UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

AUTOMATED HYDROPONIC IRRIGATION SYSTEM, DEVELOPMENT AND RESEARCH

by

Elias Alexiou

Submitted in partial fulfillment of the requirements for the degree of Diploma in Mechanical Engineering at the University of Thessaly

Volos, 2025

Approved by the Committee on Final Examination:

Advisor Γιώργος Κ.Δ. Σαχαρίδης

Member Γιώργος Λυμπερόπουλος

Member Δημήτριος Παντελής

Date Approved: [June, 27, 2025]

AUTOMATED HYDROPONIC IRRIGATION SYSTEM, DEVELOPMENT AND RESEARCH

Alexiou Elias

Department of Mechanical Engineering, University of Thessaly

Supervisor: Dr George Saharidis
Associate Professor of Operations Research Methods in Industrial Management

ABSTRACT

This diploma thesis investigates the development of an automated hydroponic greenhouse system optimized for tomato cultivation, focusing on efficiency, sustainability, and simplicity. Hydroponics, a soil-free farming technique, offers solutions to critical agricultural challenges, including water scarcity, soil degradation, and excessive pesticide use. By leveraging the passive Kratky method, known for its low energy demands and accessibility, this thesis demonstrates a practical approach to modern hydroponics.

The system integrates advanced automation technologies, including sensors for pH, electrical conductivity (EC), temperature, and liquid levels, to maintain optimal growing conditions. Automated peristaltic pumps ensure precise nutrient and water delivery, while air pumps enrich the nutrient solution with oxygen, mitigating common issues like root rot. Two cultivation tanks were constructed using black plastic containers and fitted with polystyrene sheets for plant support. Vilma tomato plants, a compact and high-yield variety, were chosen to validate the system's performance.

Observations reveal that the automated hydroponic system significantly reduces water usage by up to 90% compared to traditional agriculture, while enabling higher crop yields in limited spaces. The integration of automation simplifies system management, making hydroponics accessible to individuals with minimal technical expertise. Challenges such as algae growth and pythium root rot were mitigated through design improvements and environmental controls.

This research highlights hydroponics' potential as a sustainable alternative to conventional farming, particularly in regions facing climate change and population growth. By demonstrating the feasibility of a small-scale, low-cost automated system, the study aims to promote broader adoption of hydroponic methods for food production. The findings contribute to the ongoing development of resource-efficient agricultural practices, emphasizing the role of innovation in addressing global food security challenges.

It is very important to clarify at this point that this thesis is part of a joint project carried out together with students Aris Karvounis and Panagiotis Alexopoulos. The content of this document focuses mostly on the hydroponic aspect of cultivation and its automation, while the thesis of my colleagues delves into climate management in the cultivation process and remote control of its parameters. While no points of interaction were created between the two subsystems, the seamless collaboration between all participants was essential to ensuring the healthy growth of the plants and thus providing encouraging results.

Key words: hydroponics, electrical conductivity, open source, Kratky

ΑΥΤΟΜΑΤΟΠΟΙΗΜΕΝΟ ΣΥΣΤΗΜΑ ΥΔΡΟΠΟΝΙΚΗΣ ΚΑΛΛΙΕΡΓΕΙΑΣ, ΚΑΤΑΣΚΕΥΗ ΚΑΙ ΑΝΑΛΥΣΗ

Αλεξίου Ηλίας

Τμήμα Μηχανολόγων Μηχανικών, Πανεπιστήμιο Θεσσαλίας, 2025

Επιβλέπων Καθηγητής: Δρ. Γεώργιος Σαχαρίδης,

Περιληψη

Αυτή η διπλωματική εργασία διερευνά την ανάπτυξη ενός αυτοματοποιημένου συστήματος υδροπονικού θερμοκηπίου βελτιστοποιημένου για την καλλιέργεια ντομάτας, με έμφαση στην αποδοτικότητα, τη βιωσιμότητα και την απλότητα. Η υδροπονία, μια μέθοδος καλλιέργειας χωρίς έδαφος, προσφέρει λύσεις σε κρίσιμες γεωργικές προκλήσεις, όπως η έλλειψη νερού, η υποβάθμιση του εδάφους και η υπερβολική χρήση φυτοφαρμάκων. Αξιοποιώντας τη μέθοδο Kratky, γνωστή για τις χαμηλές ενεργειακές απαιτήσεις και την προσβασιμότητά της, αυτό το έργο παρουσιάζει μια πρακτική προσέγγιση στη σύγχρονη υδροπονία.

Το σύστημα ενσωματώνει προηγμένες τεχνολογίες αυτοματισμού, όπως αισθητήρες για pH, ηλεκτρική αγωγιμότητα (EC), θερμοκρασία και επίπεδα υγρών, ώστε να διατηρούνται οι βέλτιστες συνθήκες ανάπτυξης. Αυτόματες περισταλτικές αντλίες εξασφαλίζουν ακριβή παροχή θρεπτικών συστατικών και νερού, ενώ αντλίες αέρα εμπλουτίζουν το θρεπτικό διάλυμα με οξυγόνο, μειώνοντας κοινά προβλήματα, όπως η σήψη των ριζών. Κατασκευάστηκαν δύο δεξαμενές καλλιέργειας χρησιμοποιώντας μαύρα πλαστικά δοχεία, εξοπλισμένα με φύλλα πολυστυρενίου για στήριξη των φυτών. Επιλέχθηκαν φυτά ντομάτας Vilma, μια συμπαγής και υψηλής απόδοσης ποικιλία, για την αξιολόγηση της απόδοσης του συστήματος.

Οι παρατηρήσεις δείχνουν ότι το αυτοματοποιημένο υδροπονικό σύστημα μειώνει σημαντικά τη χρήση νερού έως και 90% σε σύγκριση με τη συμβατική γεωργία, ενώ επιτρέπει μεγαλύτερες αποδόσεις σε περιορισμένους χώρους. Η ενσωμάτωση αυτοματισμού απλοποιεί τη διαχείριση του συστήματος, καθιστώντας την υδροπονία προσβάσιμη σε άτομα με ελάχιστη τεχνική εξειδίκευση. Προκλήσεις, όπως η διαχείριση της άλγης και η προστασία των ριζών από το πύθιο και άλλες ασθένειες, αντιμετωπίστηκαν μέσω βελτιώσεων στον σχεδιασμό και τήρησης αυστηρότερων πρωτοκόλλων καθαριότητας.

Η έρευνα αυτή αναδεικνύει τη δυνατότητα της υδροπονίας ως βιώσιμης εναλλακτικής στη συμβατική γεωργία, ιδιαίτερα σε περιοχές που επηρεάζονται άμεσα από την κλιματική αλλαγή καθώς και την αύξηση του πληθυσμού. Παρουσιάζοντας την δυναμική αλλά και τις απαιτήσεις, ενός μικρής κλίμακας, χαμηλού κόστους αυτοματοποιημένου συστήματος, η μελέτη στοχεύει στην προώθηση της ευρύτερης υιοθέτησης υδροπονικών μεθόδων για την παραγωγή τροφίμων. Τα ευρήματα συμβάλλουν στην περαιτέρω ανάπτυξη γεωργικών πρακτικών με αποδοτική χρήση πόρων, υπογραμμίζοντας τον ρόλο της καινοτομίας στην αντιμετώπιση των προκλήσεων της παγκόσμιας επισιτιστικής ασφάλειας.

Είναι πολύ σημαντικό στο σημείο αυτό να διευκρινιστεί ότι αυτή η διπλωματική αποτελεί μέρος ενός κοινού εγχειρήματος που πραγματοποιήθηκε μαζί με τους φοιτητές Άρη Καρβούνη και Παναγιώτη Αλεξόπουλο. Όσα αναλύονται σε αυτό το κείμενο εκφράζουν το υδροπονικό κομμάτι της καλλιέργειας, ενώ η διπλωματική των συναδέλφων μου εμβαθύνει στη διαχείριση του κλίματος κατά τη διάρκεια της καλλιέργειας και στην εξ 'αποστάσεως διαχείριση αυτού. Τα δυο υποσυστήματα, υδροπονία-έλεγχος κλίματος, δεν αλληλοεπιδρούν. Παρ 'όλα αυτά, η στενή από κοινού συνεργασία όλων των συμμετεχόντων ήταν απαραίτητη για τη διασφάλιση της υγειούς ανάπτυξης των φοιτών και ήταν αυτή που μας έδωσε ενθαρρυντικά αποτελέσματα.

Λέξεις-κλειδιά: υδροπονία, ηλεκτρική αγωγιμότητα, ανοιχτός κώδικας, Kratky

TABLE OF CONTENTS

ABSTRACT IV

ΑΥΤΟΜΑΤΟΠΟΙΗΜΕΝΟ ΣΥΣΤΗΜΑ ΥΔΡΟΠΟΝΙΚΗΣ ΚΑΛΛΙΕΡΓΕΙΑΣ, ΚΑΤΑΣΚΕΥΗ ΚΑΙ ΑΝΑΛΥΣΗ VI

ΠΕΡΙΛΗΨΗ VI

TABLE OF CONTENTS VII

1 INTRODUCTION 1

1.1 Motivation 1
1.2 Thesis Organisation 1

2 UNDERSTANDING HYDROPONICS 3

2.1 History, Definition and Etymology 3
2.2 Different Hydroponics Systems 4
2.3 Substrates 8
2.3.1 Why Substrates Are Important in Hydroponics 9
2.3.2 Water Consumption 9
2.3.3 Pesticide and Herbicide Consumption 10
2.3.4 Enhanced Production 10
2.3.5 Absence of Soil 10
2.4 Deeper Understanding of Passive hydroponics 11
Drawbacks 12
2.4.1 Viruses 12
2.4.2 Algae 13
2.4.3 Pythium Root Rot 15

3 UNDERSTANDING PH AND EC 17

3.1 The Importance of pH in hydroponics 17
3.2 Managing pH levels 17
3.3 The Role of Electrical Conductivity 17

4 THE PLANTS 19

4.1 About Tomato 19
4.1.1 The Vilma variety 19
4.1.2 Seedling 20

5 ASSEMBLY 22

5.1 The Concept 22
5.2 Sensors and Materials 23
5.2.1 DFRobot Gravity: Analog Electrical Conductivity Meter V2 24
5.2.2 Aqua Master E50 Pro handheld EC meter 24
5.2.3 DFRobot Gravity: Analog pH meter V1 25
5.2.4 Other Sensors Used 26
5.2.5 Other Equipment 27
5.2.6 Pumps 27
5.2.7 Cultivation Tanks 28
5.2.8 Nutrients Used 29
5.3 Construction 30
5.3.1 The cultivation tanks 30

6 CONNECTIONS AND CODE 35

6.1 Arduino Uno and electrical components 35
6.1.1 LRS-50-12 Power Supply 35
6.1.2 Relays 36
6.1.3 Breadboard 37
6.1.4 Overall System Integration 38
6.1.5 Electrical Connections 38
6.2 Coding the system 39

7 RESULTS 42

7.1 Observations 42
7.2 Challenges 45
7.2.1 Challenges in Hydroponic Cultivation 45
7.2.2 Growing system modifications 45
7.2.3 Hydraulic and mechanical problems 46

8 CONCLUSION 48

REFERENCES 49

APPENDIX 51

8.1 Code for conservation mode 51
8.2 Code for filling mode 64

[1]

TABLE OF FIGURES

Figure 2.1 : Representation of NFT method 4
Figure 2.2 Representation of the wick system 5
Figure 2.3 Representation of the Flood and Drain system when the system is drained 5
Figure 2.4 Representation of the Flood and Drain system when the system is flooded 6
Figure 2.5 Representation of the Drip system 6
Figure 2.6 Representation of an Aeroponic System 7
Figure 2.7 Representation of a Kratky System with Time Progression 12
Figure 2.8 Signs of possible Viral Infection on Tomato Leaves 13
Figure 2.9 Algae Growth in Roots of A Tomato Plant 15
Figure 2.10 Example of pythium root rot, in a tomato plant in our system 16
Figure 4.1: Cutting Rockwool into Smaller Pieces (Left). Placing Tomato Seeds on the Rockwool (Right) 20
Figure 4.2 Clockwise from top left) - Ice Tray Partially Submerged in Water and Inside Sealed Container. Seedlings after 1 week. - Seedlings after 3 weeks. - Young tomato plant after 4 weeks 21
Figure 5.1 The Grow Tent 23
Figure 5.2 Electrical Conductivity Probe (Left), Signal Conversion Board (Right) 24
Figure 5.3 handheld EC meter 25
Figure 5.4 pH Probe 25
Figure 5.5 Temperature Sensor 26
Figure 5.6 Liquid Level Sensor 26
Figure 5.7 Air Pump 27
Figure 5.8 Air Stone 27
Figure 5.9 Left 12v Peristaltic Pump, Right 5v Pump 28
Figure 5.10 90lt tank 28
Figure 5.11 Net Pot 29
Figure 5.12 A and B Nutrient Solutions 30
Figure 5.13 Making Net Pot Pattern (Left), Opening Holes Using Soldering Rod (Right) 30
Figure 5.14 Final Fitting of The Net Pot 31
Figure 5.15 The Test Tray 32
Figure 5.16 The test tray with arrows pointing up (out) or down (in) corresponding to liquid flow 32
Figure 5.17 Assembly of frame 33
Figure 5.18 Peristaltic pumps a and b with pH peristaltic pump in the middle 34
Figure 5.19 Cultivation tank sketch and components 34

Figure 6.1 Arduino UNO R3 board 35
Figure 6.2 Power Supply.. 36
Figure 6.3 5v relay module 37
Figure 6.4 Breadboard 37
Figure 6.5 Wiring of the system 38
Figure 6.6 Arduino board compartment... 39
Figure 6.7 Flowchart illustration.. 41
Figure 7.1 Irrigation Water Requirements for Tomato Production Across Different Growing Systems 42
Figure 7.2 Tomato production over a 15-day period by 2 tomato plants 43
Figure 7.3 EC readings 44
Figure 7.4 pH readings... 44
Figure 7.5 Temperature readings 45
Figure 7.6 Head pressure system 46
Figure 7.7 Signs of Water Damage In 5v Pump 47

1 INTRODUCTION

1.1 Motivation

Hydroponics is an alternative method of cultivation or crop production where plants are grown without soil, relying on a liquid nutrient solution to provide the essential nutrients needed for their growth. The roots are placed in a completely inorganic medium, supplied with a nutrient solution. This characteristic—the absence of soil—enables hydroponics to offer solutions in areas where conventional agriculture faces significant challenges.

1.2 Thesis Organisation

Chapter 1: Introduction

Introduces motivation, research objectives, and an overview of the system.

Chapter 2: Understanding Hydroponics

Covers hydroponic principles, system types, substrates, advantages, and challenges such as algae and pythium.

Chapter 3: Understanding pH and EC

Explains the significance of pH and electrical conductivity (EC) in hydroponics and methods for their optimization.

Chapter 4: The Plants

Focuses on crop selection, specifically the Vilma tomato variety, and seedling development.

Chapter 5: Assembly

Details the design and construction of the system, including cultivation tanks, test trays, and supporting components.

Chapter 6: Connections and Code

Presents the electrical and software integration for system automation.

Chapter 7: Results

Discusses observations, system performance, challenges, and key findings.

Chapter 8: References

Lists all cited sources.

Chapter 9: Code Index

Provides the system's automation code for reference.

2 UNDERSTANDING HYDROPONICS

2.1 History, Definition and Etymology

Hydroponics is a widely used method for growing plants without soil, allowing precise control over the nutrient environment surrounding the roots. It is defined as the cultivation of plants by placing the roots in liquid nutrient solutions rather than in soil. This challenges the traditional belief that plants require soil to grow, as hydroponics demonstrate that essential nutrients, not dirt, are what truly sustain plant development.

The term "hydroponics" was coined in the 1930s by Dr. W.F. Gericke, a California scientist who combined the Greek words *hydro* (water) and *ponos* (labor), meaning "working water" [1]. Although the term itself is relatively new, the practice of growing plants in water containing essential nutrients dates back centuries, with early civilizations possibly utilizing primitive hydroponic systems for agricultural purposes. One of the earliest recorded hydroponic systems is believed to be the **Hanging Gardens of Babylon**, one of the Seven Wonders of the Ancient World, where plants were irrigated using pumps. Similarly, the **Aztecs** developed floating gardens, known as **chinampas** [2], by creating rafts anchored to lake beds to grow crops in nutrient-rich water.

The scientific study of hydroponics began in the 17th century when John Woodward conducted one of the earliest recorded experiments using a water culture method without a solid substrate [3]. In 1699, he discovered that substances in water, rather than water itself, contributed to plant growth3. During the 18th century, researchers experimented with different soil and water mixtures to understand plant growth, but major breakthroughs occurred in the 19th century when scientists such as De Saussure, Sachs, Boussingault, and Knop identified essential elements necessary for plant development. Wilhelm Knop played a crucial role by developing a standardized nutrient solution that served as the foundation for modern hydroponic formulations. Later, Arnon and Hoagland introduced an improved nutrient solution based on the elements absorbed by tomato plants, which gained widespread acceptance due to its efficiency and stability.

The first large-scale commercial hydroponic systems were established during **World War II** by the U.S. Army in the South Pacific to supply fresh fruits and vegetables to troops stationed in remote locations [4], proving the practicality of hydroponics for food production in challenging environments. While commercial hydroponics briefly flourished in the United States after the war, its widespread use has since expanded in regions like **England, Western Europe, and the Middle East**, primarily for the production of winter vegetables such as tomatoes, cucumbers, and lettuce. Hydroponic techniques are also widely applied in indoor agriculture, urban farming, and even decorative plant installations in malls, offices, and homes.

Modern applications of hydroponics continue to expand, including its use in space research, where NASA investigates hydroponic systems for growing food on long-duration space missions. With the increasing demand for sustainable agriculture, hydroponics offers an efficient solution for overcoming challenges like land scarcity, climate change, and global food security, making it a vital innovation in modern farming.

2.2 Different Hydroponics Systems

Different Hydroponic Structures and Their Operations: Hydroponic systems can be classified based mostly on water flow mechanisms or the absence of them. Below are the main types:

Nutrient Film Technique (NFT): A thin film of nutrient solution flows continuously over plant roots housed in sloped channels. This system ensures efficient nutrient delivery and oxygenation, making it ideal for leafy greens as shown in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**.

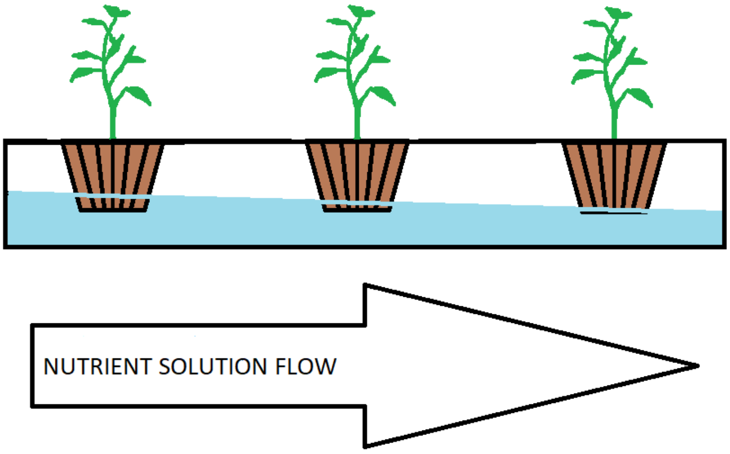

Figure 2.1 : Representation of NFT method

Deep Water Culture (DWC): Roots are suspended directly in a nutrient solution, with oxygen supplied via air stones or diffusers. This promotes rapid growth and supports large plants with extensive root systems.

Wick Systems: Using absorbent materials, nutrient solution is drawn from a reservoir to plant roots without electricity. It is suitable for small plants needing minimal water.It is best suited for amateur growing as it requires no maintenance and minimal monitoring.

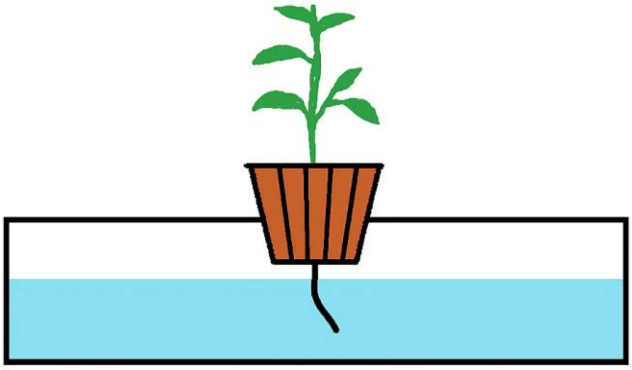

Figure 2.2 Representation of the wick system

Ebb and Flow (Flood and Drain): Grow beds are periodically flooded with nutrient solution and then drained, providing nutrients and oxygen to the roots. This versatile method supports a wide range of plants, most commonly used for leafy greens and herbs.

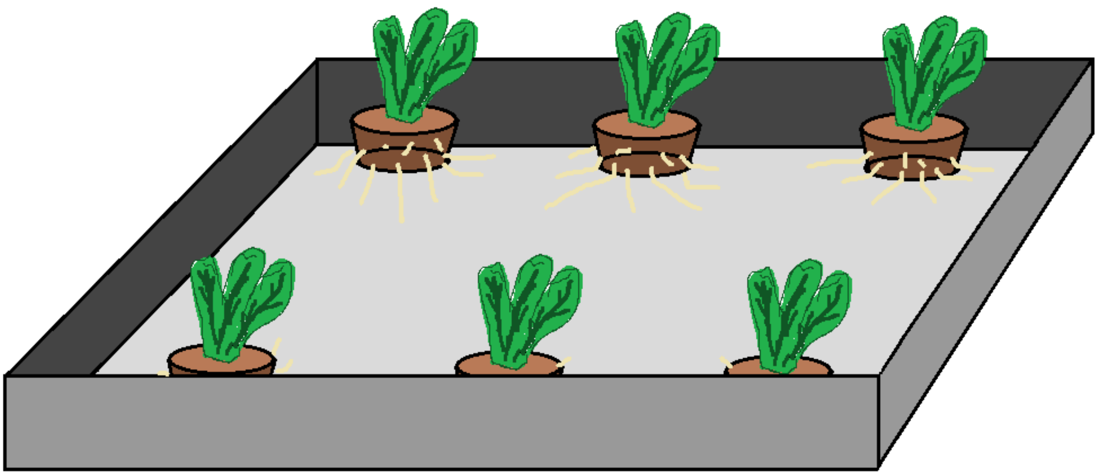

Figure 2.3 Representation of the Flood and Drain system when the system is drained

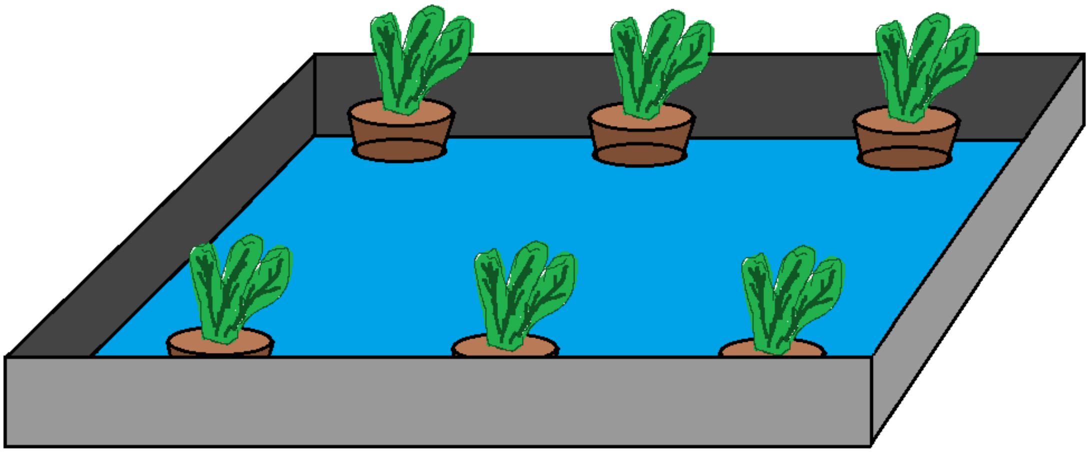

Figure 2.4 Representation of the Flood and Drain system when the system is flooded

Drip Systems: Nutrient solution is delivered directly to plant bases through a network of tubes and drippers, typically into a substrate like rockwool or coco coir Flow rates can be adjusted to meet specific crop needs.

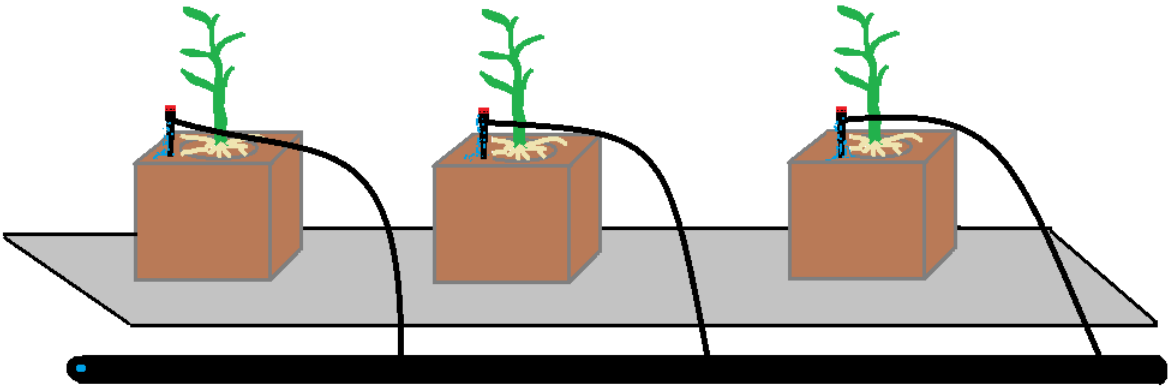

Figure 2.5 Representation of the Drip system

Aeroponics: Plant roots are suspended in air and misted with nutrient solution. This method provides high oxygen levels, accelerating growth rates but requires precise maintenance.

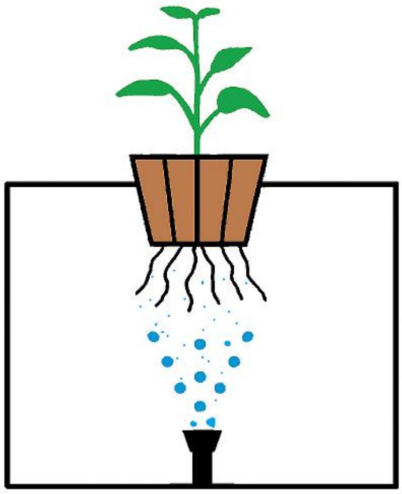

Figure 2.6 Representation of an Aeroponic System

Kratky Method: A passive system where plant roots are suspended above a nutrient solution, naturally absorbing nutrients and oxygen as water levels decrease. The roots adapt to this change by creating modified 'air roots', portions of plant roots that grow above the water level, exposed to air, allowing them to absorb oxygen directly from the environment

Hydroponic systems vary significantly in design, function, and performance, each offering advantages depending on the grower's goals, available resources, and crop type. The **Nutrient Film Technique (NFT)** is widely used for leafy greens due to its efficiency in delivering a continuous stream of nutrients while ensuring oxygenation, although it requires precise slope management and uninterrupted flow. In contrast, **Deep Water Culture (DWC)** submerges roots in aerated nutrient solution, supporting faster growth and making it ideal for larger, fruiting plants—but it demands continuous aeration and monitoring. The **Kratky method** and the **wick system** are passive systems requiring no pumps or electricity, they are excellent for low-tech growing, but limited to small, low-demand crops. **Ebb and Flow (Flood and Drain)** systems provide flexibility by periodically soaking roots in solution and then draining it away, promoting both nutrient uptake and aeration, making it popular for medium-sized plants. Most usually practiced on large tables this technique offers very high plant density. **Drip systems** deliver a controlled flow of nutrients directly to the root zone, usually into a substrate, and are highly scalable and adaptable to different plant types-though emitter maintenance is critical and substrate increases the cost as well as environmental impact. **Aeroponics** offers the highest oxygenation and growth rates by misting roots suspended in air, but it comes with high technical demands, little scalability and a narrow margin for error.

In commercial hydroponics, there is no universal cultivation method that guarantees the best economic or agronomic outcome in every situation. The most suitable system for a given region depends on a combination of factors such as climate, energy and labor costs, material availability, and the grower's experience. Even within a single system developed by a specific company, design and implementation can vary significantly from one project to another. This is because effectiveness also relies heavily on how well irrigation frequency and volume are calibrated, which differs between systems based on the physical and chemical characteristics of the root environment. While hydroponic techniques offer general frameworks, they often serve more as flexible guidelines than fixed solutions. All systems can perform effectively when properly matched to the crop and conditions, but increasing demand for efficiency, resource optimization, and site-specific adaptation has highlighted the growing need for personalized, modular systems.

The dogmatic belief that agriculture must be uniform needs to be re-evaluated. Throughout history, each civilization developed its own unique cultivation techniques, adapted to local climates, resources, and cultural practices. Hydroponics should be approached with the same mindset—not as a one-size-fits-all solution, but as a flexible and diverse set of systems tailored to the needs of each grower. Whether for a small-scale hobbyist or a large commercial operation, and whether in arid, tropical, or temperate climates, hydroponic systems must be adapted to suit specific crops, environments, and goals. True innovation in agriculture lies not in standardization, but in personalization.

2.3 Substrates

As mentioned above, a common element in almost all hydroponic techniques is the use of a substrate. In hydroponics, a substrate, also known as a growing medium, is a material used to support plant roots and create a stable environment for growth.

Unlike soil, it does not provide nutrients but serves primarily to anchor the plant and maintain moisture and oxygen levels. The required nutrients are supplied to the plant through a water-based nutrient solution. In the method used in this project the substrate will act mainly as an anchor for the roots and will not have a role in the watering process after the first month since after that, the roots will have outgrown the medium and will be exposed directly to the water-nutrient solution. It is important however to describe the substrates used, since they play an important role in hydroponics in general and the sector needs new and better alternatives. Any medium used for rooting must provide mechanical support, water, and oxygen [5].

A substrate must have the following properties, it must be inert, inorganic sterile and must be able to retain water and nutrients for root uptake and porous to allow plant roots to move but have some structure to provide support. Substrates stabilize plants, allowing roots to grow securely. There are not many materials with the forementioned properties, so the industry is having to rely heavily on those with the most of the forementioned qualities. Some of the most widely used substrates and their respective properties are listed here:

Rockwool: A material manufactured by heating basaltic rock to 1500°C, adding specific additives, and then feeding the molten mixture onto a rapidly spinning drum, which transforms it into fibers. Excellent for water retention and aeration, commonly used for seed germination and in systems like NFT or drip irrigation.

Coco Coir: Made from coconut husks, it is lightweight, retains moisture well, and provides good aeration for roots. Eco-friendly and widely used in various hydroponic systems.

Clay Pellets (Hydroton): Lightweight expanded clay aggregates (LECA) that are durable, reusable, and provide excellent aeration. Often used in ebb-and-flow systems.

Perlite: A volcanic glass that expands when heated, providing a porous structure for aeration and drainage. Often mixed with other substrates to improve their structure.

Vermiculite: A mineral substrate that retains moisture and nutrients effectively. Commonly used with perlite or coco coir for better water retention.

Peat Moss: Organic material that retains water well but may require supplementation with other substrates for improved drainage.

Sand: Provides excellent drainage but may compact overtime, limiting aeration.

Gravel: Inexpensive and durable, used in basic hydroponic setups but does not retain much moisture.

2.3.1 Why Substrates Are Important in Hydroponics

While not necessary for all hydroponic methods, substrates play a crucial role in most hydroponic systems by providing essential support for plants, allowing their roots to grow securely and maintain stability. In addition to structural support, substrates aid in moisture retention, helping to hold water and nutrients that roots can absorb as needed. They also promote proper aeration by ensuring that roots receive sufficient oxygen, which is vital for healthy growth and nutrient uptake. Furthermore, many commonly used substrates, such as clay pellets and coco coir, offer the benefit of reusability, as they can be cleaned and recycled for multiple growing cycles, making them both cost-effective and environmentally friendlyAdvantages

2.3.2 Water Consumption

Water is one of the most critical resources in agriculture, and its efficient use is paramount for sustainable food production. Hydroponics, as an alternative cultivation method, offers significant advantages in water conservation compared to conventional agriculture. Globally, conventional agriculture accounts for approximately 70% of total human blue water use with irrigation water consumption estimated to reach 2,500 km^3 per year [6]. Of this, nearly 90% is consumed by agricultural blue water use, which includes water transpired productively through crops or evaporated unproductively from soils, water bodies, and vegetation canopies, amounting to approximately 1,200–1,800 km^3 annually. This heavy reliance on water places immense pressure on freshwater resources, especially in regions where water scarcity is prevalent [7].

Hydroponics addresses this issue by using 70–90% less water than traditional soil-based farming. With minimal evaporation and runoff losses, as well as potentially zero deep water infiltration into the soil. For example, hydroponics utilizes only about 10% of the water required by conventional farming methods, showcasing its superior water management capabilities. In comparison to greenhouse farming, hydroponics consumes seven times less water, and its water usage is four times lower than open-field cultivation. These efficiencies make hydroponics an ideal solution for arid regions and areas with limited water availability.

In Greece, agriculture remains the largest consumer of water resources. The percentages of water consumption related to agriculture range from 11% to 92% across various water districts, with an average of 74% nationwide. This underscores the critical need for water-saving agricultural practices in the country and is representative of the situation in the Mediterranean basin [8].

By reducing the reliance on large quantities of irrigation water, hydroponics provides a sustainable approach to food production. It not only mitigates the impact of agricultural water use on freshwater ecosystems but also ensures resilience in regions facing increasing water scarcity due to climate change and population growth.

2.3.3 Pesticide and Herbicide Consumption

Modern agriculture relies heavily on the use of pesticides and herbicides, Glyphosate-based herbicides are currently among the most widely used agricultural chemicals globally. Sold under the trade name Roundup® (RU), glyphosate-based herbicides by 2002 where the most used in the United States [9]. In agriculture, GLP mainly serves to control weeds and clear vegetation cover before sowing crops [10]. The average use of herbicides in the agricultural sector at the EU 28+3 level can be estimated at 0.62 kg of a.i. per hectare. Apart from increasing the cost for farmers International Agency for Research on Cancer (IARC) classified it as "probably carcinogenic" in 2015 [11]. Hydroponics eliminates the need for herbicides because plants are grown in a soilless environment, preventing weed growth. Without soil, weeds have no medium to establish themselves, removing competition for nutrients and space.

Another key advantage in Controlled-Environment Agriculture and, consequently, hydroponic farming, is that the greenhouse acts as a protective barrier against insect infestations, reducing the need for insecticides. This not only lowers pest control costs but also makes organic cultivation a more feasible option.

2.3.4 Enhanced Production

More specifically, within the next decade, the food industry should increase its production by 15% to meet the nutritional needs of the increasing population, while by 2050 a necessary increase of 50% is estimated [12]. With the global population rising and limited agricultural land, hydroponics provides an efficient and industrialized green vegetable production system. The growth rate of hydroponic plants is 30–50% faster than that of soil-grown plants [13], enabling higher yields in smaller spaces. Hydroponic tomatoes yield 280–700 tons/ha compared to 37 tons/ha in soil-based cultivation [14].

2.3.5 Absence of Soil

Soil degradation through erosion, salinization, and nutrient loss is a critical global threat to agriculture and food security. With a growing population and rising demand for meat, grain, and biofuels, pressure on land resources is intensifying. Erosion in many regions outpaces natural soil regeneration by 30 to 40 times [15], while salinity often caused by poor irrigation practices and over-fertilization reduces irrigated land by 1–2% annually. **Hydroponics offers a sustainable alternative**, bypassing soil entirely and reducing dependence on degraded land while maintaining high crop productivity.

While the adoption of hydroponic cultivation faces challenges such as high initial costs, energy consumption, and the need for technical expertise, this thesis aims to address some of these issues.

By designing a small-scale automated hydroponic greenhouse for tomato production, we will attempt to demonstrate how sensors and open-source software automation can reduce the need for technical expertise. Additionally, we will explore how at smaller scales, simplified, personalized hydroponic systems can lower initial costs, paving the way for broader adoption of this innovative farming method.

2.4 Deeper Understanding of Passive hydroponics

‘’Passive’’ is a term used in hydroponics to describe systems that eliminate the need for pumps, timers, or electricity, making them highly accessible and cost-effective.

For example, the Kratky method is a simple and innovative passive hydroponic technique. In this system, plant roots are suspended above a reservoir containing a nutrient solution, allowing them to absorb nutrients and oxygen naturally as the water level decreases [16]. This low-maintenance approach requires minimal intervention, making it ideal for beginners or those seeking a low-energy, sustainable method of hydroponics.

The absence of active components reduces operational costs and mechanical failures, while its scalability makes it suitable for both small-scale home gardening and larger agricultural applications. By leveraging the benefits of passive hydroponics, the Kratky method offers a practical and resource-efficient solution, especially in regions with limited access to electricity or high-tech farming equipment, it comes with several drawbacks that can limit its effectiveness and scalability.

One major challenge is the static nature of the nutrient solution, which may lead to uneven nutrient distribution and potential deficiencies as plants grow and consume the solution. Additionally, the lack of aeration in the water can result in reduced oxygen availability for the roots, especially in larger or densely populated reservoirs, potentially stunting plant growth. Another problem caused commonly by low levels of oxygen is pythium rot, a parasitic organism that hinders plant development and production and can even cause destruction of the crop. This method is less adaptable for crops with high water or nutrient demands and is primarily suitable for short-term crops like leafy greens or herbs. Another limitation is its susceptibility to environmental factors such as temperature fluctuations, which can affect the nutrient solution and plant health. Moreover, the Kratky method requires careful monitoring of water levels to prevent the roots from drying out or becoming waterlogged as the solution depletes, adding a layer of manual maintenance. These drawbacks highlight the need for careful planning and consideration of crop type and environmental conditions when adopting this passive hydroponic technique.

With minimal changes to the Kratky method the advantages of passive hydroponics can be multiplied. Deep water culture, as forementioned, relies on air pumps to bring air into the system, when combined with Kratky method, a hybrid system can be created that leverages the strengths of both approaches. In this hybrid setup, plants are allowed to develop air roots above water level, like in the Kratky method, while the submerged roots benefit from the oxygenation provided by the DWC system. This design significantly reduces the amount of oxygen that needs to be pumped into the system because the air roots naturally absorb oxygen from the surrounding environment.

By merging these techniques, the hybrid system achieves better aeration, reduces the risk of issues like pythium root rot, and requires less frequent intervention, creating an efficient, sustainable solution suitable for a wide range of crops and growing conditions.

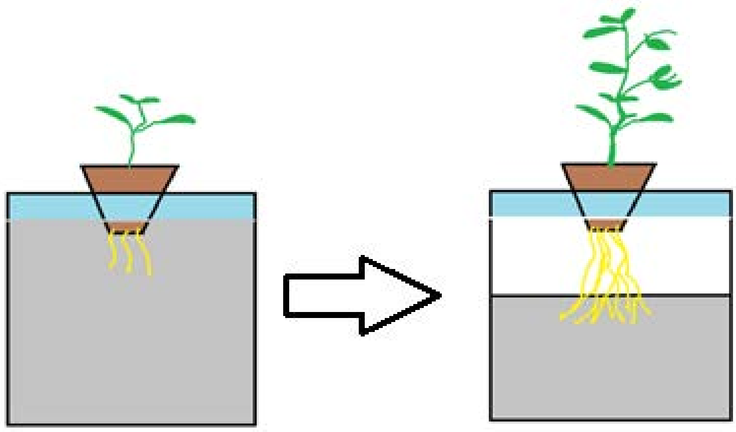

Figure 2.7 Representation of a Kratky System with Time Progression

Drawbacks

While efficient and advantageous for crop production hydroponic systems carry significant disease risks due to the recirculation of nutrient solutions and planting density. Because plants are grown in proximity and share nutrient solutions, the rapid spread of pathogens can devastate entire crops, posing a serious threat to annual production and food supply stability.

2.4.1 Viruses

Viruses, such as Tomato Mosaic Virus (ToMV) and Pepper Mild Mottle Virus (PMMV), have been shown to persist in recirculating systems and remain infective for extended periods. Once introduced into the system they can spread and infect healthy plants within as little as 10 days [17]. They have a significant impact on annual production, leading to substantial yield losses and reduced fruit quality in commercial hydroponic systems. A couple of common pathways for virus entry are listed below:

Infected Plant Material: Introducing infected seeds, seedlings, or cuttings into the system can introduce viruses that spread through the water or plant-to-plant contact [18].

Contaminated Water: Viruses present in irrigation water, especially if sourced from untreated or contaminated supplies, can easily spread in the closed-loop hydroponic system [19].

Vectors: Pests like aphids, whiteflies, or thrips can act as carriers, introducing viruses when they feed on plants in the system.

Human Handling: Tools, hands, or equipment contaminated with viral particles from infected plants or external sources can introduce the virus into the hydroponic system.

Contaminated Nutrient Solutions: Using nutrient solutions or additives that have been exposed to virus-infected environments can spread the virus.

Airborne Spread: In some cases, certain viruses can enter through airborne pathways, although this is less common in hydroponic setups.

Once inside, the recirculating water can quickly spread the virus throughout the system, infecting multiple plants (**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**). Prevention involves strict hygiene practices, pest control, using virus-free planting material, and ensuring water and nutrient solutions are free from contamination [20].

Figure 2.8 Signs of possible Viral Infection on Tomato Leaves

2.4.2 Algae

Although not considered a pathogen it is important to mention how hydroponic systems are particularly prone to algae growth. Generally, algae are considered to be aquatic, oxygen-evolving photosynthetic autotrophs that are unicellular, colonial or are constructed of filaments or composed of simple tissues [21] . Algae can enter the system in one of the following ways:

Uncovered Reservoirs: Light reaching the nutrient solution reservoir encourages algae growth. Algae thrive in water exposed to light due to photosynthesis.

Transparent Materials: Using clear or translucent pipes, tanks, or containers allows light to penetrate, creating a conducive environment for algae [22].

Contaminated Water Sources: If the water used in the hydroponic system is not properly filtered or treated, it may introduce algae spores directly into the system.

Airborne Spores: Algae spores are naturally present in the air and can settle into an open system, especially in outdoor setups.

Contaminated Equipment: Tools, containers, or growing media that haven't been sterilized may carry algae spores. Using previously contaminated materials can introduce algae to the system.

Growing Media: Algae can hitch a ride on growing media, such as rockwool, coco coir, or expanded clay pellets, if they were stored improperly or exposed to spores before use.

Nutrient Solution Spill or Residue: If nutrient-rich water spills and remains exposed to light on system surfaces, it can support algae growth, which may eventually spread to the main system.

Algae can cause problems with the water supply system by clogging drippers or drip lines. In addition, algae represent competitors for nutrients and certain species are known to produce toxins which might inhibit or even stop crop growth [23]. Therefore, it is common practice to cover the root system with black plastic sheets to prevent, or at least reduce, algal growth. Alternatively, algicides are used occasionally. These precautions cause additional costs for the farmers as well as the production of pollutants.

Microalgae impact water quality in hydroponic systems by altering pH, dissolved oxygen, and nutrient availability, often competing with target crops [13]. However, microalgae can benefit plant growth by producing oxygen through photosynthesis, preventing anaerobic conditions, and protecting roots. Additionally, crop root respiration and exudation that promote microalgal photosynthesis, like that of *Chlorella infusionum*, can enhance crop biomass in hydroponic systems.

In conclusion the effects of algae on hydroponic systems vary significantly and cannot be universally generalized, as they largely depend on the composition and density of the algal community, the type of crop being grown, and the prevailing climatic conditions.

In **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** we can observe a large volume of algae in an experimental cultivation in a container where conditions remained identical to the tomato plants in the tanks, but light wasn’t blocked from entering the container. No deterioration of plant health was observed. The root area of the plant seems to be healthy, but the biomass of algae has clogged the system.

Figure 2.9 Algae Growth in Roots of A Tomato Plant

2.4.3 Pythium Root Rot

Pythium is a genus consisting of many species, formerly classified as fungi have recently been moved to the genus of Stramenopila, it is parasitic and can be terrestrial or aquatic [24].

Tomato is particularly susceptible to pythium root rot, pythium can enter the system in similar ways to algae, either by airborne spores, or contaminated tools, water and substrates. [25] Pythium encysts the root area and produces inoculum, which is highly contaminating. Once these pathogens enter the system, controlling them becomes extremely challenging, often leaving the grower with no option but to destroy the crop. Pythium spp. can infect the delicate feeder roots of tomato grown in hydroponic systems, leading to a decrease in yield, even in plants that show no visible symptoms. It has been reported to be highly destructive in hydroponic systems, with the potential to devastate an entire crop within days.

Pythium root rot can be avoided by thorough decontamination of all surfaces of the hydroponic system in advance. Chemical or biological agents can be used to reduce damages [26].

Water temperature is directly related to the extent of damage caused by pythium root rot. At lower temperatures the damage has been reported to be less extensive [27]. Water temperature regulating systems can be expensive and were consequently avoided in this project. Nutrient tank temperatures were observed to fluctuate between 17- 20 degrees Celsius while ideal growing temperatures are at 18 degrees. The inability to regulate the tank's temperature was mitigated by storing the freshwater reservoirs outside of the greenhouse where ambient temperature was significantly lower. Another step towards alleviating root rot was the addition of an air bubbler. Higher levels of diffused oxygen aid in root health, without sufficient oxygen to support respiration, roots lose their ability to absorb water and nutrients, eventually leading to their death [28].

Figure 2.10 Example of pythium root rot, in a tomato plant in our system

Plants that were infected showed gradual deterioration and evidently complete necrosis.

3 UNDERSTANDING pH AND EC

3.1 The Importance of pH in hydroponics

In hydroponic systems, maintaining the correct pH is critical for plant health and nutrient uptake [29]. The pH level of the nutrient solution determines the availability of essential nutrients to the plants. If the pH deviates too far from the ideal range, plants may experience nutrient deficiencies or toxicities, even if the nutrients are present in the solution. For most hydroponic crops, an optimal pH range of 5.5 to 6.5 is recommended, as it ensures that nutrients remain soluble and accessible to the roots.

3.2 Managing pH levels

Monitoring and adjusting pH levels in hydroponic systems is essential for optimal plant growth. The pH of the nutrient solution can fluctuate due to various factors, including the type of nutrients used, water quality, and plant activity. Chemical adjustment is a common practice used to lower the pH by adding acids. The pH level is closely influenced by the concentrations of HCO_3^- and CO_3^{2-} ions. When an acid is added, the CO_3^{2-} ion is converted to HCO_3^-, which is further transformed into H_2CO_3. Carbonic acid (H_2CO_3) partially dissociates into water (H_2O) and carbon dioxide (CO_2) [30]. Typically, pH regulation involves the use of nitric, sulfuric, or phosphoric acids, which can be applied either separately or in combination. Regular testing with pH meters or test kits allows growers to maintain stability. If the pH drifts too high, acidic solutions such as phosphoric acid can be added to lower it. Conversely, if the pH drops too low, alkaline substances like potassium hydroxide can be used to raise it. Automated systems with pH sensors can further simplify this process, ensuring consistent levels without frequent manual adjustments.

3.3 The Role of Electrical Conductivity

Electrical Conductivity (EC) is a measure of the concentration of dissolved salts, or nutrients, in the hydroponic solution. It serves as an indicator of nutrient availability and the overall health of the nutrient solution. EC is measured in milliSiemens per centimeter (mS/cm), with optimal ranges varying depending on the type of crop being grown. Maintaining proper EC levels ensures that plants receive adequate nutrition without the risk of over-fertilization, which can lead to salt buildup and root damage.

It is important to note that Electrical Conductivity (EC) serves as an approximate indicator of the total salt concentration (TSC) in a nutrient solution due to the linear relationship between them [31]. When inorganic salts dissolve in water, they dissociate into cations and anions in a consistent ratio, allowing EC to be used as a proxy for TTS. Studies analyzing various hydroponic nutrient solutions have confirmed this relationship through regression analysis, demonstrating that EC can reliably estimate total salt concentration within a certain range. While minor discrepancies may exist, EC remains a practical and widely used tool for nutrient management in commercial hydroponic systems.

Plants require 17 essential elements for proper growth, which include carbon (C), hydrogen (H), oxygen (O), phosphorus (P), potassium (K), nitrogen (N), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), boron (B), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), chlorine (Cl), and more recently, nickel (Ni), which was identified as essential in 2004.

The most fundamental elements—carbon, hydrogen, and oxygen—are primarily obtained from air (carbon dioxide, CO_2) and water (H_2O). The remaining 14 elements, known as mineral nutrients, are absorbed through the plant's roots, usually from the growing medium or nutrient solution in hydroponic systems [32].

These nutrients are categorized into macronutrients and micronutrients based on the quantity required by plants. Macronutrients—needed in larger amounts include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). In contrast, micronutrients required in much smaller quantities (parts per million, ppm) include iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), chlorine (Cl), molybdenum (Mo), and nickel (Ni). In hydroponics, nutrients are dissolved in water in inorganic and ionic forms, ensuring efficient uptake by plant roots. While some nutrients may come from the water itself (e.g., well water in Florida contains calcium, sulfur, magnesium, and iron), most essential mineral nutrients are provided through fertilizers. This precise control over nutrient availability is one of the key advantages of hydroponic systems, ensuring optimal plant growth and productivity.

The ideal EC range for most hydroponic crops lies between 1.5 and 2.5 dS/m. ideal EC for tomatoes has been found to be between 1.7-2.7 after the mark of 2.7 decrease in yield has been observed. [33] The relationship between EC levels and climatic conditions, meaning temperature humidity, light intensity and light period has been found to vary and an exact relationship hasn't been established, as existing papers haven't reached a consensus the only reasonably well established fact is that a High EC value will hinder nutrient absorption by roots of the plants due to osmotic pressure, whereas significantly low value of EC will affect the crop health and its yield.

Optimizing EC for Plant Growth

To optimize EC, growers must consider the specific requirements of their crops and monitor changes in the solution caused by plant uptake or evaporation. Regular EC measurements, typically taken with an EC meter, help ensure that nutrient concentrations remain within the desired range. Adjustments can be made by adding fresh water to dilute the solution or by supplementing additional nutrients to increase the EC. Maintaining a balance is crucial, as both excessively high and low EC levels can adversely affect plant health and productivity. Automated systems that integrate EC sensors can streamline this process, providing real-time feedback and precise adjustments to maintain optimal growing conditions.

An important aspect of taking EC measurements in hydroponics is the relationship between electrical conductivity and temperature. This is generally nonlinear, however, within the temperature range typically observed in environmental monitoring (0–30 °C), the nonlinearity is minimal. Consequently, a linear equation is often used to describe this relationship:

$$EC(t) = EC(25) \cdot [1 + a(t - 25)] \tag{1.1}$$

Here, $EC(t)$ represents the electrical conductivity at a given temperature ($°C$), $EC(25)$ is the electrical conductivity at a standard temperature of $25\,°C$, and a is the temperature compensation coefficient, $a = 0.02$ [34].

4 THE PLANTS

4.1 About Tomato

Tomato (*Solanum lycopersicum L.*) [35] is one of the most widely consumed vegetables worldwide, ranking after potatoes and before onions in terms of global consumption. With a production of nearly 160 million tonnes in 2011 and 189.1 million tonnes in 2021 [36] it stands as the seventh most important crop species, following maize, rice, wheat, potatoes, soybeans, and cassava [37]. Global tomato production, both fresh and processed, has seen nearly a threefold increase over the past four decades (1970-2010). By 2005, the Food and Agriculture Organization (FAO) estimated total production at approximately 123 million tons, cultivated across an area of around 4.5 million [38]. Interestingly, countries with the highest yield per unit area are in northern Europe, where tomatoes are primarily grown in controlled greenhouse environments. The widespread use of tomatoes in culinary applications, including fresh consumption, juice, sauce, paste, concentrate, powder, and processed products—has contributed to its rising demand. The local production of tomatoes plays a vital role in promoting sustainability and reducing environmental impact. Germany imported 738,000 metric tons of fresh tomatoes in 2016, with 54% sourced from the Netherlands (402,000 metric tons) and 25% from Spain (188,000 metric tons) [39].

The Germany-Spain tomato trade illustrates how importing large quantities of tomatoes shifts resource consumption and ecological burdens to the producing regions. In Spain, greenhouse cultivation in arid areas like Almería places immense pressure on water resources, contributing to depletion and long-term sustainability concerns. Additionally, transporting tomatoes over long distances increases carbon emissions, further exacerbating environmental challenges

The continued rise in tomato consumption highlights its indispensable role in global food systems, with hydroponic and greenhouse technologies playing a crucial role in optimizing production efficiency in regions with unfavorable climatic conditions.

4.1.1 The Vilma variety

The *Vilma* tomato variety was chosen for this project. It is a determinate, dwarf cherry tomato known for its compact growth habit, making it ideal for container gardening or indoor cultivation. This variety is particularly suited for small spaces due to its manageable size and high yield of small, flavorful fruits.

Plant Characteristics

The plant exhibits a determinate growth habit, characterized by a compact, bush-like form that typically reaches a height of 20–30 cm (8–12 inches). It is sturdy and self-supporting, requiring minimal staking or structural support. The flowers are self-pollinating, with pollination facilitated naturally through wind or gentle vibration. It produces cherry tomatoes, which are small—averaging 1–2 cm (0.4–0.8 inches) in diameter and bright red when ripe, with glossy skin. The fruits are known for their sweet and tangy flavor, high sugar content, and balanced acidity. Their firm yet juicy texture and smooth, crack-resistant skin make them ideal for fresh consumption. In terms of growing conditions, the plant thrives in full sunlight, needing 6–8 hours of light per day, and performs best in warm temperatures ranging from 18–25°C.

4.1.2 Seedling

In hydroponics, especially as an amateur grower, raising seedlings is an essential step because hydroponic-ready plants are not typically available in the market. Unlike traditional gardening, where you can purchase soil-grown plants from nurseries and transplant them directly, hydroponic systems require plants that have been specifically grown and adapted for soilless environments. Raising your own seedlings also enables you to choose specific varieties of plants that are well-suited to hydroponic conditions, giving you greater flexibility in what you grow. While it may require more effort, it is cost effective and more productive in the long run.

As most times in conventional farming, in hydroponics also, seedlings need to be sawn separately and after reaching a certain point of maturity are finally transplanted. In large scale agriculture, seedlings are sown in protected conditions that ensure better percentages of germination. Seeds need high temperatures and high humidity in order to germinate, also a lack of sunlight during the first few days and later are introduced to stronger light levels.

In this project tomato seedlings were sown in rockwool blocks, nestled inside ice cube trays. Each slot of the tray has a hole opened in the bottom from where water can seep through onto the rockwool. The tray is placed inside a large container where the desired water level is maintained, and the lid is closed to ensure higher humidity levels. The container was placed at room temperature since highest germination percentage (81% to 86%) is observed in the range of 20-30 degrees Celsius.

No nutrient solution was used in this stage as salinity negatively affects tomato seed germination rate and speed, therefore seedlings received only water for the first 15 days [40].

Figure 4.1: Cutting Rockwool into Smaller Pieces (Left). Placing Tomato Seeds on the Rockwool (Right)

Figure 4.2 Clockwise from top left) - Ice Tray Partially Submerged in Water and Inside Sealed Container. Seedlings after 1 week. - Seedlings after 3 weeks. - Young tomato plant after 4 weeks

5 Assembly

5.1 The Concept

After many designs, much research and testing, the final design concept is the following. The system can be broken down into three subsystems:

- Cultivation tanks;
- Test tray;
- Supporting systems;
- Microcontroller and electrical systems.

Inside a grow tent the plants are placed on the top of cultivation tanks with their roots submerged in the water/nutrient solution below, the tanks are interconnected with a 1cm rubber tube. Outside the grow tent the test tray acts as the decision-making hub. Through a pump in the cultivation tanks, water and nutrient mix flows to the test tray where pH and EC readings are taken by the sensors. Then adjustments are made accordingly. If pH is out of range, pH down acid solution is dosed into the tanks, if EC is too high, fresh water is pumped into the tanks and finally if EC is found low nutrients are dosed. A water level sensor inside the cultivation tanks avoids system overflow. The test tray subsystem can both fill the tanks prior to cultivation, this will be called filling mode and maintain ideal plant conditions throughout their life cycle, this will be referred to as conservation mode. An air pump with two airstone diffusers is in constant operation to enrich nutrient solution with air. The test tray system, operated by an Arduino uno, provides a dynamic element to the setup affecting productivity in a positive manner.

This automated hydroponic system is part of a larger integrated setup designed to optimize plant cultivation under controlled conditions. The entire system is housed within a 2x1.5meter plastic grow tent located indoors, providing an enclosed environment for precise control and monitoring. Complementary to this hydroponic system, climate and light control systems were developed by Aris Karvounis and Panos Alexopoulos as part of their respective theses. These systems regulate temperature, humidity, and lighting conditions, ensuring the plants receive optimal growth environments throughout their lifecycle. Together, these subsystems form a fully automated system, demonstrating the potential of hydroponics when paired with precise environmental management.

Figure 5.1 The Grow Tent

5.2 Sensors and Materials

In this chapter, we examine the various sensors and equipment employed in the system, focusing on their functionality, technical specifications, and integration. The discussion includes an analysis of electrical conductivity (EC) meter, pH sensor, temperature sensor and liquid level sensor. Furthermore, the chapter explores the role of air pumps, peristaltic pumps, cultivation tanks, and nutrient solutions in optimizing system performance and ensuring the longevity of critical components.

5.2.1 DFRobot Gravity: Analog Electrical Conductivity Meter V2

Figure 5.2 Electrical Conductivity Probe (Left), Signal Conversion Board (Right)

To take EC readings the Gravity: Lab Grade Analog EC Sensor Kit (K=1) was used to measure electrical conductivity (EC) for nutrient level monitoring in the hydroponic system. Dfrobots' Gravity: Analog Electrical Conductivity Meter V2, K=1 (**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**), is an electrical conductivity sensor compatible with Arduino uno, it supports a Voltage Input of 3.0~5.0V Supports two-point calibration, it automatically identifies standard buffer solutions, integrates a temperature compensation algorithm, and has a detection range of 0~20ms/cm, ideal for EC values found in hydroponics. The sensor was calibrated according to the manufacturer's instructions before the first use and then every few days to ensure accurate readings. Unfortunately, the probe is laboratory grade and cannot be used for long periods of submersion, with a life of use of approximately 0.5 years. Therefore, an attempt was made to extend the life of the probe by using it only when necessary, meaning when the design was finalized, and rinsing it with distilled water after each use.

5.2.2 Aqua Master E50 Pro handheld EC meter

At the first stages of the project, for taking measurements on the fly and to alleviate the use of V2, Aqua Master's E50 Pro handheld EC meter was used (**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**). This proved very helpful as a means of calibrating the v2 sensor which tends to be less reliable and is prone to malfunction and inaccurate readings, so being able to use it only when the design was complete and only in necessity to prolong its life was made possible by swapping it for the handheld EC meter at times.

Figure 5.3 handheld EC meter

The Aqua Master E50 Pro can detect EC and temperature with a range of 0.0 to 19.9 mS/cm for EC and 0°C to 50°C) for temperature. It offers a resolution of 0.1 mS/cm for EC and 0.1°C for temperature, with an accuracy of ±2% F.S. for EC and ±0.5°C for temperature. The device includes automatic temperature compensation within the range of 0°C to 50°C. Powered by three 1.5 Volt AG-13 button cell batteries.

5.2.3 DFRobot Gravity: Analog pH meter V1

Figure 5.4 pH Probe

The DFRobot Gravity: V1 Analog pH Sensor was used. This is a low-cost Ph sensor, compatible with Arduino uno that supports a supply range of 3.3V to 5.5V.A two-point calibration method automatically recognizing standard buffer solutions of pH 4.0 and 7.0. Detection Range: 0 to 14 pH Temperature Range: 5°C to 60°C. The electrode was immersed in an 3NKCL solution for eight hours to activate before first use according to manufacturer’s advice.

Ph indicator paper was used as a quick way to crosscheck for sensor accuracy or to take measurements on the spot.

5.2.4 Other Sensors Used

Waterproof Temperature Sensor - DS18B20

The waterproof DS18B20 temperature sensor operates within a range of -55 to 125°C with an accuracy of ±0.5°C and a working voltage of 3.0V to 5.5V; in this system, it is used for EC value corrections by incorporating its temperature readings into the EC compensation process.

Figure 5.5 Temperature Sensor

Waveshare Liquid Level Sensor

The sensor offers a detection depth of 48 mm and operates within a voltage range of 2.0V to 5.0V, providing a cost-effective solution for reliable measurements in various applications.

Figure 5.6 Liquid Level Sensor

5.2.5 Other Equipment

An air pump was used to enrich nutrient mixture with oxygen. Even though the Kratky method doesn’t require additional oxygen, improvement in plant vigor and root health was observed with added oxygenation.

Therefore, the use of this air pump with total volumetric air flow of 3lt/ min was deemed necessary. The pump has 2 outputs, one for each tank, connected by a 2mm plastic tube with an air stone at each end. The pump runs continuously, enriching the nutrient solution with air

Figure 5.7 Air Pump

Two 100mm air stones were used, one in each tank. Air stones are made from porous stone, they help to diffuse air into the water tank

Figure 5.8 Air Stone

5.2.6 Pumps

For nutrient injection in the system two peristaltic pumps were used with the following specifications: Peristaltic Liquid Pump 12V DC - Tube 3x5mm Flow 19-100ml/min, ideal for small volume dosing, these pumps can offer very good accuracy of the dispensed volume. Referred to as pumpA and pumpB in the code, each will be responsible for dosing nutrient solution A and nutrient solution B.

To regulate the pH, another peristaltic pump was used to dose 1-3 ml of pH down solution when necessary.3

Figure 5.9 Left 12v Peristaltic Pump, Right 5v Pump

5.2.7 Cultivation Tanks

Figure 5.10 90lt tank

For the cultivation of the plants, two rectangular tanks were selected: one with a capacity of 65 Liters and another with a capacity of 90 Liters, both made of rigid black plastic. The 90-liter tank has the following dimensions: 32 cm in height, 77.5 cm in length, and 55.5 cm in width, while the 65-liter tank measures 32 cm in height, 68.5 cm in length, and 46.5 cm in width.

These tanks were chosen because their depth allows for maximum utilization of the greenhouse space. The depth is sufficient for the roots of the plants to develop properly. According to standard practice, they are made of black plastic to minimize light penetration.

To position the plants on the tanks, expanded polystyrene sheets were used. Specifically, FIBRAN XPS 300 extruded polystyrene was selected due to its satisfactory mechanical strength, insulating properties, low cost, and ease of processing.

The sheets were cut to the dimensions of the tanks, and holes were then made to accommodate the net pots.

Net pots with a diameter of 8 cm were used to accommodate the plants. Hard plastic net pots, usually made from polypropylene are specifically used in hydroponics, are cheap and reusable

Figure 5.11 Net Pot

5.2.8 Nutrients Used

For plant nutrition, B’cuzz Hydro A was used, a versatile nutrient solution specifically formulated for hydroponic systems. It contains essential macronutrients such as nitrogen (4.9% w/w) and potassium (4.7% w/w), along with secondary nutrients like calcium (3.8% w/w) and magnesium (1.3% w/w). Additionally, it includes trace elements like iron (0.04% w/w), ensuring a balanced nutrient supply for healthy plant growth. B’cuzz A and B nutrient solutions are formulated to support the plant through its entire life cycle, providing all necessary macro and micronutrients from early growth to harvest without the need to switch formulas. This made them an ideal option for this project, as it simplified nutrient management and reduced the risk of imbalance or deficiencies. Their competitive pricing and availability in volumes suited to amateur growers further added to their suitability. Additionally, their liquid form made them far easier to use compared to cheaper solid nutrients, which often require extensive mixing and are difficult to dose with precision. This convenience and consistency contributed to a more efficient and hassle-free growing process.

Figure 5.12 A and B Nutrient Solutions

A predictable upward trend in pH within our system was observed, therefore, only pH Down is required to maintain stability. for the pH down solution an acid solution was used, containing nitric acid, phosphoric acid, and organic regulators.

5.3 Construction

5.3.1 The cultivation tanks

The polystyrene sheets were cut to the dimensions of the tanks, and holes were then made to accommodate the net pots.

Figure 5.13 Making Net Pot Pattern (Left), Opening Holes Using Soldering Rod (Right)

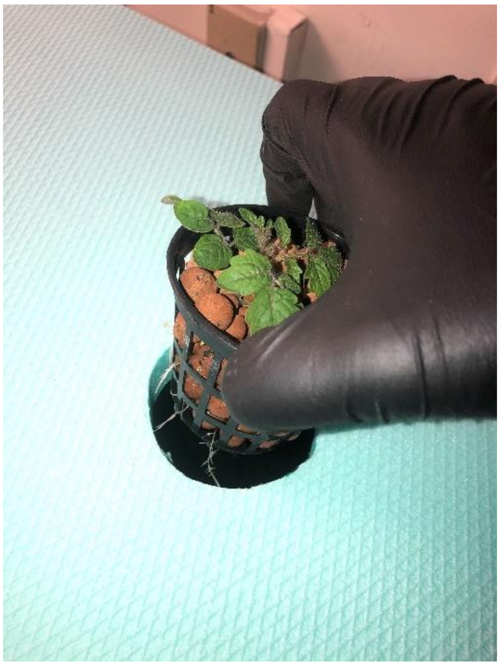

Figure 5.14 Final Fitting of The Net Pot

In hydroponics, A and B nutrient solutions are kept separate and not mixed directly to prevent the precipitation of certain nutrients. This issue arises because specific ions in the solutions can react with each other and form insoluble compounds that precipitate out of the solution, making those nutrients unavailable to plants. Another limitation is that nutrient solutions cannot be directly pumped into the cultivation tanks. To ensure solubility 1-3 ml of nutrient solution must be mixed with 1 liter of water before they can be added to the rest of the water and nutrient mix [41]. Therefore, a specific tank was made where nutrients could be premixed with fresh water before they are moved to the larger tanks. This tank, which is a 30x21x17 cm, 7 L PET container with holes made on its lid, is food grade, cheap and easy to modify (see figure 5.14). Wholes made on the lid accommodate the EC and pH sensors. The tray is placed out of the greenhouse, ensuring that the extremely fragile sensors operate under lower temperatures and significantly lower humidity and light induced damage, this, together with the fact that the user now has easy access to clean them, when necessary, significantly prolongs their life and possibly improves accuracy in the long term.

Inside the tray, a smaller 1-liter container is securely fixed at the bottom. This smaller container is essential as it serves as the mixing chamber where nutrients are combined with water. Using a smaller volume ensures more efficient and thorough mixing. A pump installed within the smaller tray transfers the nutrient solution to the larger container as needed. A pump inside the large container moves the nutrient solution to the grow tanks

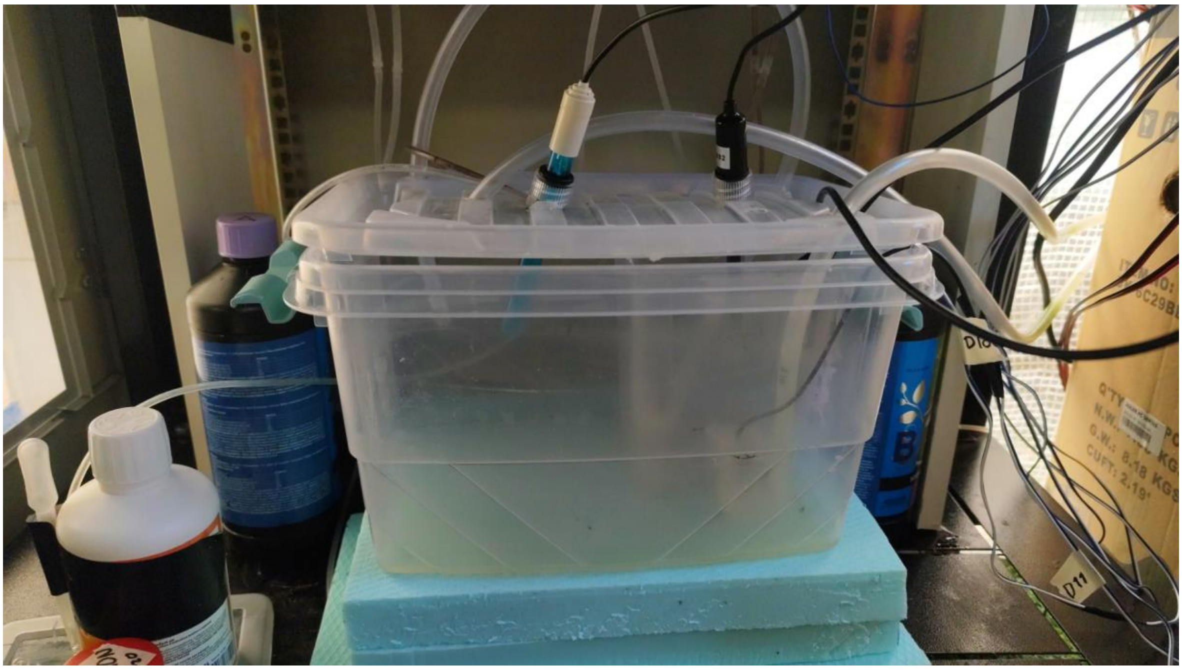

Figure 5.15 The Test Tray

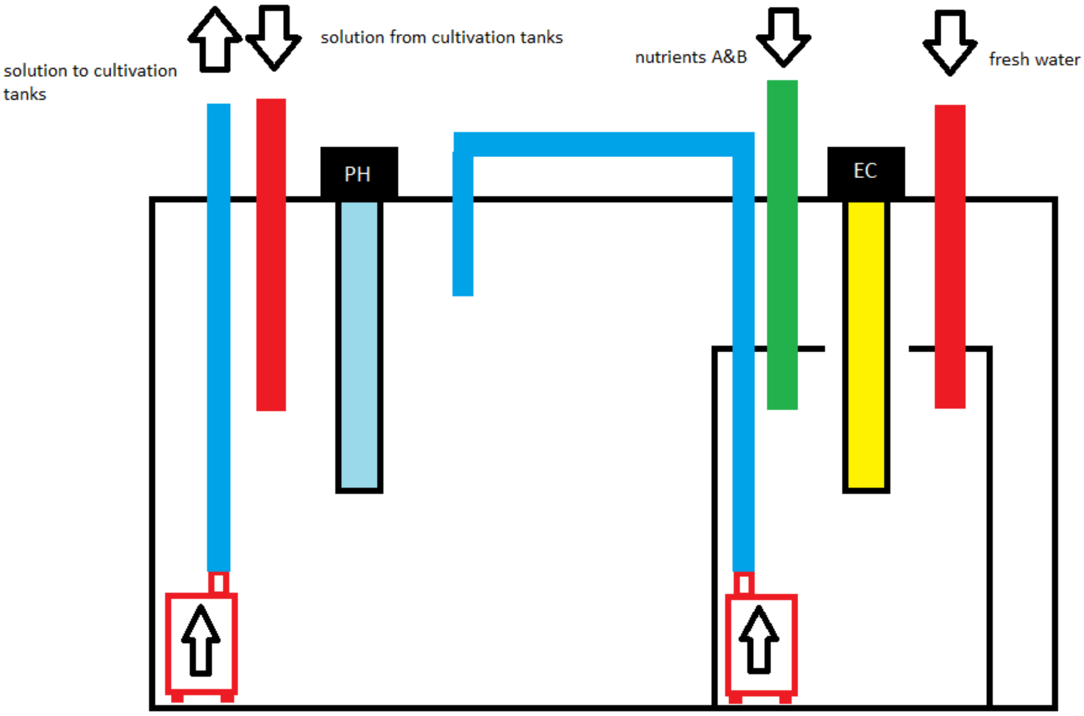

Figure 5.16 The test tray with arrows pointing up (out) or down (in) corresponding to liquid flow

The pumps are ideally placed almost directly above the test tray, when the pump is positioned closer to the liquid source, with a shorter pipe length, it reduces the lag time between the pump's operation and the liquid being drawn or discharged. By shortening the pipe length, the pump achieves a more immediate response, ensuring that the desired volume of liquid is delivered consistently and accurately, which is crucial for precise nutrient dosing. A frame was designed to hold pumps securely in place. One horizontal 60x10cm plank and two equal length 41x12cm vertical planks were cut. Pilot holes were drilled where the legs attach to the top plank, aligned, and secure with screws. For extra strength, hot glue was used at the joints. The horizontal plank at the top acts as a mounting surface where the peristaltic pumps were attached with hot glue. This setup allows the pumps to be elevated above the ground, providing easy access to the tubing and ensuring proper alignment with the liquid reservoirs below. A side by side placement of the pumps facilitates efficient wiring because it minimizes the distance between each pump, reducing the amount of cable required for connections.

Figure 5.17 Assembly of frame

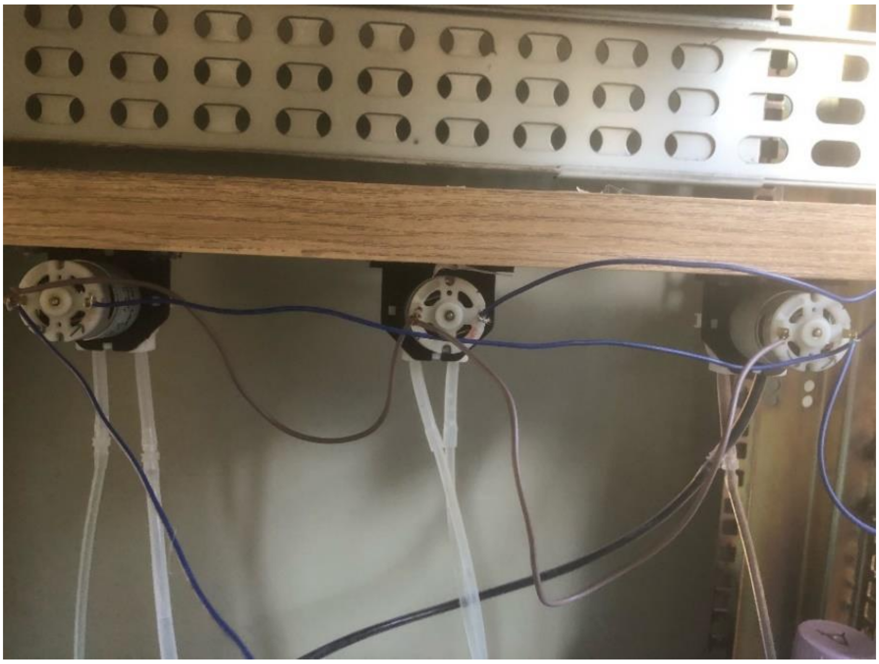

Figure 5.18 Peristaltic pumps a and b with pH peristaltic pump in the middle

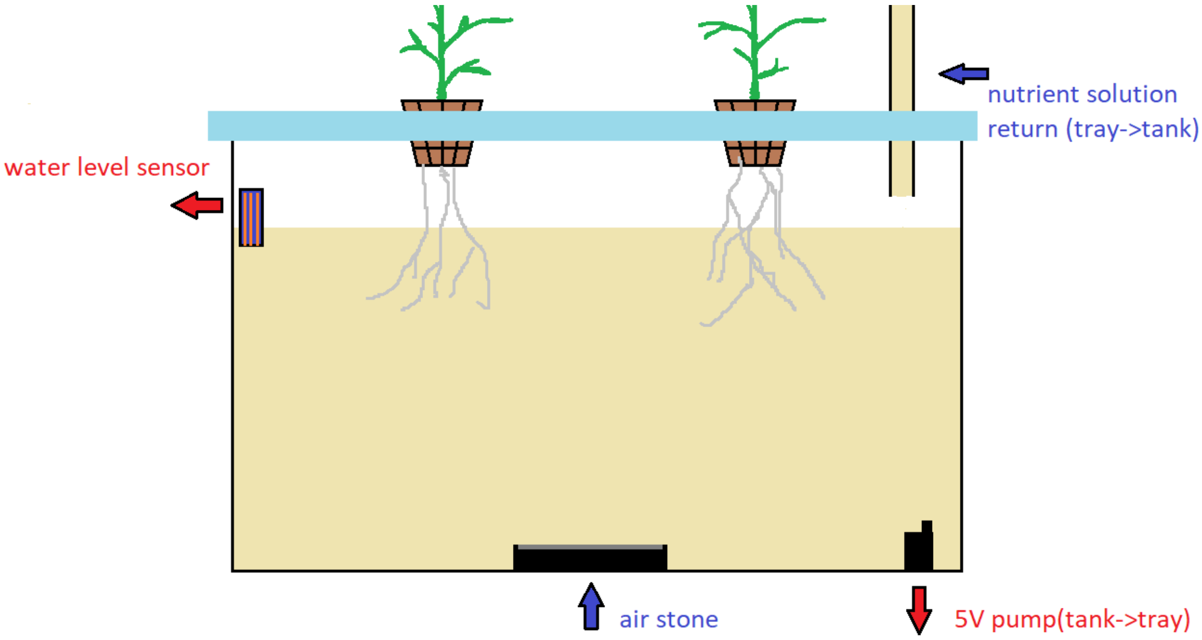

Figure 5.19 Cultivation tank sketch and components

6 CONNECTIONS AND CODE

6.1 Arduino Uno and electrical components

For the purposes of this project an Arduino uno microcontroller with integrated WiFi connectivity was used. The Arduino Uno is a highly versatile microcontroller board based on the ATmega328P microchip, widely recognized for its reliability and ease of integration into electronics and automation applications. It is equipped with 14 digital input/output pins, 6 analog input pins, a USB interface for programming, and a power jack, making it suitable for a broad range of tasks. Its open-source architecture and extensive community support further enhance its accessibility and functionality. In automated systems such as hydroponic greenhouses, Arduino Uno plays a critical role as a central control unit, facilitating the management of sensors, actuators, and other components to ensure precise and efficient system operation as well as remote monitoring and coding.

Figure 6.1 Arduino UNO R3 board

On the top side, a series of digital input/output pins are labeled 0 to 13, with PWM-enabled pins marked by a tilde (~). Below these, there are analog input pins labeled A0 to A5. These pins allow the board to interact with various sensors and devices.

6.1.1 LRS-50-12 Power Supply

The LRS-50-12 is a 50W AC-to-DC power supply with a 12V DC output. It has a compact, perforated design for efficient cooling and includes built-in protections against overvoltage, overload, and short circuits. This power supply is used to provide a stable 12V DC power source for the system. It powers components such as the relays and motors, ensuring consistent and reliable operation.

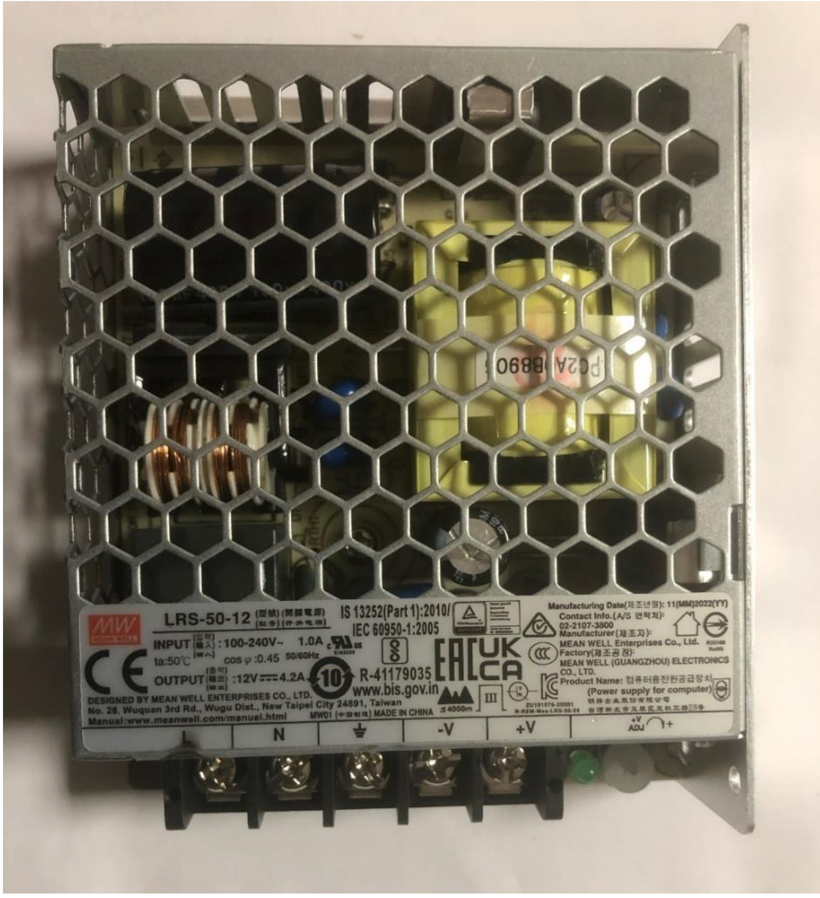

Figure 6.2 Power Supply

6.1.2 Relays

The relays act as electrical switches, allowing the low-power signals from the microcontroller (Arduino UNO) to control high-power devices like motors. In the circuit, two 5V relay modules are used, one of the peristaltic pumps and a 5v pump and the other for the rest of the 5V pumps.

Figure 6.3 5v relay module

6.1.3 Breadboard

Purpose: The breadboard serves as a platform for connecting various components in the circuit without soldering. It allows for flexible prototyping and easy adjustments.

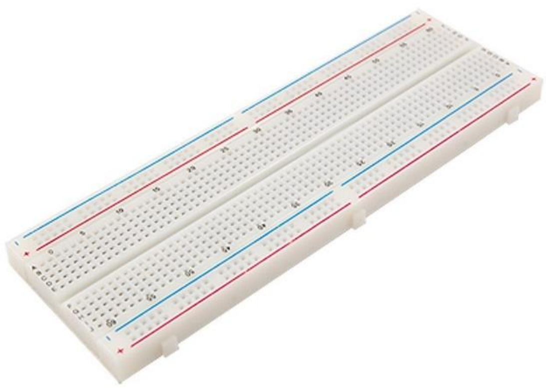

Figure 6.4 Breadboard

6.1.4 Overall System Integration

The system uses the LRS-50-12 to provide a stable power source, while the Arduino serves as the control center. The relays act as intermediaries, allowing the low-power control signals from the Arduino to switch on and off the pumps. The breadboard simplifies connections, while sensors provide the essential input for actions.

6.1.5 Electrical Connections

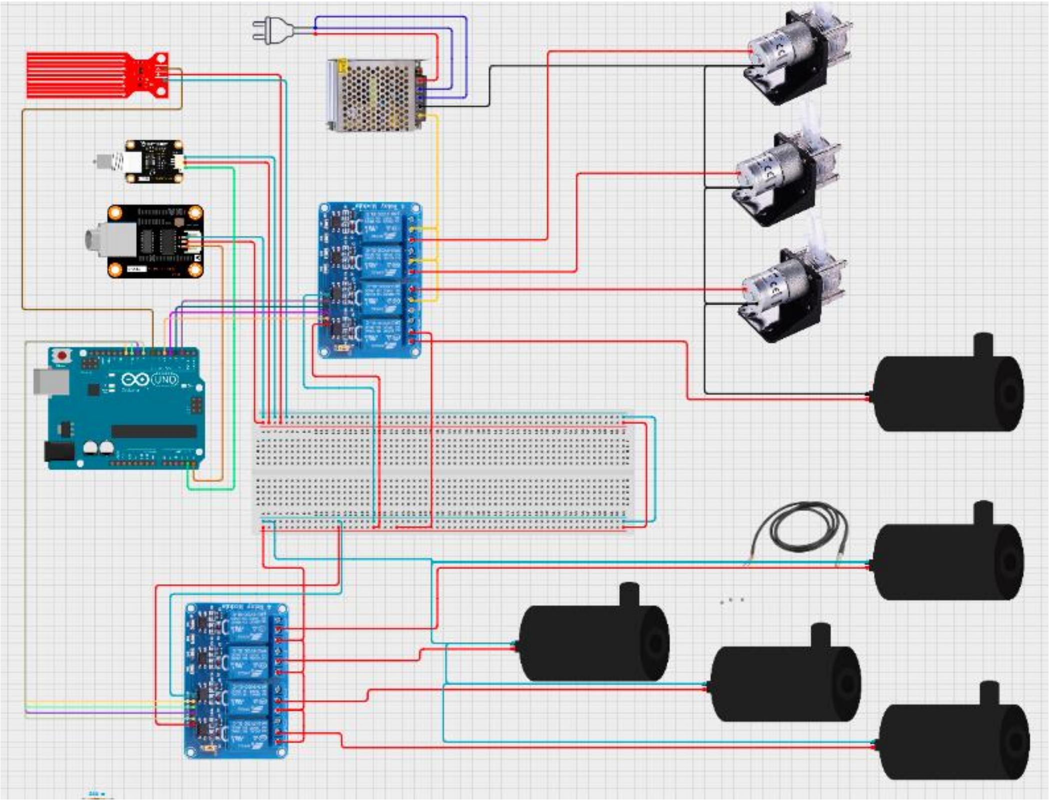

Figure 6.5 Wiring of the system

Wiring connections exposed directly to liquid or to humid environment were waterproofed with Teflon tape. Which is food grade and easily available.

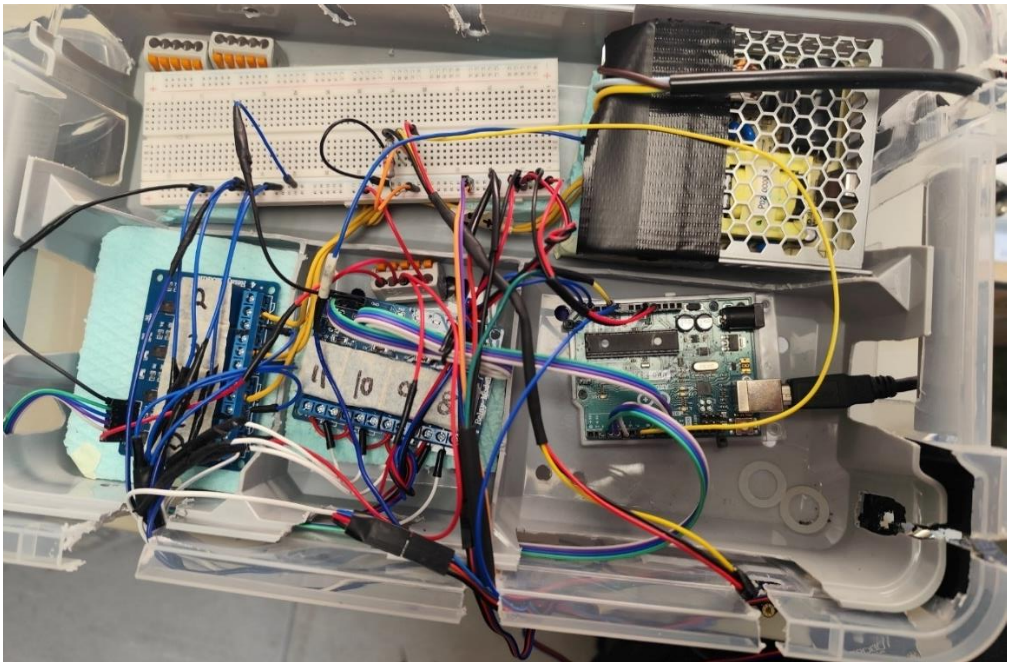

Figure 6.6 Arduino board compartment

6.2 Coding the system

The Arduino Uno operates using the Arduino Integrated Development Environment (IDE), an open-source software platform designed for programming and uploading code to Arduino boards. The IDE supports a simplified version of C/C++ and provides a comprehensive library ecosystem, enabling users to implement a wide range of functionalities efficiently. It features a straightforward interface for writing, debugging, and compiling code, as well as a serial monitor for real-time communication with connected devices. This software serves as a critical tool for developing and managing automated systems, such as those utilized in small scale hydroponic greenhouses.

In the following decision flow diagram, the logic of the system is explained and in figure 6.7 an illustration presenting the equivalent flowchart is provided.

A. **Fill Test Tray with Water**
    - Turn on pumpTestTrayIn.
    - Wait for pumpTestTrayInRunTime (4 minutes).
    - Turn off pumpTestTrayIn.

B. **Measure pH**
    - Call measureAveragePH().
    - Calculate average pH over 1 minute.

C. **Is pH > pH_Threshold?**
    - **Yes**:
        - Turn on peristalticPH for peristalticPHRunTime (3 seconds).
        - Turn off peristalticPH.

- **No**:
  - Skip pH adjustment.

D. **Measure EC**
- Call measureAverageEC().
- Calculate average EC over 1 minute.

E. **Check Water Level**
- Read liquidLevelSensorPin.
- **Is water level HIGH?** (sensorValue > wetThreshold)
  - **Yes**:
    - Skip fertilizer addition.
    - Proceed to **Final Flush**.
  - **No**:
    - Proceed to EC check.

F. **Is EC < EC_Threshold?**
- **Yes**:
  - Proceed to **Add Fertilizers**.
- **No**:
  - Skip fertilizer addition.
  - Proceed to **Final Flush**.

G. **Add Fertilizers**
- Turn on pumpTestTrayOut for 3 minutes.
- Turn off pumpTestTrayOut.
- Turn on pumpOut for 45 seconds.
- Turn off pumpOut.
- Turn on peristalticA for (1 second).
- Turn off peristalticA.
- Turn on freshAB for 32 seconds.
- Turn off freshAB.
- Turn on pumpOut for 40 seconds.
- Turn off pumpOut.
- Turn on peristalticB for (2.1 seconds).
- Turn off peristalticB.
- Turn on freshAB for 40 seconds.
- Turn off freshAB.
- Turn on pumpOut for 40 seconds.
- Turn off pumpOut.

H. **Final Flush**
- Turn on pumpTestTrayOut for 1.1 minutes.
- Turn off pumpTestTrayOut.
- Turn on pumpOut for 40 seconds.
- Turn off pumpOut.

I. **Wait for Next Cycle**
- Delay for 60 seconds.
- Return to **Step 2** (Fill Test Tray with Water).

J. **End**

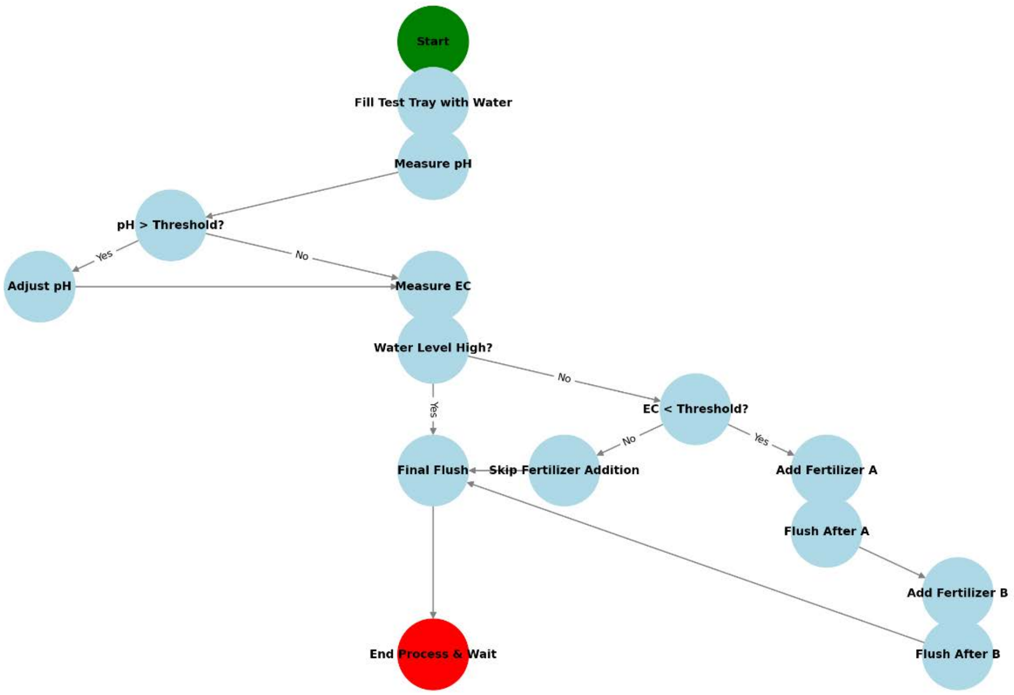

Figure 6.7 Flowchart illustration

7 RESULTS

7.1 Observations

In a cultivation period of 3 months, we successfully achieved a water efficiency of 30 liters per kilogram of tomatoes in a hydroponic system, despite significant challenges during the productive cycle. For most of the cycle, tomato plants were affected by a virus, which typically hampers growth and productivity. However, the precise control of water and nutrient delivery, combined with the automated environmental monitoring system, allowed us to mitigate the adverse effects of the virus. This demonstrates the resilience and efficiency of the hydroponic system, even under suboptimal conditions, further highlighting its potential for sustainable agriculture. The following table (Figure 7.1 Irrigation Water Requirements for Tomato Production Across Different Growing Systems

) represents water consumption among different cultivation systems and provides comparison between our selective data.

Climate and Growing System	**Tomato (kg water per kg produce)**
Open field production	60
Spain, unheated plastic "parral"	40
Israel, unheated glass	30
Spain, unheated "parral", regulated ventilation	27
Holland, climate-controlled glass, CO2 enrichment	22
Holland, as above, with re-use of drain water	15

Figure 7.1 Irrigation Water Requirements for Tomato Production Across Different Growing Systems

In **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**, the tomato production over a 15-day period by 2 plants in the system is shown. The average production is calculated to be close to 4 tomatoes per plant per day. Meaning that the 5 plants system can easily achieve 20 tomatoes daily. The recorded data was taken before the air bubblers were incorporated into the system, meaning that this is possibly the minimum production capacity of the system. An estimation taking into consideration the increase in production caused by sufficient oxygenation calculates daily production to be 26 units.

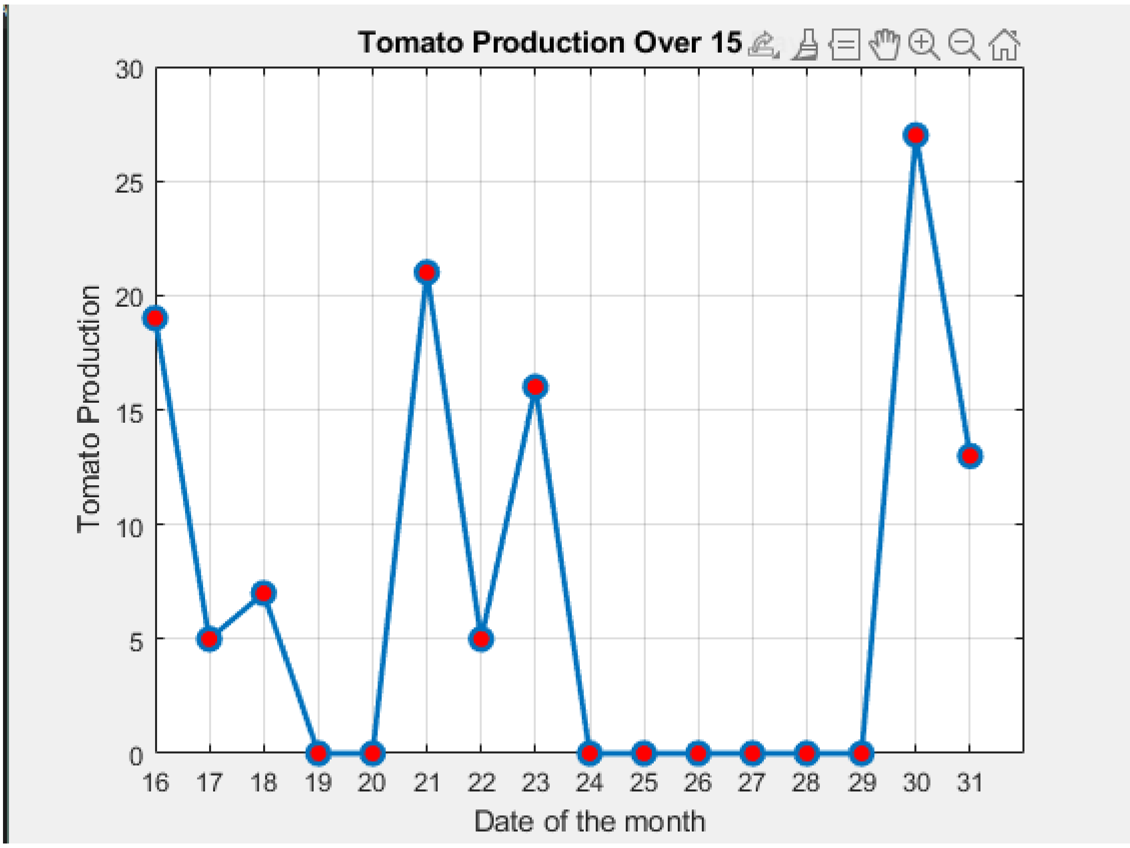

Figure 7.2 Tomato production over a 15-day period by 2 tomato plants

Figures **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε. - Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** illustrate the **average EC (Electrical Conductivity), pH, and temperature** readings collected from the **Arduino Cloud** over a selected period.

For a more detailed explanation of the process of connecting **Arduino** to the **IoT Cloud**, as well as its individual functions and capabilities, you can refer to the thesis by **Aris K. and Panos A.**, titled **"**Smart Greenhouse - Climate Control and Lighting System**"**, which extensively explored this subject. In the context of this thesis, the **IoT Cloud** was primarily used for generating **graphs**, enabling the visualization of **sensor readings** and providing a clearer understanding of fluctuations throughout the day. Therefore, it is presented here in a summarized manner.

Figure 7.3 EC readings

Figure 7.4 pH readings

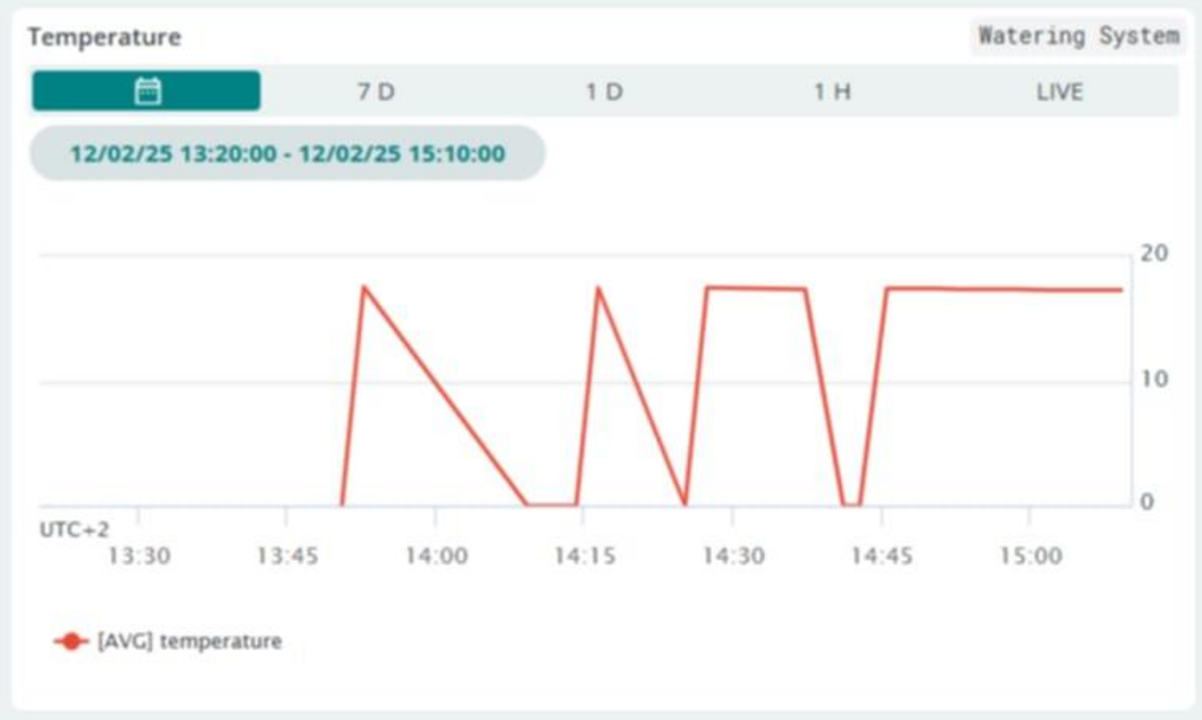

Figure 7.5 Temperature readings

7.2 Challenges

In the duration of this project a series of challenges arose, both of agricultural and of technical nature.

7.2.1 Challenges in Hydroponic Cultivation

One of the major challenges faced during cultivation was the occurrence of root rot. This disease thrived in the nutrient-rich, recirculating solution, leading to significant damage to plant roots, stunting growth, and ultimately causing crop losses. Compounding the issue, there was an outbreak of a virus, which spread rapidly through the hydroponic system via the recirculated nutrient solution and infected nearly all plants. The severity of the outbreak rendered the crop unsalvageable, necessitating a complete halt in operations. The entire system had to be thoroughly sanitized to prevent further contamination, involving draining and replacing the nutrient solution, sterilizing equipment, and disinfecting all surfaces. These events highlighted the critical importance of proactive disease management, regular monitoring, and stringent sanitation protocols to ensure the sustainability of hydroponic cultivation.

7.2.2 Growing system modifications

Initially designed as a Kratky system, the hydroponic setup relied on passive oxygenation by leaving a gap between the nutrient solution and the plant roots, allowing natural air exchange. While this method is effective for short-term or low-demand crops, it became evident that the plants, having higher oxygen requirements, were showing signs of stress, and root rot. To address these issues, the system was revised into a modified Deep -Water Culture (DWC) set up by incorporating air pumps and air stones. This active aeration system ensured a consistent supply of dissolved oxygen to the roots, promoting healthier growth and preventing such issues.

7.2.3 Hydraulic and mechanical problems

The small 5V water pumps in the system often encountered **airlock problems**, a situation where air becomes trapped inside the pump, disrupting the flow of water and preventing the pump from operating efficiently. This issue typically occurred when the pumps were turned off or when liquid levels dropped below the intake level of the pump, allowing air to enter the system through minor leaks or backflow. Once trapped, the air formed pockets that hindered the pump's ability to prime itself, leading to inconsistent or null water flow.

To resolve this, a head pressure system mechanism was introduced, as shown in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**. A reservoir or elevated water column was strategically placed above the pump, creating additional pressure in the system without increasing significantly the pump's load. When the pumps were turned off, the water from the elevated reservoir rushed back down into the pump due to gravity. This sudden influx of water effectively expelled the trapped air, ensuring that the pump remained primed and ready for operation upon restarting.

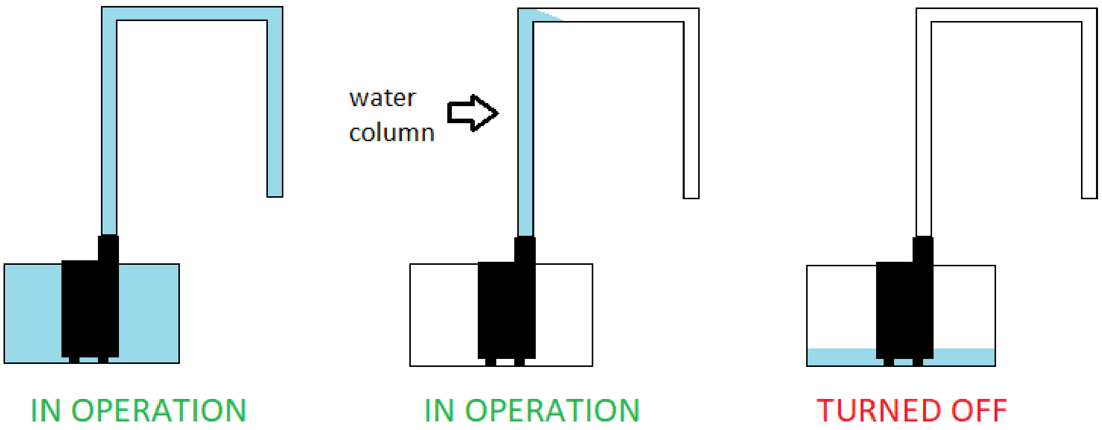

Figure 7.6 Head pressure system

This simple modification eliminated the airlock issue, stabilized the water flow, and enhanced the overall reliability of the hydroponic system. The solution also required little to no maintenance, making it a practical choice for long-term operation while keeping costs minimal.

Another downside to these pumps was the lack of sealing mechanisms, which led to bidirectional flow. This means that when the pump is turned off, liquid can flow back into the system through the pump, potentially mixing with unwanted substances. This bidirectional behavior occurs because these pumps do not have integrated check valves or other mechanisms to prevent backflow, leaving the system vulnerable to liquid movement in the reverse direction when turned off.

To mitigate this issue, the pumps were strategically placed at a specific height relative to the reservoir, in addition the ends of the tubing were never submerged in the liquid volumes but remained in contact only with atmospheric air. This design prevented the reverse flow caused by the principle of communicating vessels, as air acted as a natural barrier.

The most significant issue with these pumps, which became noticeable in the later stages of this project, was that they began to fail. Upon closer inspection water damage was deemed responsible. The combination of poor sealing, substandard materials, inadequate insulation, and continuous operation likely led to water ingress and corrosion, resulting in damage visible in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**. Investing in higher-quality pumps with better waterproofing, corrosion-resistant materials, and robust construction can significantly increase durability and prevent such failures.

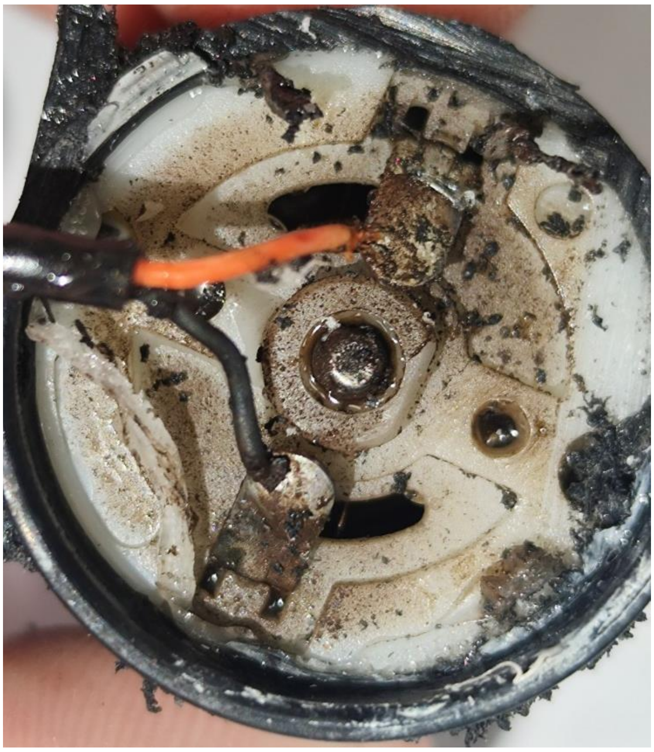

Figure 7.7 Signs of Water Damage In 5v Pump

Another issue not accounted for in the beginning of the process is Arduino Uno's dynamic memory capacity, the microcontroller provides only 2 KB of SRAM. As the code grew more complex with added functions, memory usage exceeded safe limits, causing instability. To address this, the program was split into two parts: one for the filling mode and another for the conservation mode. This reduced memory usage in each phase, allowing the system to run reliably despite the hardware constraints.

8 Conclusion

So far, hydroponics appears to be the only viable solution capable of reducing the pathologies affecting conventional agriculture. Climate change, increased production demands, environmental impact, and soil degradation all contribute to the growing challenges in agriculture. Hydroponics is presented as an ideal solution to address these issues. Europe, particularly its southern regions, will soon face increasingly harsh conditions for cultivation, as has already been observed. Prolonged droughts, flooding, heatwaves, and other adverse weather events are becoming more frequent. Hydroponics offers solutions, provided that governments and relevant organizations begin to favor it over conventional methods.

However, large-scale hydroponic installations, which require substantial initial capital and land, cannot be the sole focus. Hydroponics must become widely accessible, from amateurs to professionals, and not just for large-scale investors. This approach would ensure that even smaller and remote areas have access to higher-quality vegetables, while increasing expertise through cumulative knowledge rather than concentrating it in the hands of a few. This would also enable faster development within the sector.

Smaller-scale systems, which focus on cost-effectiveness without neglecting production optimization, are crucial areas for further research. They not only allow for the exploration of hydroponic principles, many of which remain largely unknown, but could also provide self-sufficiency for households and potentially, in the future, for large urban centers. Such systems could also contribute to the reclamation of abandoned lands.

In this thesis, we observed many of the weaknesses in passive cultivation systems, particularly with regard to the excessive reduction in the cost of components. With a clearer understanding of the operational limits of the equipment required by such systems, we hope that future research by our peers will explore the optimal balance between initial investment and the quantity and quality of production. This will help make the system even more resilient and sustainable.

REFERENCES

[1] B. McDonald, "Hydroponics: Cr oponics: Creating Food for Today and for Tomorrow," Indiana State University, 2015.

[2] R. Ebel, "Chinampas: An Urban Farming Model of the Aztecs and a Potential Solution for Modern Megalopolis," *HortTechnology* , 1 February 2020.

[3] J. B. Jones, " Hydroponics: Its history and use in plant nutrition studies," *Journal of Plant Nutrition,* 1982.

[4] J. B. Jones, "Growing Plants Hydroponically," *The American Biology Teacher,* 6 September 1985.

[5] M. Raviv and R. Wallach, "The effect of physical properties of soilless media on plant performance - A review," 2004.

[6] G. Page, B. Ridoutt and B. Bellotti, "Fresh tomato production for the Sydney market: An evaluation of options to reduce freshwater scarcity from agricultural water use," 2011.

[7] S. Rost, D. Gerten, A. Bondeau, W. Lucht, J. Rohwer and S. Schaphoff, "Agricultural green and blue water consumption and its influence on the global water system," 04/09/2008.

[8] N. N. Kourgialas, "A critical review of water resources in Greece: The key role of agricultural adaptation to climate-water effects," vol. 775, 2021.

[9] R. Annett, H. R. Habibi and A. Hontela, "Impact of glyphosate and glyphosate-based herbicides on the freshwater environment," 2014.

[10] F. Maggi, D. l. Cecilia, F. H. Tang and A. McBratney, "The global environmental hazard of glyphosate use," 2020.

[11] J. Tarazona, Court-Marques, T. M. D. and e. al., "Glyphosate toxicity and carcinogenicity: a review of the scientific basis of the European Union assessment and its differences with IARC," 2017.

[12] E. B. F. K. K. A. A. Maira Lykogianni, "Do pesticides promote or hinder sustainability in agriculture? The challenge of sustainable use of pesticides in modern agriculture," *Science of The Total Environment,* 15 November 2021.

[13] S. Huo and e. al, "The influence of microalgae on vegetable production and nutrient removal in greenhouse hydroponics," 2020.

[14] K. M. V. M. V. L. Pomoni DI, "A Review of Hydroponics and Conventional Agriculture Based on Energy and Water Consumption, Environmental Impact, and Land Use.," *Energies.,* 2023.

[15] R. C. J. W. Catherine DeLong, "The Soil Degradation Paradox: Compromising Our Resources When We Need Them the Most," *sustainability,* 13 January 2015.

[16] B. A. Kratky, "A Capillary, Noncirculating Hydroponic Method for Leaf and Semi-head Lettuce," *HortTechnology,* 1993.

[17] L. BROADBENT, "The epidemiology of tomato mosaic," 1965.

[18] M. d. C. Córdoba-Sellés, A. García-Rández, A. Alfaro-Fernández and C. Jordá-Gutiérrez, "Seed Transmission of Pepino mosaic virus and Efficacyof Tomato Seed Disinfection Treatments," 2007.

[19] R. D. Pares, L. V. Gunn and G. C. Cresswell, "Tomato Mosaic Virus Infection in a Recirculating Nutrient Solution," 1992.

[20] Y. ANTIGNUS, "THE MANAGEMENT OF TOMATO YELLOW LEAF CURL VIRUS IN GREENHOUSES AND THE OPEN FIELD, A STRATEGY OF MANIPULATION," 2007.

[21] M. D. Guiry, "HOW MANY SPECIES OF ALGAE ARE THERE?," 2012.

[22] S. Agrawal, "Factors affecting spore germination in algae — review," 2008.

[23] D. Schwarz, "Algae affecting lettuce growth in hydroponic systems," 2015.

[24] D. o. P. P. a. E. M. PennState. [Online]. Available: https://plantpath.psu.edu/pythium/module-1/pythium.

[25] C. R. S. N. O.-G. L. G. C. H. L. B. John Clifford Sutton, "Etiology and epidemiology of Pythium root rot in hydroponic crops: current knowledge and perspectives".

[26] R. Utkhede, C. Lévesque and D. Dinh, "Pythium aphanidermatum root rot inhydroponically grown lettuce and the effect ofchemical and biological agents on its control".

[27] B. A. Fortnum, "Nutrient Solution Temperature Affects Pythium Root Rot of Tobaccoin Greenhouse Float Systems," 1999.

[28] J. J. Benton Jones, Complete Guide for Growing Plants Hydroponically, CRC Press, 2014.

[29] T. Asao, Hydroponics: A Standard Methodology for Plant Biological Researches, BoD – Books on Demand, 2012.

[30] G. D. Rijck and E. Schrevens, "pH Influenced by the elemental composition of nutrient solutions," 1997.

[31] K. A. Dimitrios Savvas, "Automated Management of NutrientSolutions Based on Target ElectricalConductivity, pH, and NutrientConcentration Ratios," *JOURNAL OF PLANT NUTRITION,* 1999.

[32] G. J. Hochmuth, "Fertilizer Management for Greenhouse Vegetables—Florida Greenhouse Vegetable Production Handbook, Vol 3," [Online]. Available: https://edis.ifas.ufl.edu/publication/CV265.

[33] C. S. a. G. WELLES, "Yield and quality of rockwool-grown tomatoes as affected by variations in," *Plant and Soil,* September 1988.

[34] M. Hayashi, "Temperature-Electrical Conductivity Relation of Water for Environmental Monitoring and Geophysical Data Inversion," vol. 96, 2004.

[35] M. Díez and F. Nuez, "Tomato," 2008.

[36] F.-X. Branthôme, "Worldwide (total fresh) tomato production in 2021," *Tomato news,* 23 February 2023.

[37] Véronique Bergougnoux, "The history of tomato: From domestication to biopharming," 2014.

[38] J. M. Costa and E. Heuvelink, "Today's worldwide tomato production," 2007.

[39] M.-J. Ibarrola-Rivas, "Telecoupling through tomato trade: what consumers do not know about the tomato on their plate," 2020.

[40] J. Singh, E. Sastry and V. Singh, "Effect of salinity on tomato (Lycopersicon esculentum Mill.) during seed germination stage," 2012.

[41] "Home / Plant Nutrition / Base nutrients / B'cuzz Hydro A&B," [Online]. Available: https://atami.com/product/bcuzz-hydro-ab/.

[42] D. o. P. P. a. E. Microbiology, "What is Pythium?," [Online]. Available: https://plantpath.psu.edu/pythium/module-1/pythium.

[43] O. v. Kooten, E. Heuvelink and C. Stanghellini, "New Development in Greenhouse Technology can Mitigate the Water Shortage Problem of the 21st Century," 2008.

[44] Π. ΕΛΕΥΘΕΡΙΟΣ, "Η ΕΠΙΔΡΑΣΗ ΤΗΣ ΑΖΩΤΟΥΧΟΥ ΛΙΠΑΝΣΗΣ ΣΕ ΔΙΑΦΟΡΑ ΧΑΡΑΚΤΗΡΙΣΤΙΚΑ ΤΗΣ ΚΑΛΛΙΕΡΓΕΙΑΣ ΤΟΥ ΑΓΓΟΥΡΙΟΥ ΣΕ ΥΔΡΟΠΟΝΙΑ," ΤΕΧΝΟΛΟΓΙΚΟ ΕΚΠΑΙΔΕΥΤΙΚΟ ΙΔΡΥΜΑ ΚΑΛΑΜΑΤΑΣ, ΚΑΛΑΜΑΤΑ, 2000.

APPENDIX

8.1 Code for conservation mode

```
#include <Wire.h>

#include <OneWire.h>

#include <DallasTemperature.h>

#include <Arduino.h>

#include <WiFiS3.h>          // Wi-Fi library for Arduino R4

#include <ArduinoIoTCloud.h>   // Arduino IoT Cloud library

#include <Arduino_ConnectionHandler.h>   //Arduino IoT Cloud connection handler library


// Replace with your network credentials

const char* ssid = "mie24";       // Replace with your hidden Wi-Fi SSID

const char* password = "36mie@fg";  // Replace with your Wi-Fi password


// Define the IoT Cloud WiFi connection handler

WiFiConnectionHandler ArduinoIoTPreferredConnection(ssid, password);


// Pin definitions

const int pumpTestTrayIn = 5;     // Pin for Pump to bring water to the test tray

const int freshAB = 8;           // Pin for Pump to fill with fresh water (combined Tray A and B)
```

```
const int pumpOut = 10;          // Pin for Pump to fill Plant Box (combined Tray A and B out)

const int peristalticA = 3;      // Pin for Peristaltic Pump A (fertilizer A)

const int peristalticB = 2;      // Pin for Peristaltic Pump B (fertilizer B)

const int peristalticPH = 4;     // Pin for Peristaltic Pump for pH adjustment

const int pumpTestTrayOut = 11;  // Pin for Pump to return water from test tray to plant box

const int ecSensorPin = A5;      // EC sensor connected to analog pin A5

const int phSensorPin = A4;      // pH sensor connected to analog pin A4

const int tempSensorPin = 7;     // Temperature sensor pin

const int liquidLevelSensorPin = A1; // Analog pin connected to the water level sensor


// Timing definitions

unsigned long pumpTestTrayInRunTime = 240000;      // Duration for Pump to fill test tray 240 sec

unsigned long freshABRunTime = 48000;           // Duration for Pump to fill with fresh water 48 sec

unsigned long pumpOutRunTime = 45000;           // Duration for Pump to fill Plant Box 45 sec

unsigned long pumpTestTrayOutRunTime = 190000;     // Duration for Pump to return water from test tray 190 sec

const unsigned long peristalticARunTime = 2000;   // 2 seconds for Peristaltic Pump A

const unsigned long peristalticBRunTime = 4300;   // 4.3 seconds for Peristaltic Pump B

const unsigned long peristalticPHRunTime = 6000;  // 6 seconds for Peristaltic Pump for pH adjustment


// Thresholds

const float EC_Threshold = 2.5;

const float pH_Threshold = 6.5;

const int wetThreshold = 490;  // Adjust based on water level sensor's reading for wet level
```

```
//Readings
float averagePH = 0;
float averageEC = 0;
float temperature = 0;
int liquid_level = 0;

// OneWire instance for DS18B20
OneWire oneWire(tempSensorPin);
DallasTemperature sensors(&oneWire);

void setup() {
  Serial.begin(9600);
  delay(1000);

  // Defined in thingProperties.h
  initProperties();

  //Arduino Initialization
  ArduinoCloud.begin(ArduinoIoTPreferredConnection);
  setDebugMessageLevel(2); // Set debug level
  ArduinoCloud.printDebugInfo();

  // Wi-Fi Connection
  Serial.println("\nConnecting to Wi-Fi network...");
  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(1000);
```

```
  Serial.println("Attempting to connect...");
}
Serial.println("\nConnected to Wi-Fi!");
Serial.print("IP Address: ");
Serial.println(WiFi.localIP());

// Initialize DS18B20 temperature sensor
sensors.begin();

// Set pump pins as outputs
pinMode(pumpTestTrayIn, OUTPUT);
pinMode(freshAB, OUTPUT);
pinMode(pumpOut, OUTPUT);
pinMode(peristalticA, OUTPUT);
pinMode(peristalticB, OUTPUT);
pinMode(peristalticPH, OUTPUT);
pinMode(pumpTestTrayOut, OUTPUT);

// Initialize all pumps to be off except pumpTestTrayIn
digitalWrite(pumpTestTrayIn, HIGH);        // Turn on Pump to fill test tray
digitalWrite(freshAB, HIGH);               // Turn off Fresh Water Pump
digitalWrite(pumpOut, HIGH);               // Turn off Pump to fill Plant Box
digitalWrite(peristalticA, HIGH);          // Turn off Peristaltic Pump A
digitalWrite(peristalticB, HIGH);          // Turn off Peristaltic Pump B
digitalWrite(peristalticPH, HIGH);         // Turn off Peristaltic Pump for pH adjustment
digitalWrite(pumpTestTrayOut, HIGH);       // Turn off Pump to return water from test tray
```

```
  Serial.println("Starting watering system test procedure...");
}

void loop() {

  // Step 1: Use Pump to bring water into the test tray
  Serial.println("Filling test tray with water...");
  digitalWrite(pumpTestTrayIn, LOW);
  delay_with_update(pumpTestTrayInRunTime);
  digitalWrite(pumpTestTrayIn, HIGH);
  Serial.println("Test tray filled.");

  // Step 2.1: Measure pH
  measureAveragePH();

  // Step 2.2: Check if average pH exceeds threshold
  if (averagePH > pH_Threshold) {
    Serial.println("pH is above threshold, activating pH adjustment pump...");
    digitalWrite(peristalticPH, LOW);   // Turn on the pump for pH adjustment
    delay_with_update(peristalticPHRunTime);        // Run pump for 3 seconds
    digitalWrite(peristalticPH, HIGH);  // Turn off the pump
    Serial.println("pH adjustment complete.");
  } else {
    Serial.println("pH is within acceptable range, no pump activation.");
  }

  // Step 3.1: Measure EC
```

```
  }


  measureAverageEC();


  // Check water level before proceeding to Step 3.2 to Step 5
  int liquid_level = analogRead(liquidLevelSensorPin);
  Serial.print("Water Level Sensor Value: ");
  Serial.println(liquid_level);


  if (liquid_level > wetThreshold) {
    Serial.println("Water level HIGH. Skipping fertilizer addition and proceeding to final flush...");
    // Proceed directly to final flush
    Serial.println("Final flush with pumpTestTrayOut for 1.1 minutes...");
    digitalWrite(pumpTestTrayOut, LOW);   // Ensure pumpTestTrayOut turns on
    delay(5000);              // Run for 1.1 minutes
    digitalWrite(pumpTestTrayOut, HIGH);  // Ensure pumpTestTrayOut turns off after delay
    Serial.println("1/2 flush complete.");


    Serial.println("Running pumpOut for 40 seconds...");
    digitalWrite(pumpOut, LOW);
    delay_with_update(30000);  // Run pumpOut for 30 seconds
    digitalWrite(pumpOut, HIGH);
    Serial.println("pumpOut turned off.");


    delay_with_update(28800000);  // Wait before the next cycle
    return; // Skip the rest of the steps
  }
```

```
Serial.println("Water level LOW. Proceeding with EC check and fertilizer addition...");

// Step 3.2: Check if average EC lower than threshold
if (averageEC < EC_Threshold) {
  Serial.println("EC is below threshold. Proceeding to add fertilizers...");

  // Step 4.1: Run pumpTestTrayOut for 3 minutes
  Serial.println("Running pumpTestTrayOut for 3 minutes...");
  digitalWrite(pumpTestTrayOut, LOW);
  delay_with_update(180000);  // 3 minutes in milliseconds
  digitalWrite(pumpTestTrayOut, HIGH);
  Serial.println("pumpTestTrayOut turned off.");

  // Step 4.2: Run pumpOut for 45 seconds
  Serial.println("Running pumpOut for 45 seconds...");
  digitalWrite(pumpOut, LOW);
  delay_with_update(45000);  // Run pumpOut for 45 seconds
  digitalWrite(pumpOut, HIGH);
  Serial.println("pumpOut turned off.");

  // Step 4.3: Run pumpTestTrayOut again for 1.05 minutes
  //Serial.println("Running pumpTestTrayOut for 1.05 minutes...");
 // digitalWrite(pumpTestTrayOut, LOW);
  //delay(5000);  // 1.05 minutes in milliseconds
  //digitalWrite(pumpTestTrayOut, HIGH);
  //Serial.println("pumpTestTrayOut turned off.");
```

```
// Step 5: Adding fertilizer without mixing
Serial.println("Step 5: Adding fertilizer without mixing...");

// Run Peristaltic Pump A for fertilizer A
Serial.println("Running Peristaltic Pump A...");
digitalWrite(peristalticA, LOW);
delay_with_update(peristalticARunTime);
digitalWrite(peristalticA, HIGH);
Serial.println("Peristaltic Pump A complete.");

// Flush system after fertilizer A
Serial.println("Running Fresh Water Pump to flush system after fertilizer A...");
digitalWrite(freshAB, LOW);
delay_with_update(32000);  // Run freshAB for 32 seconds
digitalWrite(freshAB, HIGH);
Serial.println("Fresh water flush complete. Waiting 1 minute...");

// Run pumpOut for 40 seconds to move the fresh water to the plant box
Serial.println("Running pumpOut to flush water after fertilizer A...");
digitalWrite(pumpOut, LOW);
delay_with_update(40000);  // Run pumpOut for 40 seconds
digitalWrite(pumpOut, HIGH);
Serial.println("PumpOut flush complete after fertilizer A.");

// Run Peristaltic Pump B for fertilizer B
Serial.println("Running Peristaltic Pump B...");
digitalWrite(peristalticB, LOW);
```

```
  delay_with_update(peristalticBRunTime);
  digitalWrite(peristalticB, HIGH);
  Serial.println("Peristaltic Pump B complete.");

  // Flush system again after fertilizer B
  Serial.println("Running Fresh Water Pump to flush system after fertilizer B...");
  digitalWrite(freshAB, LOW);
  delay_with_update(32000);  // Run freshAB for 32 seconds
  digitalWrite(freshAB, HIGH);
  Serial.println("Fresh water flush complete. Waiting 1 minute...");

  // Run pumpOut for 40 seconds again to move the water after fertilizer B
  Serial.println("Running pumpOut to flush water after fertilizer B...");
  digitalWrite(pumpOut, LOW);
  delay_with_update(40000);  // Run pumpOut for 40 seconds
  digitalWrite(pumpOut, HIGH);
  Serial.println("PumpOut flush complete after fertilizer B.");
} else {
  Serial.println("EC is above threshold. Skipping fertilizer addition.");
}

// Final flush with pumpTestTrayOut for 1.3 minutes
Serial.println("Final flush with pumpTestTrayOut for 1.3 minutes...");
digitalWrite(pumpTestTrayOut, LOW);   // Ensure pumpTestTrayOut turns on
delay_with_update(80000);             // Run for 1.3 minutes
digitalWrite(pumpTestTrayOut, HIGH);  // Ensure pumpTestTrayOut turns off after delay
Serial.println("Final flush complete.");
```

```
  // Wait for a while before next measurement cycle
  delay_with_update(60000);  // Adjust delay for the next cycle, if necessary

  // Update cloud variables
  ArduinoCloud.update();
}

// Function to measure average pH over 1 minute, taking readings every 5 seconds
void measureAveragePH() {
  float totalPH = 0;
  int numReadings = 12;  // 12 readings over 1 minute

  for (int i = 0; i < numReadings; i++) {
    int sensorValue = analogRead(phSensorPin);
    float voltage = sensorValue * (5.0 / 1023.0);  // Convert analog reading to voltage
    float phValue = voltage * 3.5;  // Adjust based on pH meter’s conversion formula

    totalPH += phValue;

    Serial.print("Reading ");
    Serial.print(i + 1);
    Serial.print(": pH Value = ");

    Serial.println(phValue);

    delay(5000);  // Wait 5 seconds between readings
```

```
  }

  averagePH = totalPH / numReadings;  // Return average pH
  Serial.print("Average pH: ");
  Serial.println(averagePH);
}

// Function to measure average EC with temperature compensation
void measureAverageEC() {
  const int numReadings = 12;
  float totalEC = 0;
  int validReadings = 0;

  for (int i = 0; i < numReadings; i++) {
    int sensorValue = analogRead(ecSensorPin);
    float voltage = sensorValue * (5.0 / 1023.0); // Convert analog reading to voltage
    float rawEC = (voltage / 0.164);            // Adjust based on EC sensor’s formula
    readTemperature();      // Read current temperature
    float compensatedEC = compensateEC(rawEC, temperature); // Apply temperature compensation

    if (i >= 2) { // Skip the first two measurements for better accuracy
      totalEC += compensatedEC;
      validReadings++;
    }

    Serial.print("Reading ");
```

```
    Serial.print(i + 1);
    Serial.print(": Raw EC = ");
    Serial.print(rawEC);
    Serial.print(" mS/cm, Compensated EC = ");
    Serial.print(compensatedEC);
    Serial.print(" mS/cm at ");
    Serial.print(temperature);
    Serial.println(" °C");

    delay(5000); // Wait 5 seconds between readings
  }

  averageEC = validReadings > 0 ? totalEC / validReadings : 0;
  Serial.print("Average EC: ");
  Serial.println(averageEC);
  Serial.print("mS/cm\n");
}

// Function to read temperature from DS18B20
void readTemperature() {
  sensors.requestTemperatures();
  temperature = sensors.getTempCByIndex(0);
  if (temperature == DEVICE_DISCONNECTED_C) {
    Serial.println("Temperature sensor disconnected!");
    temperature = 25.0; // Default to 25°C for safety
  }
}
```

```
// Function to calculate temperature-compensated EC
float compensateEC(float rawEC, float temperature) {
  const float referenceTemperature = 25.0;
  const float compensationFactor = 0.02; // 2% per degree deviation
  float deltaTemperature = temperature - referenceTemperature;

  return rawEC / (1 + (compensationFactor * deltaTemperature));
}

void delay_with_update(int delay_time) {
  int cycles = delay_time / 1000;  // Calculate how many full 1000ms cycles fit in delay_time
  int rem = delay_time % 1000;      // Get the remaining milliseconds that don't fit into full
seconds

  for (int i = 0; i < cycles; i++) {  // Loop for each full 1000ms cycle
    delay(1000);                     // Pause execution for 1000ms
    ArduinoCloud.update();           // Call cloud update after each second
  }

  if (rem > 0) {                     // If there’s a remainder (less than 1000ms left)
    delay(rem);                      // Delay for the remaining time
    ArduinoCloud.update();           // Call cloud update one last time
  }
}

void initProperties(){
```

```
  ArduinoCloud.addProperty(averageEC, READ, 60 * SECONDS, NULL);
  ArduinoCloud.addProperty(averagePH, READ, 60 * SECONDS, NULL);
  ArduinoCloud.addProperty(temperature, READ, 60 * SECONDS, NULL);
  ArduinoCloud.addProperty(liquid_level, READ, 10 * SECONDS, NULL);
}
```

8.2 Code for filling mode

```
#include <Wire.h>
#include <OneWire.h>
#include <DallasTemperature.h>
#include <Arduino.h>


// Pin definitions
const int pumpTestTrayIn = 5;
const int freshAB = 8;
const int pumpOut = 10;
const int peristalticA = 3;
const int peristalticB = 2;
const int peristalticPH = 4;
const int pumpTestTrayOut = 11;
const int ecSensorPin = A5;
const int phSensorPin = A4;
const int tempSensorPin = 7;
const int liquidLevelSensorPin = A1;
```

```
// Thresholds
const int wetThreshold = 397;
const float EC_Threshold = 2.5;
const float pH_Threshold = 6.5;

// Timing definitions
const unsigned long peristalticARunTime = 2000;
const unsigned long peristalticBRunTime = 4300;
const unsigned long freshABRunTime = 48000;
const unsigned long pumpOutRunTime = 45000;
const unsigned long pumpTestTrayOutRunTime = 190000;
const unsigned long pumpTestTrayInRunTime = 240000;

void setup() {
  Serial.begin(9600);

  pinMode(pumpTestTrayIn, OUTPUT);
  pinMode(freshAB, OUTPUT);
  pinMode(pumpOut, OUTPUT);
  pinMode(peristalticA, OUTPUT);
  pinMode(peristalticB, OUTPUT);
  pinMode(peristalticPH, OUTPUT);
  pinMode(pumpTestTrayOut, OUTPUT);

  digitalWrite(pumpTestTrayIn, HIGH);
  digitalWrite(freshAB, HIGH);
```

```
  digitalWrite(pumpOut, HIGH);
  digitalWrite(peristalticA, HIGH);
  digitalWrite(peristalticB, HIGH);
  digitalWrite(peristalticPH, HIGH);
  digitalWrite(pumpTestTrayOut, HIGH);

  Serial.println("Starting Filling Mode...");
  fillingMode();
}

void fillingMode() {
  int cycleCount = 0;

  while (true) {
    cycleCount++;
    Serial.print("Nutrient Injection Cycle: ");
    Serial.println(cycleCount);

    Serial.println("Running Peristaltic Pump A...");
    digitalWrite(peristalticA, LOW);
    delay(peristalticARunTime);
    digitalWrite(peristalticA, HIGH);

    Serial.println("Running FreshAB Pump...");
    digitalWrite(freshAB, LOW);
    delay(freshABRunTime);
```

```
digitalWrite(freshAB, HIGH);

Serial.println("Running PumpOut...");
digitalWrite(pumpOut, LOW);
delay(pumpOutRunTime);
digitalWrite(pumpOut, HIGH);

Serial.println("Running Peristaltic Pump B...");
digitalWrite(peristalticB, LOW);
delay(peristalticBRunTime);
digitalWrite(peristalticB, HIGH);

Serial.println("Running FreshAB Pump...");
digitalWrite(freshAB, LOW);
delay(freshABRunTime);
digitalWrite(freshAB, HIGH);

Serial.println("Running PumpOut...");
digitalWrite(pumpOut, LOW);
delay(pumpOutRunTime);
digitalWrite(pumpOut, HIGH);

Serial.println("Running PumpTestTrayOut for 1.5 minutes...");
digitalWrite(pumpTestTrayOut, LOW);
delay(pumpTestTrayOutRunTime);
digitalWrite(pumpTestTrayOut, HIGH);
```

```
if (cycleCount % 10 == 0) {
  Serial.println("Taking PH and EC Measurements...");

  Serial.println("Filling test tray with water...");
  digitalWrite(pumpTestTrayIn, LOW);
  delay(pumpTestTrayInRunTime);
  digitalWrite(pumpTestTrayIn, HIGH);

  float averagePH = measureAveragePH();
  float averageEC = measureAverageEC();

  if (averagePH > pH_Threshold) {
    Serial.println("pH is above threshold, activating pH adjustment pump...");
    digitalWrite(peristalticPH, LOW);
    delay(2000);
    digitalWrite(peristalticPH, HIGH);
  }

  if (averageEC > EC_Threshold) {
    Serial.println("EC is above threshold, running FreshAB pump...");
    digitalWrite(freshAB, LOW);
    delay(60000);
    digitalWrite(freshAB, HIGH);
  }
```

```
      Serial.println("Running PumpOut for 1.2 minutes...");
      digitalWrite(pumpOut, LOW);
      delay(72000);
      digitalWrite(pumpOut, HIGH);
    }
  }
}

float measureAveragePH() {
  float totalPH = 0;
  int numReadings = 5;
  for (int i = 0; i < numReadings; i++) {
    int sensorValue = analogRead(phSensorPin);
    float voltage = sensorValue * (5.0 / 1023.0);
    float phValue = voltage * 3.5;
    totalPH += phValue;
    delay(1000);
  }
  return totalPH / numReadings;
}

float measureAverageEC() {
  float totalEC = 0;
  int numReadings = 5;
  for (int i = 0; i < numReadings; i++) {
    int sensorValue = analogRead(ecSensorPin);
```

```
    float voltage = sensorValue * (5.0 / 1023.0);
    float rawEC = voltage / 0.164;
    totalEC += rawEC;
    delay(1000);
  }
  return totalEC / numReadings;
}
```