: *Aquaponic system [36].*

to grow in the air with artificial support. Plant roots are suspended in the open, exposed to the atmosphere, and given atomized nutrients and water in this air and water culture growth process [36].

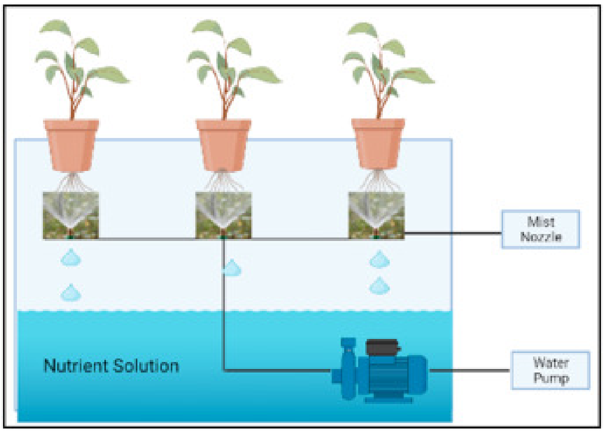


Figure 1.4: *Aeroponics system[36].*

1.4 Smart greenhouse

A smart greenhouse is a modern farming setup designed to take care of plants automatically. It uses sensors, control systems, and devices like pumps and fans to create the best possible environment for plant growth [4]. By constantly keeping an eye on certain environmental conditions such as temperature, humidity, light, and CO levels, the system can automatically handle tasks such as watering, air circulation, and lighting—helping plants thrive with minimal human intervention.

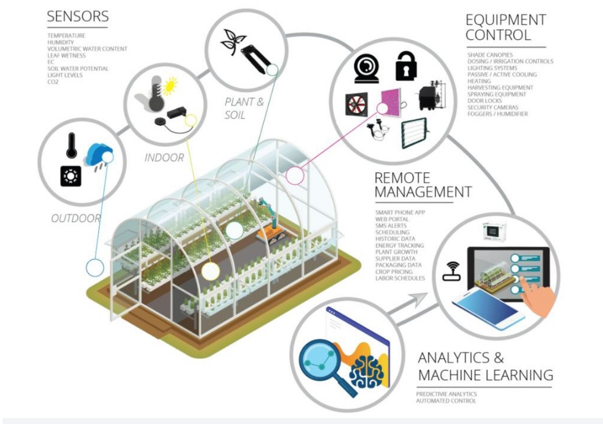


Figure 1.5: *Smart greenhouse | Sustainable Food System Innovation Platform [5]*

Integrating automation technologies into your greenhouse is essential to effectively controlling the indoor environment and increasing the profitability of your business. With an automated greenhouse, you will get:

- Savings on labor costs
- Maintaining an optimal growing environment
- Control fungal diseases by maintaining the crop in conditions of low relative humidity
- Control of plant physiological processes
- Increase in production and quality of crops
- Data recording which makes it possible to verify the effects of climate on the crop by adjusting the parameters
- Greenhouse management by telematic communication
- Alarm system that warns in the event of controller malfunction

1.4.1 Environmental conditions

The key environmental factors in a greenhouse include temperature, humidity, light, and CO levels, all of which significantly influence plant growth and crop quality. A stable microclimate is produced by these measures, permitting production all year round without risks from weather or pests. Here's a brief overview of these critical conditions:

1.4.1.1 Light control

Light is the most important factor for photosynthesis. During cloudy periods or shorter daylight hours, full-spectrum LED lamps can supplement natural light to meet the specific needs of the crops.

Artificial lighting must be included in order to improve the lighting. extending the amount of time spent in light during the brief winter days or in overcast areas by using electrical lamps, such as sodium vapor or LED bulbs.

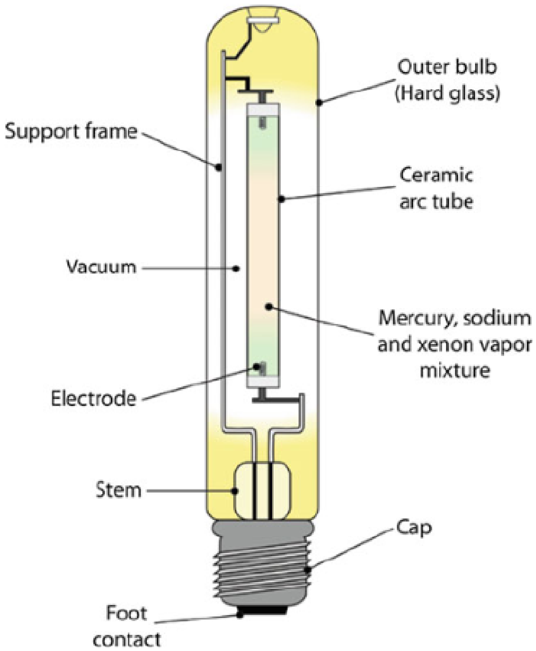


Figure 1.6: *Structure of a high-pressure sodium vapor lamp [24]*

Use of Direct Solar Reflectors: This is aimed at redirecting natural sunlight for maximum utilization especially on urban gardens or spaces where there is not direct access to sunlight.

However, to reduce the lighting, there is a need to use one of the following techniques:

- Shading Screens: It is an internal or external arrangement of shade netting under which plants are protected from direct sunlight and at the same time protected from sun burn.
- Motorized Curtains: installation of curtains that could either automatically drawn or closured as conditioned by the weather and light.

1.4.1.2 Carbon dioxide control

Elevated CO_2 concentrations can enhance photosynthesis and increase yields. However, levels must be carefully managed, as excessively high CO_2 can have adverse effects. For CO_2 enrichment, technicians use CO_2 generators (See Figure 1-7). These devices burn propane or natural gas to produce CO_2 which is then released into the greenhouse.

Figure 1.7: *Carbon dioxide generator manufactured by Johnson Gas Appliance Company (Iowa). The generator operates with either propane or natural gas and has pressure gauge to control the size of burner [18]*

Another technique is called Dry ice method [33]. It consists of adding CO2 in solid form which sublimates directly into gas to enrich the air.

Centralized distribution systems are used to distribute CO2 over the greenhouse in a homogeneous way through a network of perforated pipes or fans for uniform distribution.

1.4.1.3 Air humidity control

Proper humidity levels are crucial, as excessive moisture can promote diseases, while insufficient humidity may cause water stress. Humidifiers or dehumidifiers are often used to maintain optimal humidity. To reduce excessive humidity, technicians use natural and fan-induced ventilation (See Figure 1-8). It enables dissipating humid air out of the building at higher external temperature levels that may be appropriate to prevent heat stress on the plants from the incoming outside air.

a) Ridge and side vents for natural ventilation. (Courtesy: HZP, West Bengal, India)

b) Fan induced ventilation system. (Courtesy: HZP, West Bengal, India)

Figure 1.8: *A greenhouse having provision for natural and fan induced ventilation [23].*

Dehumidifiers, on the other hand, remove surplus moisture from the air by condensing it. In cold climates when ventilation is not an option, such devices are very helpful in maintaining consistent humidity levels.

Four main techniques are used to manage humidity:

- Heating the air: Quite hot air utilizes a great deal of humidity and then venting to purge oil from the air.

- Mist: Use misting systems that release a fine spray of water into the air. This not only adds humidity but also helps cool down the environment, creating a more comfortable and suitable atmosphere for plant growth.

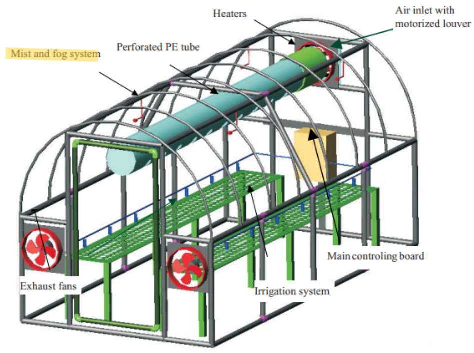


Figure 1.9: *The constructed Quonset greenhouse to carry out experiments [31].*

- Soil irrigation: High evaporative processes can be created in the ambient environment by moistening the earth surface so that some water will naturally evaporate into the air.
- Desert Coolers: This system is capable of increasing the ambient moisture through evaporative cooling, where water accumulates in the atmosphere and increases humidity through cooling.

1.4.1.4 Temperature Control

Temperature plays a vital role in optimizing photosynthesis and preventing thermal stress. Each crop has an ideal temperature range, and maintaining it within narrow limits is essential for maximum growth. This can be achieved using heating systems or fans for cooling.

For cooling, technicians use a sample method called natural cooling. It is based on the use of windows or vents to allow hot air to escape and new cool air in. Another technique is called evaporative cooling. It consists of passing the air through wet pads while fans suck in this air into the greenhouse. Water evaporating would absorb heat, thereby lowering the temperature.

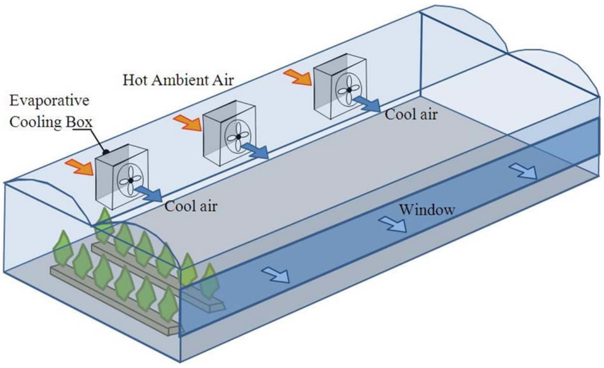


Figure 1.10: *Evaporative cooling boxes in greenhouse [22].*

Shade screens are another key cooling method. Awnings or curtains that cut off part of sunlight are installed to minimize the heat trapped in the greenhouse. These screens can be retracted for precision control.

However, the inverse paradigm to cooling, which is heating, includes the use of electric systems. Electric radiators are controlled by thermostats to maintain the minimum temperature at cold times.

Gas heating remains another key heating technique using gas as fuel, for the distribution of heat throughout the greenhouse. This type of heating is effective for large installations.

Another method used is heat pumps that transfer heat from external sources into the greenhouse. Air-source heat pumps extract warmth from the outside air, while ground-source (geothermal) heat pumps utilize underground temperatures. Both types are energy-efficient and can provide both heating and cooling as needed.

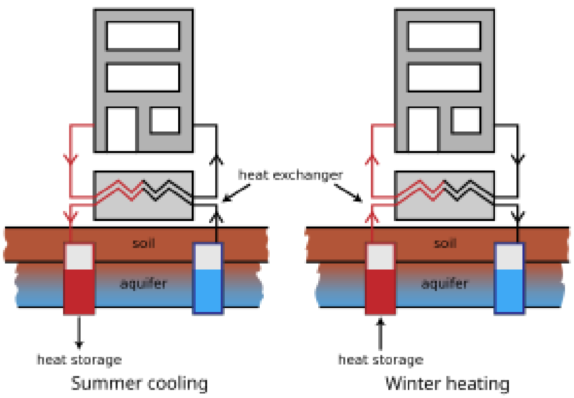


Figure 1.11: *A heat pump in combination with heat and cold storage [2].*

The last heating technique is under-floor heating systems. It is done by heating the roots of the plants by pipes underground, thus, reducing the need for air heating.

It should be noticed that an effective ventilation system helps regulate both of humidity and temperature while ensuring adequate oxygen supply for the plants [20].

1.4.2 Environmental Management Systems in Greenhouses

A range of systems is integrated into greenhouses to help create and maintain suitable conditions for plant growth. The following subsections describe some of the main systems commonly found.

1.4.2.1 Irrigation systems

Irrigation is essential in agriculture to ensure an efficient water supply. Methods vary depending on the terrain, crop needs, and water availability. Surface irrigation, the oldest method, relies on gravity to distribute water across fields. Mechanized pivot systems provide controlled circular distribution, while sprinkler irrigation disperses water under pressure, simulating rainfall. Drip irrigation, whether surface or subsurface, maximizes efficiency by delivering water directly to the roots, minimizing losses. Furrow irrigation, suited for row crops, channels water between plant rows to optimize usage.

1.4.2.2 Ventilation systems

Good ventilation in greenhouses is required to control temperature, refresh air, and prevent humidity from reaching a level at which plant diseases may occur. Two principal ventilation systems are in common use : natural ventilation, where air flows into ports on the roof and sides to create air movement, and forced ventilation, which is designed to create constant airflow irrespective of external conditions, using electric fans.

1.4.2.3 Heating systems

Greenhouse heating is important to protect plants in cold climates, or on cool nights. There is a heat solution for everyone from a basic gas or fuel-powered hot air blower to a hot water pipe system running under benches or around walls. Renewable heating solutions in the form of biomass boilers and heat pumps are becoming more widely used to limit environmental damage.

1.4.2.4 Shading and lighting systems

Plants have different needs for light according to their stage of growth and the season of the year. Shading systems comprising shutters or fixed nets can also control unwanted light and overheating in the summer. In contrast, artificial lighting, such as energy-efficient LED lamps, may be used to complement the natural sunlight, to lengthen the daylight hours in the winter and to stimulate photosynthesis.

1.4.2.5 Systems for climate control and automation

Digital world Because of digital technology, many greenhouses are equipped with sensors, and are automated. Those appliances will be always monitoring temperature, humidity, light, and CO concentration. They can automatically initiate actions like opening vents, turning on irrigation, or controlling lights to condition grow spaces and prevent the need for manual involvement.

1.5 Conclusion

This first chapter provided an in-depth overview of modern agricultural practices, with a focus on innovations in greenhouse cultivation. We first presented the characteristics of modern agriculture, highlighting its evolution toward more sustainable and technological methods. We then explored the various greenhouse cultivation techniques, such as vertical farming, hydroponics, aquaponics, and aeroponics, which optimize space and resources while reducing environmental impact.

Finally, we analyzed the concept of the smart greenhouse, detailing the importance of controlling environmental conditions (temperature, humidity, light, etc.) and the various automated control systems. These technological advances significantly improve the productivity and energy efficiency of agricultural greenhouses.

Chapter 2

Internet of Things for Smart Greenhouses

2.1 Introduction

The evolution of information and communication technologies has profoundly transformed the traditional computing landscape. Today, computer systems are no longer limited to internet-connected computers but incorporate a multitude of embedded and intelligent devices. This convergence between computing and electronics has given rise to a revolutionary concept: the Internet of Things (IoT). This paradigm embodies the idea of ubiquitous computing, where information processing is directly integrated into everyday objects, enabling seamless interaction between the physical and digital worlds.

The Internet of Things represents a crucial technological infrastructure that bridges the gap between simple sensors, which provide raw and sometimes imperfect data, and high-level applications offering sophisticated and personalized services. Objects gain intelligence through this connectedness, enabling them to gather, process, and send data instantly.

This paradigm is revolutionizing digital agriculture. IoT devices are employed to track soil moisture, weather patterns, crop development, and livestock activity. This real-time information enables farmers to make faster, data-driven decisions, significantly enhancing the efficiency of farming operations.

2.2 Internet of Things (IoT)

Internet of Things and connected objects are terms that may seem vague. It is difficult to determine when an object becomes "connected" and when the era of the Internet of Things truly begins. To clarify these two concepts, it is essential to start by defining what a connected object is.

A formal definition is given in [48] as: "The Internet of Things is an extension of the current Internet to all objects that can communicate directly or indirectly with electronic devices that are themselves connected to the Internet. This new dimension of the Internet brings with it significant technological, economic, societal, and governance challenges."

Conceptual definition is presented in [8] as: "The emergence of new objects identities.According to some definitions, the Internet of Things consists of objects with virtual identities and personalities, operating in smart spaces and using intelligent interfaces to connect and communicate within diverse usage contexts. Others speculate that the Internet of Things is a revolution because it makes it possible for anybody, anywhere, at any time, to connect people and things."

For technical definition, it is given as follows [8]: "Technically, IoT is an extension of the internet naming system and reflects a convergence of digital identifiers in the sense that it is possible to uniformly identify digital information elements (e.g., URLs of websites) and physical elements (e.g., a pallet in a warehouse or a sheep in a flock)."

The fundamental characteristics of the IoT are as follows [32]:

- **Interconnectivity**: With regard to the IoT, anything can be interconnected with the global information and communication infrastructure.
- **Things-related services**: The IoT is capable of providing thing-related services within the constraints of things.
- **Heterogeneity**: The devices in the IoT are heterogeneous as based on different hardware platforms and networks.
- **Dynamic changes**: The state of devices change dynamically.
- **Enormous scale**: The number of devices that need to be managed will be at least an order of magnitude larger than current Internet.
- **Safety**: We must design for safety including the safety of our personal data and physical well-being.
- **Connectivity**: Enables network accessibility and compatibility.

2.3 Architecture of an IoT system

The architecture of the Internet of Things (IoT) is made up of several layers, each representing a different set of technologies that work together to support IoT systems. These layered models highlight the modular, scalable, and adaptable nature of IoT deployments across various use cases. Depending on the complexity and goals of the application, different architectural models can be used. For instance, the basic three-layer model includes perception, network, and application layers, while more advanced models like the five-layer version introduce additional layers for data processing (middleware) and business logic. There are also approaches based on service-oriented architecture (SOA) and fog computing, which bring computing resources closer to the data source. Each model is designed to meet specific needs and offers unique benefits depending on the context of the application.

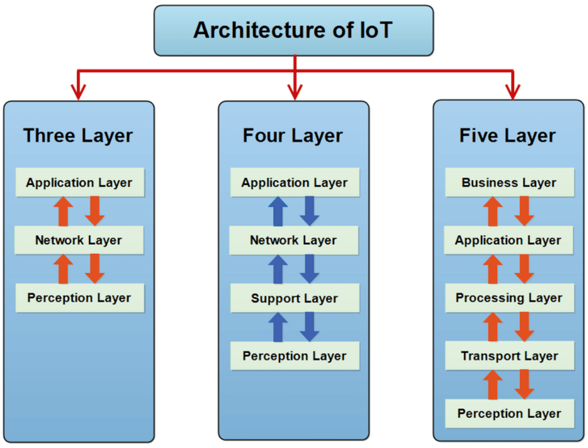


Figure 2.1: *The-layered-architectures-of-IoT-three-four-and-five-layers [15].*

Now, let's describe in detail the 5-layer IoT architecture model as illustrated in the following figure:

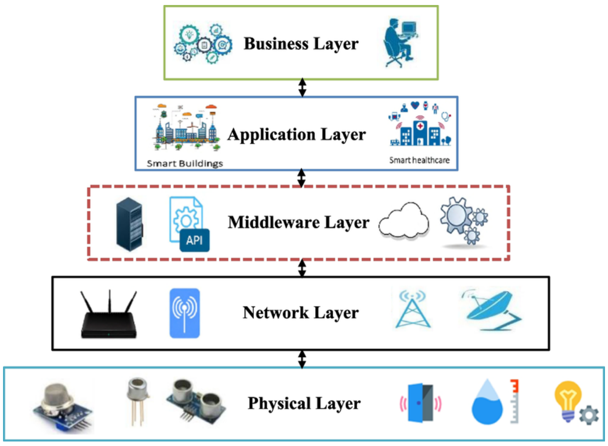


Figure 2.2: *Five-layer-architecture-of-IoT [12].*

Physical/Perception layer

This layer contains the sensors, actuators, and edge devices that are used to sense, collect information, and interact with the desired environment.

Network/Transport/Connectivity layer

This layer is responsible for transferring the collected sensor data to the processing layer and vice versa through networks such as local area networks (LAN) and wide area networks (WAN) using wired or wireless technologies such as WiFi (wireless fidelity), Ethernet, Bluetooth, near field communications (NFC), Zig-Bee, cellular networks, and low-power wide-area network (LPWAN).

Middleware/Processing layer

Data accumulation and abstraction are the two main stages in this layer. The layer is used to capture, store, analyse and process massive amounts of data coming from the network layer. Moreover, it can be used to manage and provide different services to the other lower layers. Many techniques such as database, cloud computing, and big data processing modules can be employed in this layer. The middleware layer should enable cooperation between heterogeneous IoT devices and provide interoperability and scalability. In addition, the function of this layer is to provide security and privacy to IoT devices.

Application Layer

This layer is responsible for delivering specific services demanded by the users, such as temperature, humidity light intensity, air pressure measurements. The application layer also offers data services such as big data storage, data warehousing, data mining, etc. for sematic data analysis. Smart building, smart healthcare, intelligent transportation system, and smart cities are examples of applications with smart user interfaces at the application layer.

Business layer

This layer manages the whole IoT system by providing business models, graphs, and flowcharts for the processed data received from the application layer. In addition, this layer supports automatic decision making and the development of intelligent business strategies, based on big data analysis.

2.4 Related Work of IoT in Greenhouses

Here, we highlight several IoT initiatives that have been developed for smart greenhouse systems. These projects include:

In this project, the authors developed a small-scale smart greenhouse system that integrates Fuzzy Logic control and IoT technology to address challenges in food production caused by population growth, climate change, and urbanization. They designed an innovative greenhouse structure using plexiglass for safety and light optimization, equipped with sensors (e.g., DHT22 for temperature/humidity, Waveshare for soil moisture, LDRs for luminosity) and actuators (e.g., fans, pumps, LED strips, servo-controlled windows) to monitor and regulate environmental conditions. A Fuzzy Logic-based control system was implemented to autonomously adjust parameters like temperature, humidity, and light, ensuring optimal plant growth. The system also featured IoT capabilities via the Arduino Cloud, enabling remote monitoring and control through a mobile app. The authors demonstrated the system's effectiveness in maintaining stable microclimates and highlighted its potential for sustainability and scalability in urban agriculture. Future work includes energy optimization and machine learning integration for advanced monitoring [44].

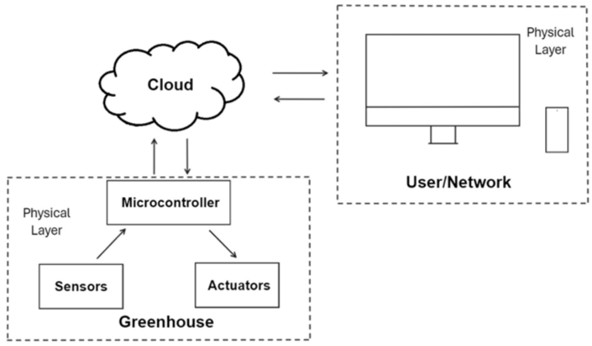


Figure 2.3: *IoT scheme [44].*

Here we have another project where researchers at the University of Doha for Science and Technology designed a Smart Sustainable Greenhouse Concept Model (SSGHCM) in Qatar to tackle food security challenges in the hot, arid GCC region. They built a small-scale greenhouse (4m x 2.5m) powered by solar panels (4.3 kW capacity) and equipped with IoT-enabled sensors (soil moisture, temperature, humidity, light) and actuators (ventilation fans, irrigation pumps, air conditioning). The system used two control methods: a LabVIEW-based wired setup and a wireless IoT platform (Blynk) for remote monitoring via smartphones. To optimize resources, the greenhouse recycled condensate water from AC units (covering 65% of irrigation needs) and employed precision irrigation, reducing water use by 40% compared to traditional methods. An economic analysis revealed the system's profitability, especially for high-value crops like strawberries, with a 340% return on investment and a 5-year payback period when scaled to commercial size. The project demonstrated how renewable energy, IoT automation, and water recycling could transform greenhouse farming in extreme climates, aligning with Qatar's national food security goals [11].

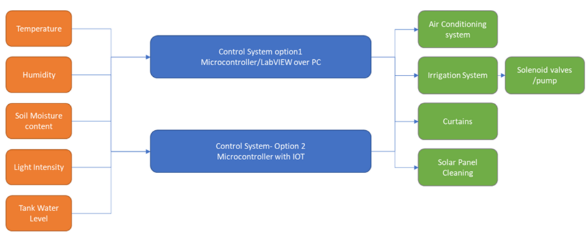


Figure 2.4: *Schematic Diagram of the control system, input and output parameters used in this control system [11].*

In this study, an IoT-enhanced hydroponic system has been developed for Chinese celery cultivation, comparing four greenhouse setups with varying levels of environmental control. The fully automated system, combining temperature regulation via misting and extended LED lighting, increased yield by 13.91% compared to natural conditions, producing 30.3 kg versus 26.6 kg. Statistical analysis confirmed significant growth differences emerging around 25 days after planting. While the controlled system delivered the highest annual net profit ($750.18), the natural setup showed better short-term returns with a 131% ROI and a 9-month payback period. The research demonstrates that temperature control has a greater impact than light extension alone on celery growth, providing practical insights for smart farming adoption. The authors recommend further studies on long-term performance and scalability across different crops and climates [43].

In another study, the authors explore the implementation of an IoT-based system to monitor and manage greenhouse environments efficiently. The research evaluates different IoT communication protocols, ultimately selecting MQTT for its lightweight design, reliability, and ability to support real-time data transmission with minimal resource usage. The proposed system focuses on tracking key environmental factors such as temperature, humidity, and gas concentrations to ensure optimal growing conditions. By leveraging a publish-subscribe model, the system enables seamless data exchange between sensors and centralized control, allowing for the instant detection of anomalies and timely corrective actions [39].

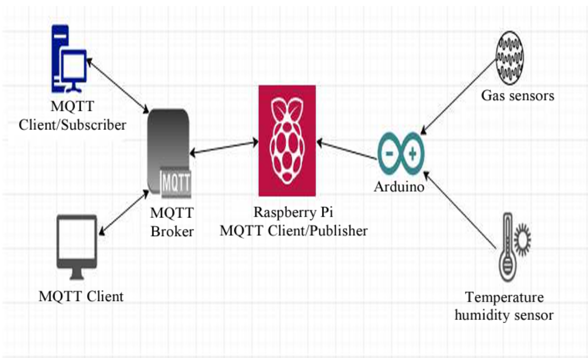


Figure 2.5: *Proposed Architecture for IOT Based GHMS [39]*

In this research, the authors examine the implementation of IoT and automation solutions for precision agriculture, particularly within greenhouse settings. The work demonstrates how smart technologies facilitate continuous tracking and adjustment of environmental variables—including temperature, humidity, and soil conditions to maximize crop yields and resource efficiency. The analysis underscores the potential of affordable sensor networks and wireless communication protocols (e.g., Wi-Fi, ZigBee) to streamline data collection and system control. By leveraging microcontroller platforms, the study illustrates practical applications in automated irrigation, climate management, and pest detection, highlighting reduced labor dependency and improved operational precision [14].

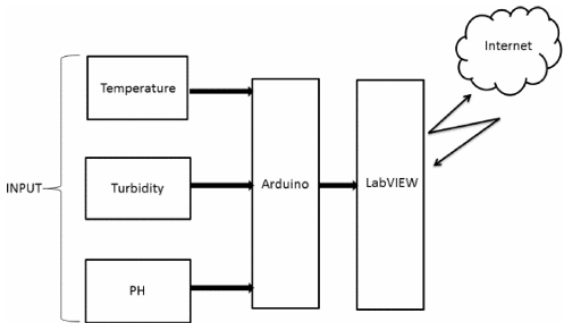


Figure 2.6: *Water Quality Monitoring Architecture [14]*

This study presents an IoT-based automated greenhouse monitoring system using Raspberry Pi 3, YL69 soil moisture sensors, and DHT11 temperature/humidity sensors to dynamically control irrigation, cooling fans, and ventilation windows based on real-time crop requirements. The system transmits data to the ThingSpeak cloud for remote monitoring via a web interface, demonstrating effective climate regulation for spinach cultivation by maintaining optimal thresholds (26.5°C temperature-humidity index, 40% soil moisture). Results show fully automated adjustments with near-zero latency, offering a scalable, energy-efficient solution that reduces manual labor while addressing calibration and cost challenges in precision agriculture [17].

Researchers from Abant İzzet Baysal University and Ege University developed an IoT-based greenhouse monitoring system using wireless MicaZ sensor nodes to track temperature, humidity, light, and pressure. The system transmits real-time data via 802.15.4 wireless networks to a central base station, where MoteView software visualizes conditions for remote access via web/mobile interfaces. Tested in a Turkish greenhouse, the prototype demonstrated reliable 36-hour operation with flexible node placement, enabling farmers to optimize crop environments while reducing cabling costs. The team plans future upgrades to integrate actuator control for full automation [10].

2.5 Proposed system architecture

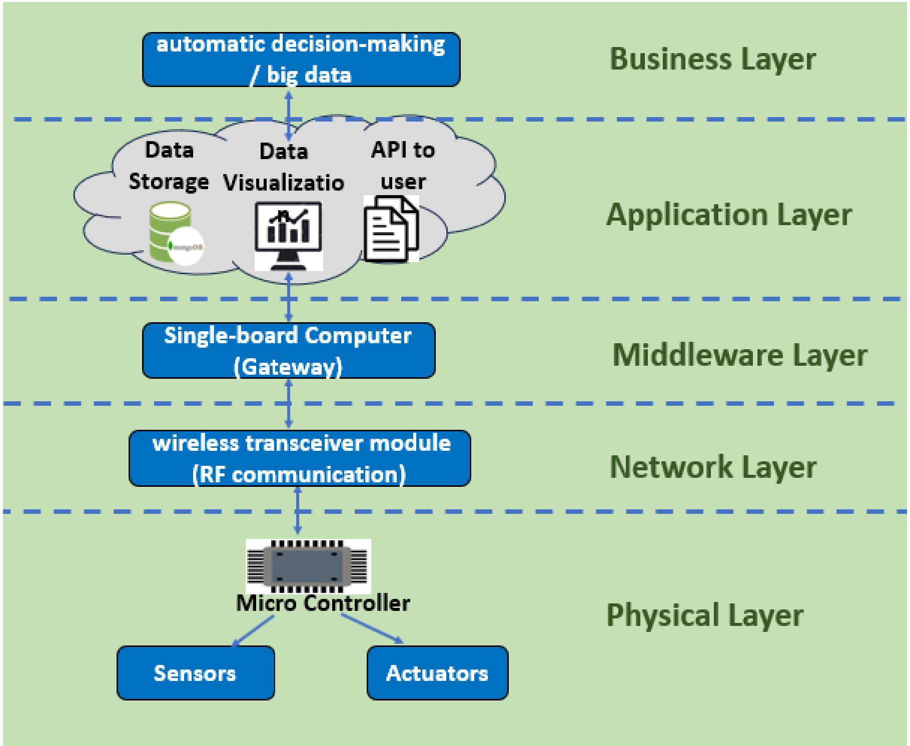


Figure 2.7: *Proposed architecture*

2.5.1 Explanation of the Architecture

In our smart greenhouse prototype, we have adopted a five-layer IoT architecture to efficiently manage environmental parameters while automating necessary interventions. This structured model ensures smooth communication between different system components, allowing for optimized monitoring and control of the greenhouse.

- Everything begins with the perception layer, which is responsible for data acquisition. At this level, various sensors continuously measure environmental conditions, collecting essential data on temperature, humidity, gas levels, light intensity, and soil moisture. This raw data is then transmitted to the next stage for processing and structuring.

- The network layer facilitates reliable and fast transmission of data to the system's central unit. Wireless communication modules ensure seamless connectivity between the data acquisition units and the processing infrastructure, allowing real-time updates on greenhouse conditions.

– Once the data is received, the middleware layer handles its initial analysis and organization. The collected information is structured and made compatible with the data management system. At this stage, all incoming data is processed by a real-time context manager, which ensures the flow of information in real time, while a database stores historical records to track changes in greenhouse conditions over time.

– The application layer allows users to access the processed information. A web application queries the database and the context manager in real time to display greenhouse parameters via interactive dashboards and graphs. If critical thresholds are exceeded, alerts are sent to notify the user.

– Finally, the business layer defines overall business logic and automation strategies. It enables intelligent scenario modeling based on the analysis of historical data and trends (e.g., prioritizing certain greenhouses, optimizing irrigation). This layer supports strategic decision-making, generates reports, and can automatically adjust control policies based on defined business objectives.

2.6 Conclusion

In this chapter, we explored the IoT-based system architecture designed for our smart greenhouse prototype. We began by introducing the Internet of Things (IoT) and its significance in automating environmental monitoring and control. We then detailed the five-layer IoT architecture, explaining the role of each layer in ensuring efficient data collection, transmission, processing, service delivery, and user interaction. Additionally, we reviewed existing IoT-based greenhouse systems, analyzing different approaches and highlighting their strengths and limitations. Finally, we presented our proposed system architecture, demonstrating how it integrates IoT components to enhance automation, real-time monitoring, and resource efficiency. This structured approach provides a solid foundation for the intelligent management of greenhouse environments, ensuring optimal growing conditions while minimizing human intervention.

Chapter 3
System Implementation

3.1 Introduction

In this chapter, we will first present the objective of our work, the principle of the proposed solution, and the overall system architecture. Then, we will detail the hardware tools, the software environments used for system development, and the various execution platforms for the different components.

3.2 Objective of the System to be Implemented

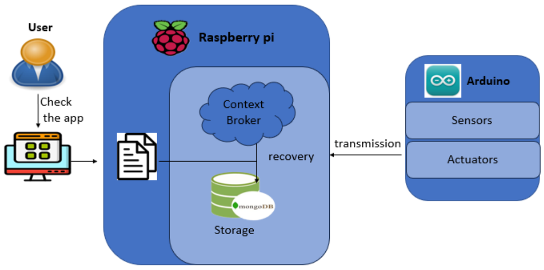


Figure 3.1: *Sytem architecture*

Our project aims to design an autonomous automation system for an agricultural greenhouse. To achieve this, it is essential to consider several key parameters. Our system will monitor and control these parameters and will be capable of triggering necessary actions based on the needs of the greenhouse.

The user will be able to specify, via a web application, the type of crops being cultivated, the required climatic conditions, and the thresholds that should not be exceeded for each parameter. The system will integrate this information to ensure optimal control of the greenhouse. Additionally, the user will be able to track the evolution of these parameters in real time through graphs generated by the application.

The parameters measured and analyzed as part of this project include:

- Air temperature
- Air humidity
- Soil moisture

- Light intensity
- CO_2 levels
- Water temperature
- Water pH
- Water flow rate
- Water level

Based on these data, our system will provide the following services:

- Plant watering and irrigation management
- Ventilation management
- Reservoir management
- Lighting management

3.3 UML Diagrams Overview

3.3.1 Sequence Diagram

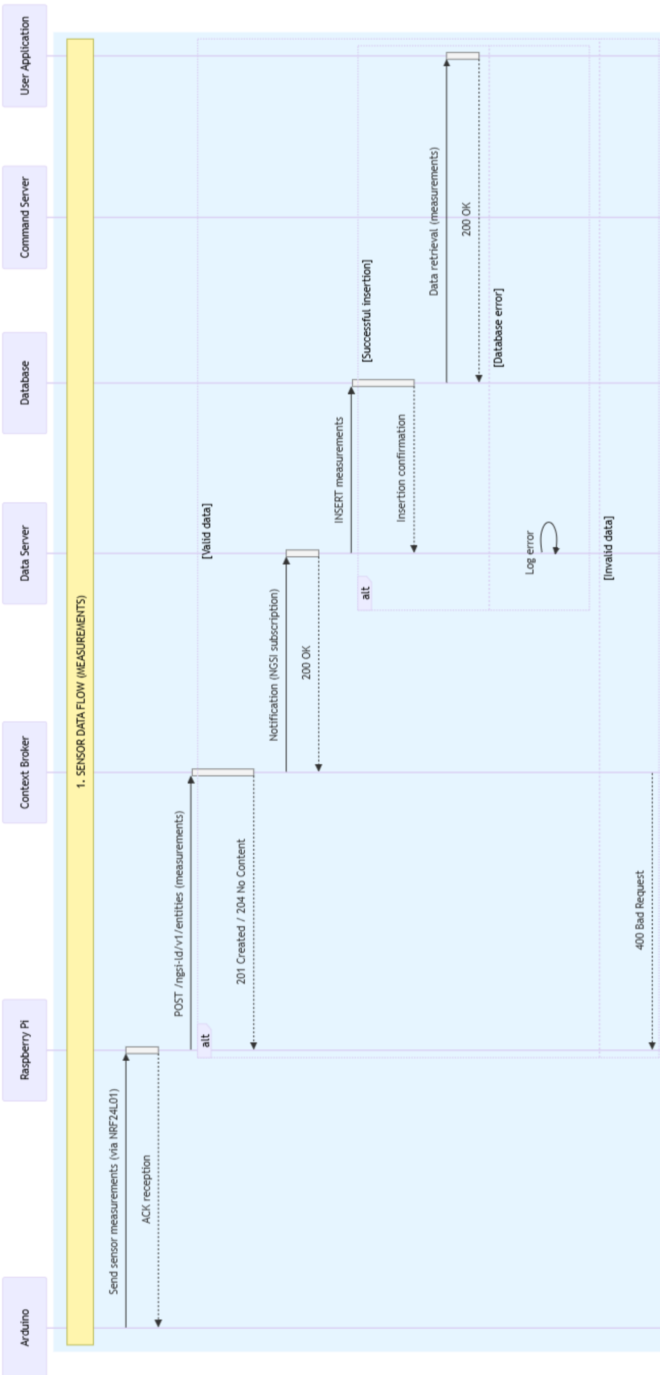


Figure 3.2: *System Sequence Diagram — Part 1*

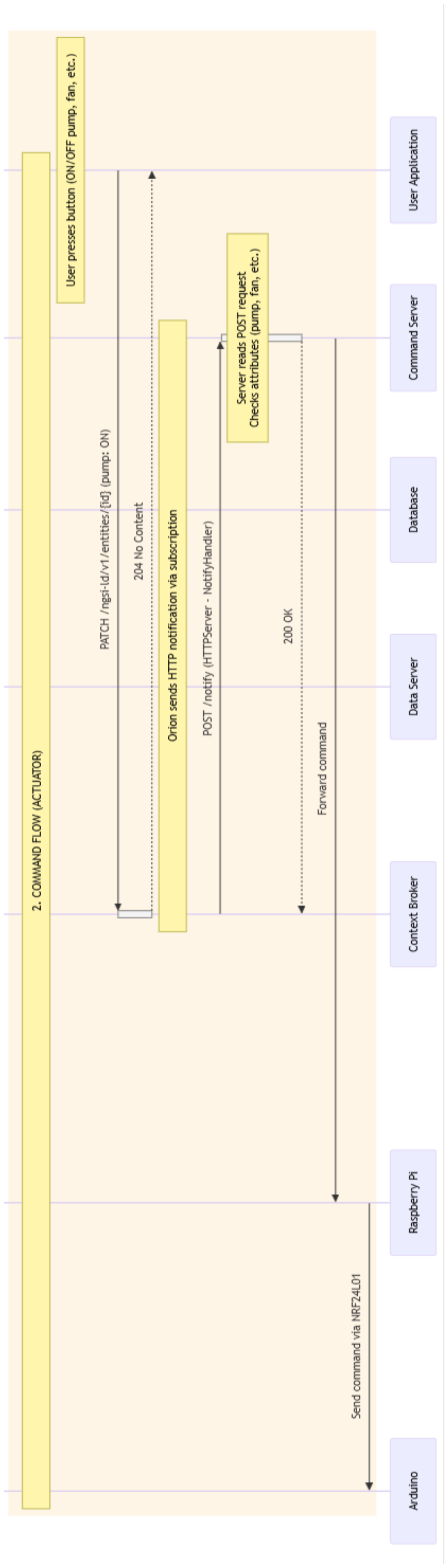


Figure 3.3: *System Sequence Diagram — Part 2*

This sequence diagram illustrates how an IoT system works in two parts: receiving sensor data and sending commands to actuators. First, the Arduino measures data (such as temperature or humidity) and sends it to the Raspberry Pi via the NRF24L01 radio module. The Raspberry Pi then transmits this data to the Context Broker (CB), which validates it and redirects it to the Data Server using a subscription system. The Data Server stores the measurements in a database, which can then be accessed by the user application. Then, when a user interacts with the application (for example, to turn on a pump), a command is sent to the Context Broker. This forwards it to the Command Server, which analyzes the request and sends the appropriate command to the Raspberry Pi, which then relays it to the Arduino to act on the relevant actuator.

3.3.2 Class Diagram

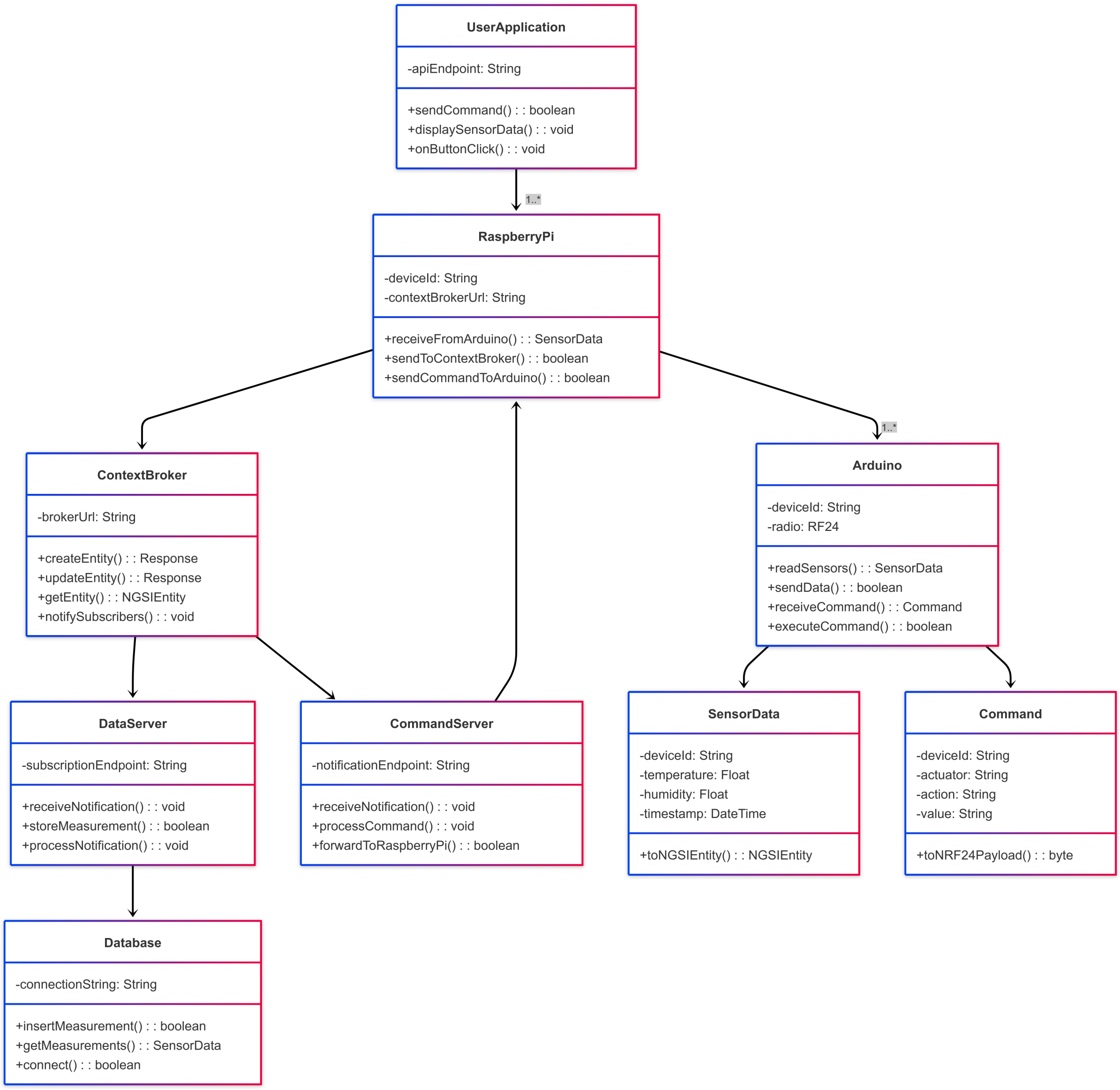


Figure 3.4: *System class diagram*

gram represents an IoT architecture where multiple Arduinos, connected to sensors and actuators, collect data and send it to the Raspberry Pi via radio communication. Each Raspberry Pi can manage multiple Arduinos, and multiple Raspberry Pis can be controlled by a single user application. The Raspberry Pi then transmits the data to the Context Broker, which centralizes the information and notifies the servers responsible for processing: the Data Server to store the measurements in a database, and the Command Server to process the commands sent by the user. The user application is used to display the sensor data and send commands to the actuators.

3.4 Tools Used

3.4.1 Boards

We used the microcontroller and single-board computer listed in the Table below: 3.1.

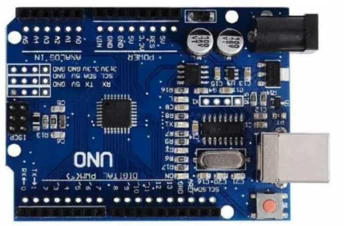
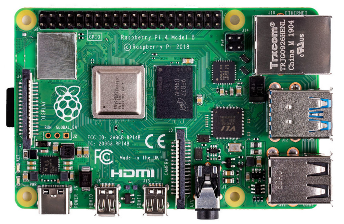
Card	Image
Arduino Uno R3	
Raspberry Pi 4	

Table 3.1: *The cards used in the System*

3.4.2 Sensors

We used the sensors listed in Table 3.3.

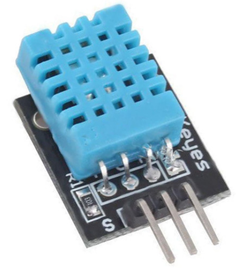
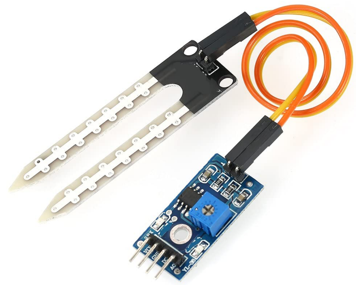
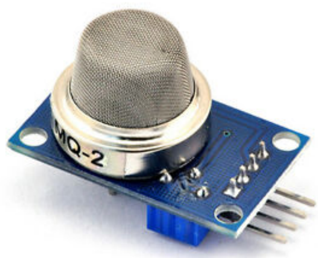
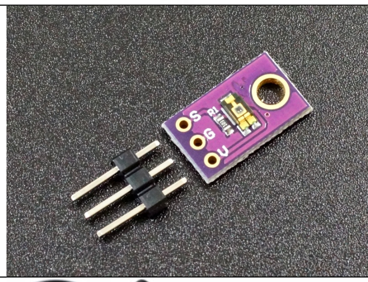
Sensor	Image
DHT11 Sensor	
Soil moisture sensor	
Gas sensor	
Light sensor	
PH meter sensor	

Table 3.2: *The sensors used in the System(Part$_1$)*

Sensor	Image
Water temperature sensor	
Water level sensor	
Water flow sensor	

Table 3.3: *The sensors used in the System (Part$_2$)*

3.4.3 Actuators

We utilized the actuators listed in Table 3.4.

Actuator	Image
Water Pump	
Fan	
SG90 Servo Motor	
Lamp	

Table 3.4: *Actuators Used in the System*

3.4.4 Other Components

Additional components include:

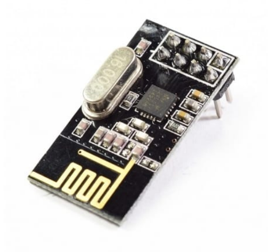
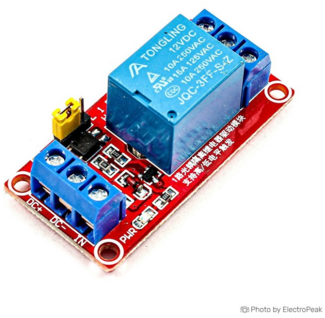
Component	Image
Module transceiver NRF24L01	
4.7 K-ohm resistor	
Relay module	
100uF 63V Electrolytic Capacitor	

Table 3.5: *Other components used in the System*

3.4.5 Development Tools Used

- Arduino IDE
- Docker
- Visual Studio Code
- Thonny

3.4.6 Programming Environment

- Windows Subsystem for Linux (Ubuntu 24.04.2 LTS)
- C/C++
- Python
- JavaScript/HTML/CSS

3.4.7 Protocol Used

- The Hypertext Transfer Protocol (HTTP)

3.5 Followed Approach

3.5.1 Description of All Tools Used

Cards

- **Arduino** [6]:
  Arduino is an open-source company specializing in hardware and software. Its community consists of developers and users who create and employ microcontroller-based boards, commonly called Arduino Modules. These modules serve as open-source platforms for prototyping and come in various configurations. Their streamlined design enables effective greenhouse monitoring and automation, enhancing agricultural efficiency.

- **Raspberry Pi 4 Model B+** [9]:
  Developed by the UK-based Raspberry Pi Foundation, this compact single-board computer aims to advance computer science education in schools. It features a Broadcom BCM2835 SoC with an ARM1176JZF-S 700 MHz CPU, VideoCore IV GPU, and initially shipped with 256MB RAM (later upgraded to 512MB in Model B/B+). The device uses SD or MicroSD cards for storage and supports Debian and Arch Linux ARM. Programming options include Python (primary), C, C++, Java, Perl, Ruby, and BBC BASIC via RISC OS or Linux emulation.

Sensors

1. **DHT11 Sensor** [41]:
   The DHT11 is a compact digital sensor that measures both humidity and temperature, providing calibrated output signals for accurate readings. It combines a resistive humidity sensor and an NTC thermistor (for temperature) with an integrated 8-bit microcontroller, ensuring fast response times, reliability, and long-term stability. Known for its affordability and precision, the DHT11 comes in a 4-pin single-row package, making it a practical choice for various environmental monitoring applications.
2. **Soil moisture sensor**[38]:
   The soil moisture sensor is an electronic device designed to measure volumetric water content in soil. It operates by detecting changes in the soil's dielectric properties, typically through resistance or capacitance measurements, which vary proportionally with moisture levels. The sensor features a simple probe-style design that can be directly inserted into soil, providing immediate readings for irrigation management and agricultural applications. This practical tool enables automated monitoring of plant hydration needs, facilitating efficient water resource management in gardening and precision agriculture systems.
   Soil Moisture Sensor Module Features and Specifications [16]:
   - Operating Voltage: 3.3V to 5V DC
   - Operating Current: 15mA

- Output Digital - 0V to 5V, Adjustable trigger level from preset
- Output Analog - 0V to 5V based on infrared radiation from fire flame falling on the sensor
- Small, cheap and easily available

3. **Gas Sensor (MQ135)**:

   The MQ-135 is a versatile air quality sensor that detects various harmful gases including NOx, ammonia (NH3), carbon dioxide (CO2), benzene, alcohol, and smoke. What makes this sensor particularly convenient is its dual output options it features both digital and analog pins. The digital output allows for simple detection (gas present/not present) without needing complex programming, while the analog output provides precise concentration measurements in parts per million (PPM).Operating at a standard 5V TTL level, the MQ-135 easily integrates with most common microcontrollers [29].

   General Specifications:

   - Detectable Gases: NOx, NH (Ammonia), CO (Carbon Dioxide), Benzene, Alcohol, Smoke
   - Operating Voltage: 5V DC
   - Current Consumption: 150mA
   - Output Type:
     - ◇ Analog Output (for measuring gas concentration in PPM)
     - ◇ Digital Output (for threshold-based gas detection)

4. **Light sensor (TEMT6000)** [47]:

   The TEMT6000 is a compact ambient light sensor that mimics how the human eye perceives light. Packaged in a tiny 1206 surface-mount design, this NPN silicon phototransistor is most responsive to visible light, with peak sensitivity at 570 nm similar to daylight vision. Its small size and accurate light detection make it ideal for automatic brightness control in displays, smart lighting systems, and other applications where natural light measurement matters.

   Features:

- Package type: surface mount
- Package form: 1206
- Dimensions (L x W x H in mm): 4 x 2 x 1.05
- AEC-Q101 qualified
- High photo sensitivity
- Adapted to human eye responsivity
- Angle of half sensitivity: j = ± 60°
- Floor life: 168 h, MSL 3, acc. J-STD-020
- Lead (Pb)-free reflow soldering
- Compliant to RoHS Directive 2002/95/EC and in accordance to WEEE 2002/96/EC

5. **PH meter sensor** :

   A pH meter sensor is a device used to measure the acidity or alkalinity of a solution, expressed as pH on a scale from 0 to 14.

   Technical parameters [42]:

   - Measure range: 0-14pH
   - Temperature range: 0-130℃
   - Temperature compensation: Pt100/Pt1000/NTC10K
   - Pressure resistant: 0   6 Bar at 0   100℃; 10 Bar at 25 ℃
   - Electrode interface: S8, VP, K2, etc. Zero potential point: 7 ± 0.5 pH
   - Membrane resistance: <50, 250
   - Practical response time: < 1 min
   - Salt bridge: OPEN salt bridge without liquid junction
   - Thread Connection: PG13.5

6. **Water temperature sensor (DS18B20)** :

   The DS18B20 is a digital water temperature sensor that measures temperature in liquids, such as water, with high accuracy. It uses a 1-Wire communication protocol, which allows multiple sensors to be connected to a single microcontroller pin, simplifying wiring.

   Benefits and Features [28]:

- Reduce Component Count with Integrated Temperature Sensor and EEPROM
  - ◇ Measures Temperatures from -55°C to +125°C (-67°F to +257°F)
  - ◇ ±0.5°C Accuracy from -10°C to +85°C
  - ◇ Programmable Resolution from 9 Bits to 12 Bits
  - ◇ No External Components Required
- Parasitic Power Mode Requires Only 2 Pins for Operation (DQ and GND)
  - ◇ Each Device Has a Unique 64-Bit Serial Code Stored in On-Board ROM
- Simplifies Distributed Temperature-Sensing Applications with Multidrop Capability

7. **Water level sensor** :

   This device detects and measures how much liquid is in a tank, container, or reservoir. It works by sensing the water height and converting it into an electrical signal that microcontrollers can understand and process. Perfect for applications like aquarium monitoring, water tanks, or flood detection systems, these sensors help automate liquid level tracking with precision.

   The specification parameters [26]:

   - Operating voltage: DC 5V
   - Working current: less than 20mA
   - Sensor Type: Analog
   - detection area: 40mm x16mm
   - Production process: FR4 double-sided HASL
   - mounting hole size: 3.0mm
   - user-friendly design: half-moon -slip handle depression
   - working temperature: 10℃ - 30 ℃
   - Weight: 3g
   - Product Dimensions : 65mm x 20mm x 8mm

8. **Water flow sensor (YF-S201)** :

   The water flow sensor primarily consists of a plastic valve body, a water flow rotor assembly, and a Hall sensor. It is typically installed at the water inlet of a water heater to measure the flow rate of water. As water flows through the rotor assembly, the magnetic rotor spins, and its speed varies with changes in the flow rate. The Hall sensor detects this rotation and generates a corresponding pulse signal, which is then sent to the controller. Based on this signal, the controller determines the water flow rate and adjusts it accordingly.

Parameters [21]:

- Operating voltage range: DC 5 to 18 V
- Load capacity: 10 mA (DC 5V)
- Operating temperature range: 80 ° C
- Use humidity range of: 35
- allows pressure: or less1.75Mpa pressure
- Accuracy (flow rate-pulse output): 1 30 L / min±Within5
- Output pulse duty cycle: 50 ± 10
- Flow rate-pulse characteristic: level test pulse frequency (Hz) = [7.5 Q] ± 3

Actuators

1. **Water pump** :

   Water pumps are the workhorses of liquid movement, using mechanical energy (typically from an electric motor) to generate pressure and transport water where it's needed. Their true potential shines in automation projects for example, pairing a DC pump with a DS18B20 waterproof temperature sensor lets you monitor and adjust water conditions dynamically, while a 5V 1-channel relay module enables seamless microcontroller control (think Arduino or Raspberry Pi). This synergy of components unlocks precise, hands-off management for applications like smart irrigation, aquaponics, or even homebrew cooling systems. [46].

   Specifications:

Parameter	Value
Operating voltage	2.5 – 6 V
Operating current	130 – 220 mA
Flow rate	80 – 120 L/h
Maximum lift	40 – 110 cm
Outlet outside diameter	7.5 mm
Outlet inside diameter	5 mm
Noise level	40 dB
Cable length	1 meter
Dimensions	45 × 24 × 30 mm
Weight	30 g

Table 3.6: *Technical specifications of the water pump [46]*

2. **Sg90 servo motor** [45]:

   This mini servo packs impressive power into a tiny package. It moves just like its full-sized cousins smoothly sweeping through about 180 degrees of motion (90° left and right). Perfect when you need big performance in small spaces for robotics, RC models, or animatronics!

   Specifications:

Parameter	Value
Weight	9 g
Dimensions	22.2 × 11.8 × 31 mm (approx.)
Stall torque	1.8 kgf·cm
Operating speed	0.1 s / 60°
Operating voltage	4.8 V (5V)
Dead band width	10 µs
Rotational range	180°
Pulse cycle	20 ms
Pulse width	500–2400 µs

Table 3.7: *Technical specifications of the SG90 servo motor [45]*

3. **Fan**:

   Fans ensure forced ventilation in the greenhouse, helping to regulate climatic parameters such as temperature, humidity, and CO levels, keeping them close to the predefined setpoints. To create our prototype, we used a PC power supply fan and controlled it by a relay.

4. **Lamp**:

   We used a 220V neon lamp, which was controlled by a relay, to provide lighting inside the greenhouse. This setup allowed us to efficiently manage the illumination, ensuring that the plants received adequate light while maintaining control over the electrical system. The relay acted as a switch, enabling us to turn the lamp on and off as needed, making the system both functional and energy-efficient.

Other components

1. **nRF24L01**:

   The nRF24L01 is a compact 2.4GHz wireless transceiver designed for low-power use. It includes a built-in protocol engine called Enhanced ShockBurst™, which helps manage data transmission efficiently making it ideal for battery-powered wireless communication.

Features of the nRF24L01 include :

Category	**Specifications**
Radio	Worldwide 2.4GHz ISM band operation 126 RF channels Common RX and TX interface GFSK modulation: 250kbps, 1 and 2Mbps 1MHz spacing at 1Mbps, 2MHz at 2Mbps
Transmitter	Programmable output power: 0, -6, -12, -18dBm 11.3mA at 0dBm output
Receiver	Fast AGC for improved dynamic range Integrated channel filters 13.5mA at 2Mbps -82dBm at 2Mbps -85dBm at 1Mbps -94dBm at 250kbps
Host Interface	4-pin hardware SPI Max 10Mbps Three 32-byte TX/RX FIFOs 5V tolerant inputs

Table 3.8: *Features of the nRF24L01 Module [30]*

2. **Relay module**:

   A relay module is an electromechanical switch that allows a low-power control signal to manage a higher-power electrical circuit. It works using a coil, a movable arm, and contacts that open or close the circuit. In our project, we used three relays to control three main actuators: the fan, the water pump, and the lamp.

3. **100uF 63V Electrolytic Capacitor**:

   This type of capacitor is commonly used in electronics to store and release electrical energy when needed. It's made up of two foil plates (anode and cathode) separated by an insulating layer and filled with an electrolyte to improve performance. In our prototype, we connected this capacitor to the NRF24L01 module to help stabilize its power supply and ensure reliable communication.

3.5.2 Development Tools Used

Arduino ide

Figure 3.5: *Arduino IDE 2.3.3*

The Arduino Integrated Development Environment (IDE) is a user-friendly platform designed for programming Arduino microcontroller boards. It facilitates the writing, compiling, and uploading of code, primarily in C and C++ languages, enabling users to create interactive electronic projects. The IDE serves as a bridge between the user and the hardware, simplifying the development process for both beginners and advanced users.

In our developed project a sketch Arduino reads sensors data and transmits it via wireless communication to a Python script running on Thonny. Concurrently, it receives actuator control commands (e.g., relay triggers) from the same script, enabling real-time bidirectional interaction.

Thonny

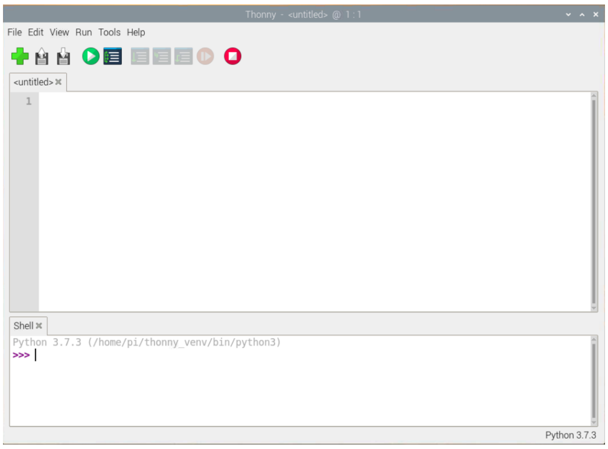


Figure 3.6: *Thonny Editor*

Thonny is a Python Integrated Development Environment (IDE) specifically designed for learning and teaching programming. It is tailored to make program visualization a natural part of the workflow for beginners, offering features such as step-by-step code execution, expression evaluation, and intuitive visualization of the call stack. Thonny also includes a mode for explaining references and heap concepts, making it an effective tool for educational purposes. It is free to use and open for extension, making it a versatile choice for both students and educators[13].

In our developed prototype a python script executed in Thonny served as a critical middleware component. It performed two core functions: (1) receiving raw sensor measurements from the Arduino, preprocessing them, and publishing to a broker for distributed access, and (2) acting as a lightweight server to receive external commands (from a web dashboard) and relay them back to the Arduino.

Docker Desktop

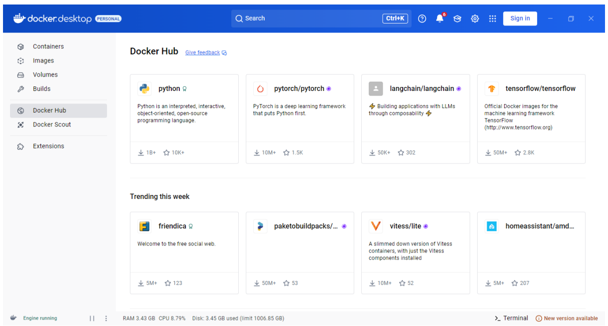


Figure 3.7: *Docker Desktop*

Docker Desktop is a platform that allows users to build, share, and run containerized applications on their desktop environments. It leverages Docker's containerization technology to provide a streamlined and efficient way to manage applications in isolated environments, ensuring that each application runs independently of others on the same system. This approach simplifies application deployment and management, making it a popular choice for developers and IT professionals.

A docker-compose.yml file standardized the deployment of the project's microservices, including the broker, MongoDB database, a second server (for measurement), and a web application. By containerizing these components, we ensured environment consistency, simplified dependency management, and enabled scalable orchestration. For instance, each of the components ran in isolated containers but communicated seamlessly via defined network bridges, demonstrating Docker's role in modular, reproducible development.

Visual Studio Code

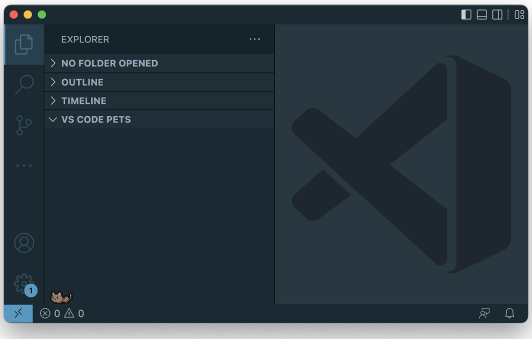


Figure 3.8: *Visual Studio Code Editor*

Visual Studio Code is a powerful, open-source code editor developed by Microsoft, designed to facilitate the development of web, mobile, and cloud applications. It stands out due to its extensive language support, customizable features, and integrated development tools, making it a preferred choice among developers.

Visual Studio Code served as the main development environment for the web application.

Protocol Used

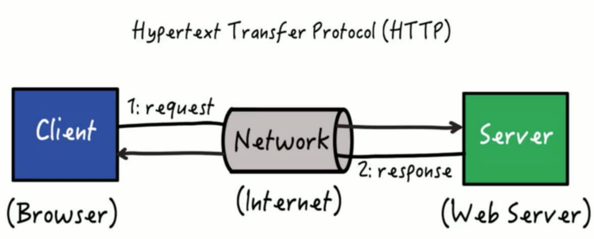


Figure 3.9: *Web Application - The Hypertext Transfer Protocol (HTTP)[3]*

*H*TTP is the backbone of the Web, defining how messages are formatted and transmitted between clients and servers. It operates over TCP connections and uses request methods (e.g., GET, POST) to perform actions on resources identified by URLs [27].

3.5.3 Hardware Assembly and Programming

3.5.3.1 Sensor Wiring Diagram

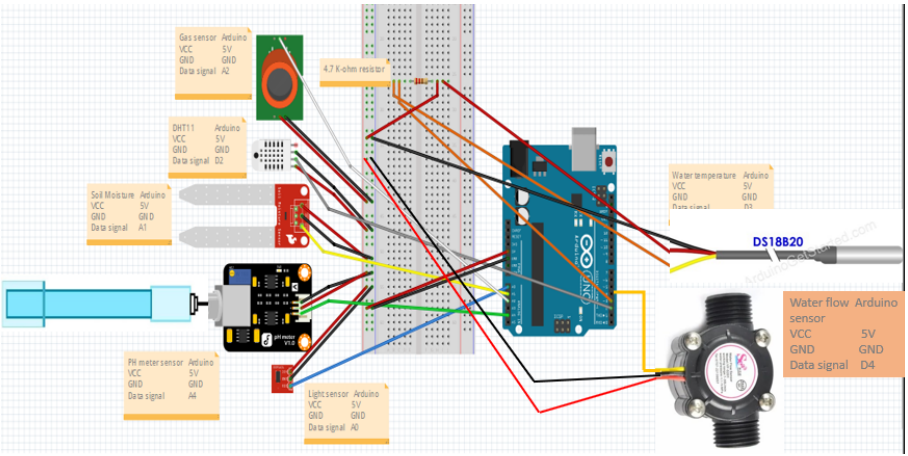


Figure 3.10: *Diagram Sensors*

In this diagram we find all the sensors used for our prototype and how they are attached to Arduino.

3.5.3.2 Actuator Wiring Diagram

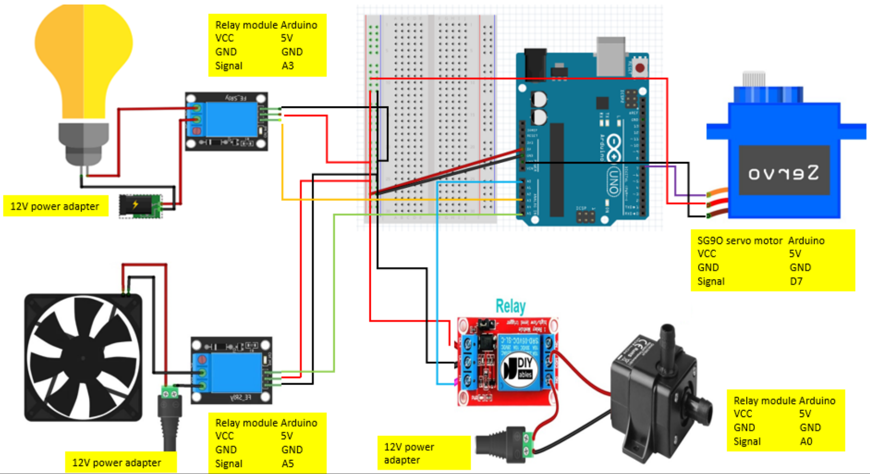


Figure 3.11: *Diagram Actuators*

In this diagram we find all the actuators used for our prototype and how they are attached to Arduino.

3.5.3.3 Communication Wiring Diagram

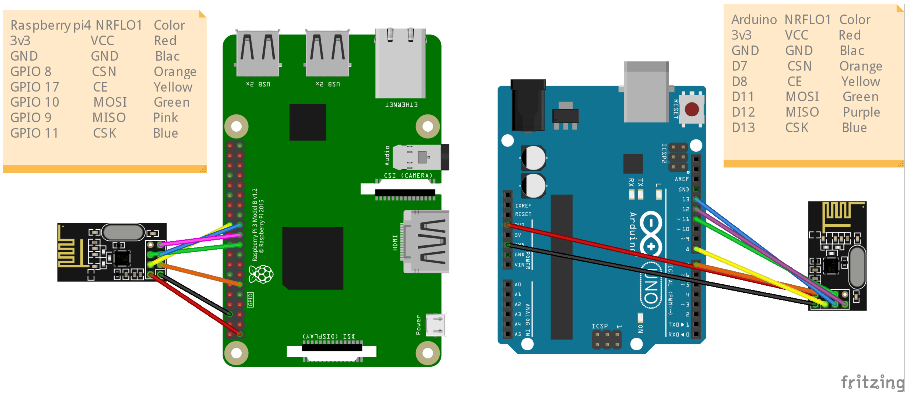


Figure 3.12: *Communication Wiring Diagram*

In this diagram we find how a wireless communication has been established between Arduino and Raspberry pi 4 using two NrfLO1 modules attached to both of them.

3.5.3.4 Actual assembly of the prototype

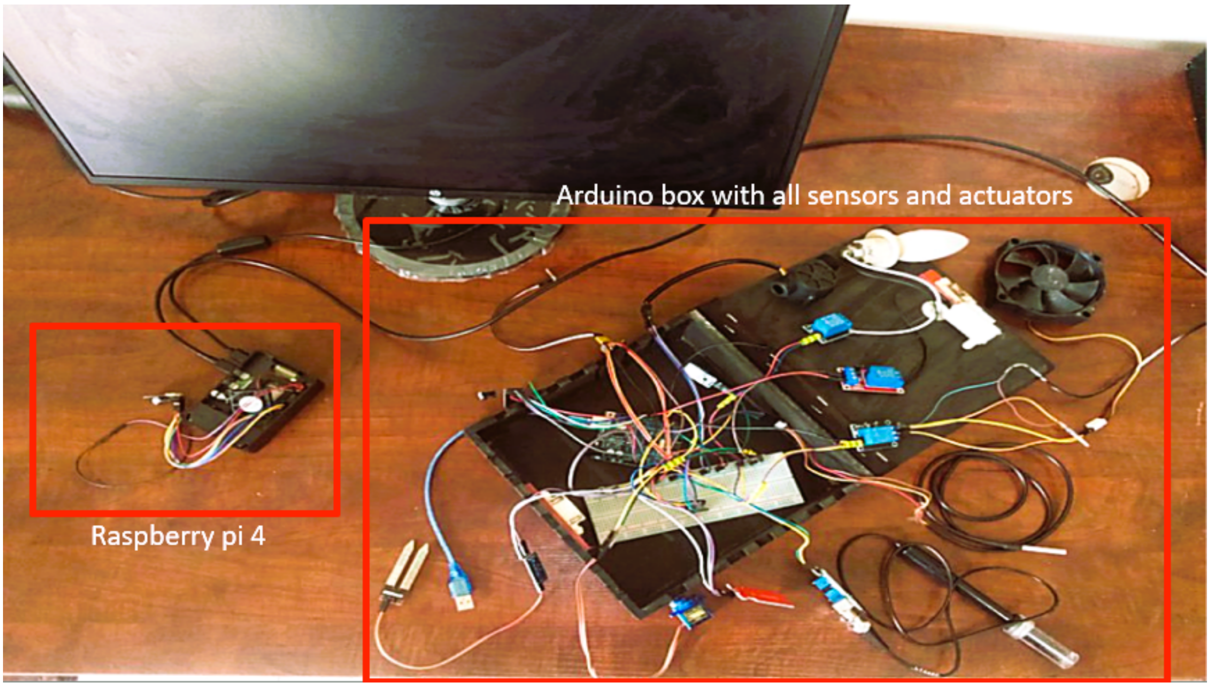


Figure 3.13: *Illustration of the actual assembly of the prototype*

This photo shows the actual wiring between the hardware components (sensors, actuators, Arduino board, etc.) used for the prototype.

3.6 The Web Application

3.6.1 Programming Languages Used

In this section, we'll break down the programming languages that power both the frontend and backend of our application. Think of it as revealing the building blocks that make everything work together from what users see and interact with to the behind-the-scenes logic that makes it all function smoothly:

Frontend Technologies

- **HTML (HyperText Markup Language)**:
  HTML is the standard language used to structure content on the web. It organizes elements like headings, paragraphs, images, and links. Essentially, it defines the layout and structure of a webpage, making it readable and interactive for users. HTML is one of the most widely used technologies for creating web pages and is fundamental to how the web works today[50].
- **CSS (Cascading Style Sheets)**:
  CSS is a style sheet language that controls the visual presentation of a webpage. Recommended by the World Wide Web Consortium (W3C), CSS allows developers to apply styles such as colors, fonts, spacing, alignment, and backgrounds to HTML elements. One of its main advantages is the separation of content from presentation: HTML handles the structure of a document, while CSS manages how that content looks. This separation makes it easier to maintain and update websites consistently across multiple pages [50].
- **JavaScript**:
  JavaScript is the primary programming language used on the web. It plays a key role

in the vast majority of modern websites and is supported by all major browsers across devices whether on desktops, tablets, smartphones, or even gaming consoles. This wide compatibility has made JavaScript one of the most widely used programming languages in history. It forms a fundamental part of the web development stack, alongside HTML, which defines the content, and CSS, which manages the visual appearance. JavaScript, in contrast, controls how web pages behave and respond to user interactions [19]. While it's best known for adding interactivity to web pages, JavaScript is also used in various non-browser environments such as Node.js, Apache CouchDB, and Adobe Acrobat. In our appliction, we used HTML and CSS to design the visual layout of the user interface, while JavaScript was responsible for handling API calls specifically through fetch requests to enable communication between the frontend and the backend.

- **Bootstrap**:
  Bootstrap is a widely used open-source front-end framework that was initially created by Twitter. It's designed to help developers build responsive, mobile-first web interfaces quickly and efficiently. The framework offers a rich collection of ready-to-use HTML, CSS, and JavaScript elements like buttons, navigation bars, forms, modals, and a powerful grid system that make it easier to design clean, consistent layouts. One of Bootstrap's key strengths is its ability to ensure that web applications look and function well across various devices and browsers [1]. In our application, we used Bootstrap to improve the look and feel of the user interface. It allowed us to integrate pre-styled components and build a responsive layout without the need to write large amounts of custom CSS.

Backend Technologies

- **Python with Flask Framework**:
  We developed a lightweight yet powerful backend using Python and the Flask framework. This component serves as the application's core, handling data processing, and communication between the frontend and database. We implemented RESTful API endpoints to manage data exchange, with routes like /api/updates for receiving sensor readings and /api/commands for controlling actuators. The backend validates incoming data, processes it using custom algorithms, and stores it efficiently in our MongoDB database.

3.6.2 Presentation of the application’s graphical interfaces

The Kharatech application features a distinctive logo (Fig. 3.14) designed to reflect its agricultural technology focus. The icon features a stylized greenhouse with a roof made of two leaf-shaped elements, symbolizing sustainability and eco-friendliness. The house has a centered window with four panes, reinforcing the idea of a smart, habitable space. On each side of the house, small leaves grow outward.

Figure 3.14: *Kharatech application logo*

When our application is launched, the main interface (login and sign-up) appears.It contains a form that allows the user (farmer) to log in or create an account.

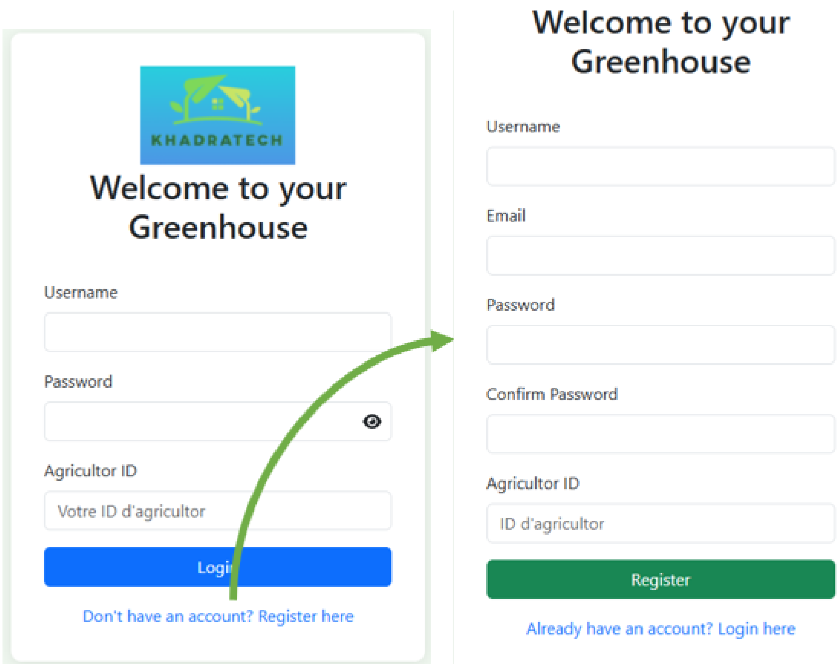


Figure 3.15: *Login and sign-up page*

Once logged in, the farmer is directed to an interface where they can either create new greenhouses by specifying custom environmental thresholds (temperature, humidity, etc.) or view existing greenhouses.

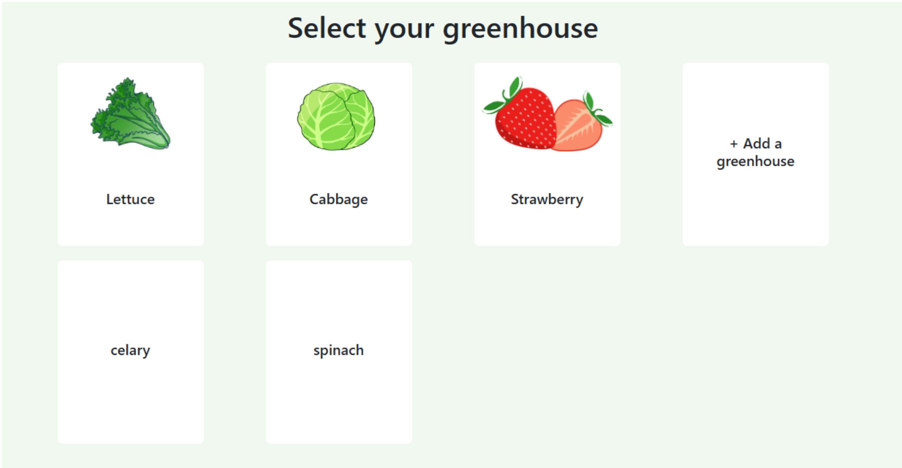


Figure 3.16: *Selection page*

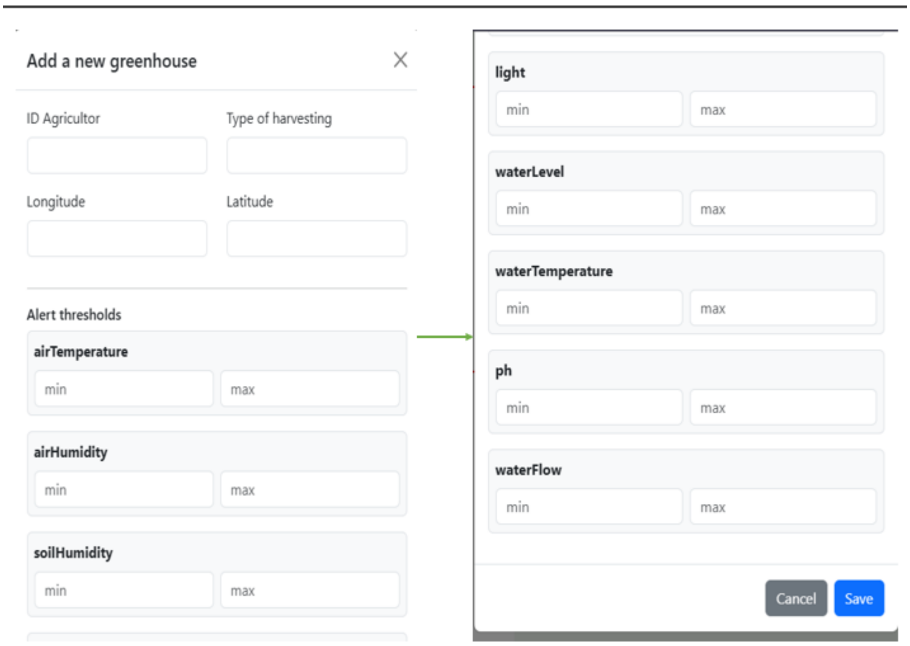


Figure 3.17: *New greenhouse form*

After selecting the desired greenhouse, the farmer will be directed to the dashboard which is divided into 4 sections as follows:

– **Alert Notification System :** A prominent alert bar appears at the top of the dashboard displaying urgent notifications when parameters exceed predefined thresholds.

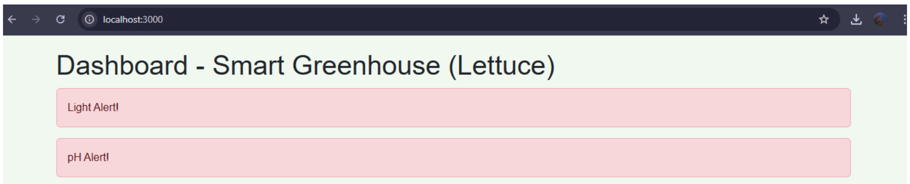


Figure 3.18: *Alert notification panel showing critical system warnings*

– **Real-Time Monitoring :** This section displays live data charts from all sensors (temperature, humidity, etc.) and visualizes trends through interactive graphs.

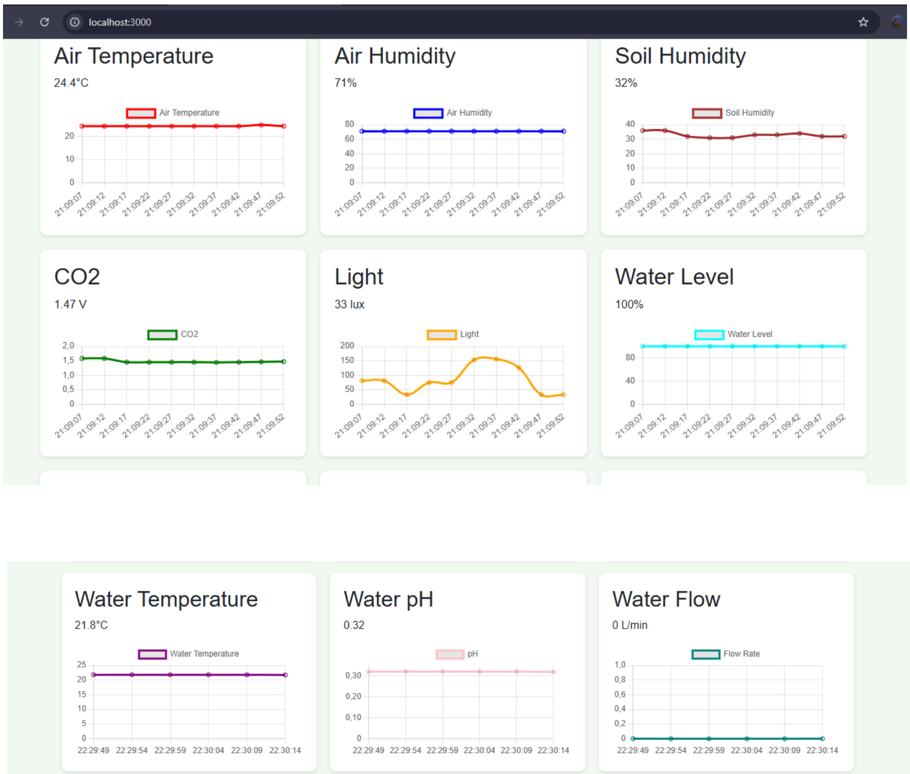


Figure 3.19: *Real-time monitoring dashboard showing sensor data visualization*

– **Remote Control Panel :** enables direct equipment management, featuring toggle switches for water pumps, ventilation systems, and lighting.

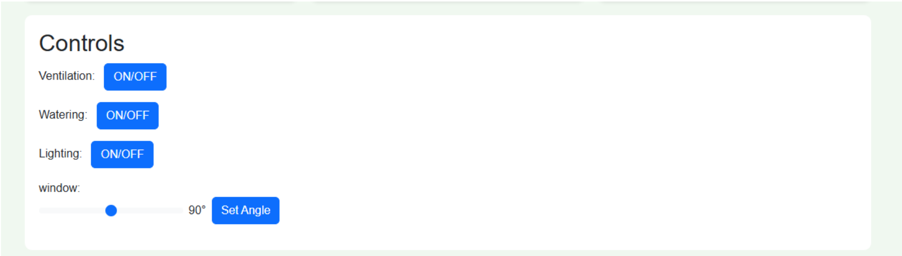


Figure 3.20: *Remote control interface for actuator management*

– **Activity Log :** It maintains complete historical records of sensor data, displays a timeline of system alerts, and allows filtering by date/time or event type.

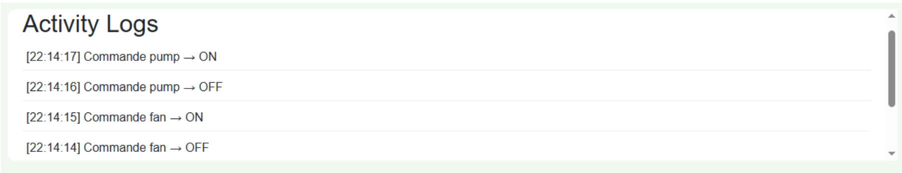


Figure 3.21: *Historical data log with filtering capabilities*

3.7 Conclusion

In this chapter, we presented the comprehensive architecture for monitoring and controlling environmental conditions in our smart greenhouse system, describing the tools and programming environment used. We focused on the approach followed to create our system by explaining the physical components of perception and actuation, including the connection diagram of all the components and the developed web application.

General Conclusion

The monitoring and management of greenhouse environmental conditions are vital to optimizing plant growth, ensuring resource efficiency, and advancing sustainable agricultural practices. Traditional greenhouse management methods, which often rely on manual observation and periodic adjustments, face limitations such as delayed responses to environmental fluctuations, labor-intensive operations, and inconsistent control over critical parameters. This thesis addressed these challenges by proposing an IoT-based intelligent system for real-time monitoring and automated control of greenhouse conditions, leveraging modern technologies to enhance precision and scalability.

In this system, a network of sensors (measuring temperature, humidity, soil moisture, light intensity, CO levels, and water quality) and actuators (pumps, fans, and lamps) was integrated into a cohesive architecture. The system employs microcontrollers, wireless communication modules, and a five-layer IoT framework (physical, network, middleware, application, and business layers) to enable seamless data acquisition, processing, and decision-making. Self-contained monitoring units were strategically deployed across the greenhouse, transmitting data to a central gateway for storage and analysis. A user-friendly web application provided real-time visualization and remote control, empowering farmers to dynamically adjust environmental thresholds.

The proposed system offers significant advantages over conventional approaches. Real-time monitoring ensures immediate detection of deviations from optimal conditions, enabling proactive interventions to prevent crop stress or resource waste. Automated control of irrigation, ventilation, and lighting systems reduces reliance on manual labor while improving consistency and accuracy. By optimizing water, energy, and nutrient use, the system promotes resource efficiency and aligns with sustainable farming goals. Additionally, the modular design allows scalability, accommodating diverse greenhouse sizes and crop types.

A functional prototype demonstrated the system's feasibility, with successful integration of hardware components, reliable wireless communication, and responsive actuation based on sensor data. While the current implementation focuses on core functionalities, future work could enhance the system through predictive analytics (using machine learning to forecast environmental trends), renewable energy integration (solar-powered sensors/actuators), and multi-crop adaptability (tailoring conditions for diverse plant species).

In conclusion, this thesis presents a transformative approach to greenhouse management by bridging IoT technologies with agricultural needs. The proposed system not only addresses current inefficiencies but also lays the groundwork for smart farming innovations. By enabling precise, data-driven control of greenhouse environments, this work contributes to global efforts in food security, climate resilience, and sustainable agriculture, fostering a future where technology and ecology thrive in harmony.

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