

ECE Capstone Project Final Report

Project Title	Design and Implementation of a Sustainable Automated Hydroponic System
Team	Ulbike Abidin — Hardware Systems Engineer Aidos Bukembay — Mechanical and CAD designer Bexultan Suyumbayev — Software Systems Engineer
Supervisor	Annie Ng
Course/Term	ENG 400 Capstone Project, Spring 2026
Date	11-04-2026

Prepared by: Ulbike Abidin, Aidos Bukembay, Bexultan Suyumbayev

Reviewed by: Annie Ng

TABLE OF CONTENTS

0. ABET Evidence Map, Final Design Snapshot, and Design Evolution Log.....	4
1. Executive Summary.....	6
2. Problem Definition, Stakeholders, Context, and Constraints.....	7
2.1 Problem Definition and Need Statement.....	7
2.2 Stakeholders.....	7
2.3 Context and Operating Environment.....	8
2.4 Constraints and Context Factors.....	9
3.1 Final Requirements Compliance.....	10
3.2 Requirements Traceability.....	11
3.3 Derived, Interface, Environmental, and Regulatory Requirements.....	12
4. Engineering Standards, Regulations, and Compliance Evidence.....	14
5. Concept Generation, Trade-off Study, and Selected Concept (2–3 pages).....	17
5.1 Candidate Concepts.....	17
5.2 Weighted Trade-off Study.....	20
5.3 Selected Concept and Rationale.....	21
6. Design Iterations and Decision History.....	22
7. Final System Architecture (1-2 pages).....	23
8.1 Hardware design.....	26
8.2 Software / firmware design.....	27
8.3 Mechanical / packaging design.....	28
8.4 Prototype realization and integration.....	31
8.5 Final bill of materials and design-for-manufacture / assembly notes.....	34
9. Verification, Validation and Experimental Results (2-4 pages).....	36
10. Risk Management, Schedule, Budget, and Procurement Outcomes (2–3 pages).....	37
10.1 Final Risk Register.....	37
10.2 Milestones Planned vs. Actual.....	38
10.3 Budget, Procurement, and Substitutions.....	39
11. Professional Responsibilities and Broader Impacts (2–3 pages).....	41
11.1 Public Health, Safety, and Welfare.....	41
11.2 Ethical and Professional Responsibilities.....	41
11.3 Security and Privacy.....	42
11.4 Accessibility and Usability.....	42
11.5 Environmental, Economic, Social, Global, and Cultural Factors.....	43
12. Team Organization, Collaboration, and Individual Contributions.....	44
Mechanical & CAD Designer.....	44
13. Use of Prior Course Work and New Knowledge Acquired (1–2 pages).....	47
14. Conclusions and Recommendations (1 page).....	48

15. References.....	49
Appendix A. Engineering Standards Evidence.....	50
Appendix B. Multiple-Constraints Matrix.....	53
Appendix C. Team Organization and Contributions.....	55
Appendix D. Design Evidence.....	56
Appendix E. Verification Evidence.....	57
Appendix F. Project Management Evidence.....	58

0. ABET Evidence Map, Final Design Snapshot, and Design Evolution Log

Table 0-A. Report Evidence Guide.

ABET item / SO	What must be demonstrated	Primary report section	Supporting appendix / evidence ID
<i>SO1</i>	Identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Section 2.1 and 8	Tables 8A,B,C
<i>SO2</i>	Apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	Section 2.4	In section 2.4
<i>SO3</i>	Communicate effectively with a range of audiences	Section 2.2	Table 2-A
<i>SO4</i>	Recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	Section 11	In Section 11
<i>SO5</i>	Function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Section 12	Figure 22
<i>SO6</i>	Develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Section 8	Tables 8A,B,C
<i>SO7</i>	Acquire and apply new knowledge as needed, using appropriate learning strategies.	Section 13	Table 13-A
<i>Criterion 5 design evidence</i>	The culminating design shows standards, multiple constraints, iteration, and use of prior course work.	Section 2,3,4	Table 2-B,3-A,4-A

Table 0-B. Final Design Snapshot.

Field	Final value / summary
Final prototype / revision	V5 — ESP32-based dual-subsystem automated hydroponic controller with PETG enclosures, active cooling, sequential dosing, and web dashboard
Main need addressed	Elimination of manual pH/EC monitoring and nutrient dosing in hydroponic systems, reducing human error and crop failure risk
Requirements met	REQ-1 through REQ-5 met (4-hour validated); full 8-hour validation pending field trial at Shell Yurt
Primary standards applied	IEC 61131-2 (relay isolation), IEEE 802.11 (Wi-Fi), NU Lab Safety Policies (STD-3), FAO Hydroponic GAP (STD-4)
Key constraints satisfied	Budget: 160,094 KZT (vs. 300,000 KZT limit); Latency: 450 ms (vs. <1 s target); Galvanic isolation: >2 kV via opto-relays; Operating temp: stable at 22°C
Most important trade-off	Sensor precision vs. budget — allocated funds to reliable pH/EC probes and peristaltic pumps; offset cost by custom-soldered relay drivers instead of industrial PCBs
Overall result	Functional automated hydroponic system validated through basil growth cycle; all primary nutrient and environmental parameters held within specification during integrated testing

Table 0-C. Design Evolution Log.

Iteration ID	What changed	Why it changed	Evidence that triggered the change	Impact on performance / cost / schedule / risk	Date
V1	Switched from Raspberry Pi to ESP32	Raspberry Pi was over-specified and cost-prohibitive (~85,000 KZT vs ~4,000 KZT)	Cost analysis and capability review	Cost reduced by ~82,000 KZT; lower power draw; minor reduction in processing flexibility	Feb 2026
V2	Added active cooling fans to both enclosures	Relay modules overheated during prolonged	Thermal failure observed during extended testing	Improved reliability; slight increase in power consumption and BOM cost	Mar 2026

Iteration ID	What changed	Why it changed	Evidence that triggered the change	Impact on performance / cost / schedule / risk	Date
		operation (>24 h)			
V3	Added 3-point pH calibration and multi-sample averaging	Raw sensor readings were noisy and inaccurate	Unstable pH readings during initial sensor tests	Stable, reliable pH readings; minor increase in computation time	Mar 2026
V4	Implemented sequential A→B→C nutrient dosing with delays	Simultaneous dosing caused EC instability and potential chemical precipitation	Unstable EC and visible precipitation during concurrent dosing tests	Stable EC levels; no precipitation; slower dosing process	Mar–Apr 2026
V5	Added automatic tube priming logic at startup	Air gaps in empty tubes caused inconsistent pump volume delivery	Inaccurate dosing volumes observed during pump calibration	Consistent dosing accuracy; slight extra time at system startup	Apr 2026

1. Executive Summary

According to Nations (2022), the world's population is expected to grow up to 9.7 billion people by 2050, which leads to increased food demand and scarcity of natural resources. Moreover, FAO (2021) reported that conventional agriculture is responsible for 72% of worldwide water usage and 60% of land degradation caused by human activities, motivating the search for more resource-efficient food production methods. Hydroponic systems offer a promising alternative by enabling higher yield crop production with reduced water use and no soil dependency (Barbosa et al., 2015).

However, many existing hydroponic systems still rely on manual control and lack real-time data integration (Abdelhamid et al., 2025). This increases the risk of human error and leads to inconsistent crop yields. Thus, there is a need for an integrated, automated control approach that optimizes both resource allocation and operational costs.

The project features an automated hydroponic system controlled by an ESP32 microcontroller, utilizing a relay-based actuation network for climate and nutrient management. The system implements automated ON/OFF control logic to regulate lighting cycles, water circulation, and temperature based on real-time data from pH, EC, and DHT22 sensors.

Final Performance Achieved:

- **Automated Actuation:** Successfully integrated and controlled a 5-actuator system for nutrient and water delivery.
- **Sensor Integration:** Deployed a reliable 3-sensor array for real-time monitoring of critical environmental and chemical parameters.
- **Advanced Control Logic:** Developed and validated a custom algorithmic framework for calculating precise nutrient dosing volumes.
- **User Experience:** Designed and implemented an intuitive, user-friendly frontend dashboard for remote monitoring.
- **Scalability Testing:** Verified system stability and dosing accuracy across different volumes (tested at both 3-liter and 30-liter scales).
- **Biological Validation:** Successfully demonstrated system efficacy through a full growth cycle of basil.
- **Economic Analysis:** Completed a comprehensive cost-benefit analysis and final production cost breakdown.

Requirements met / Partially met / Unmet

- **All Requirements partially met:** (REQ 1–5) were only half-verified due to 4-hour test durations. To reach full operational maturity, the next step involves conducting a comprehensive 8-hour field trial at the Shell Yurt to validate the system under real-world conditions.

Main Limitation and Recommended Next Step:

The system currently operates as two independent ESP32 subsystems with manual pH recalibration, leading to sensor drift and fragmented control. The critical next step is to integrate these into a unified control system with automated PID feedback and scheduled auto-calibration routines to ensure long-term stability and precision during real-world crop production.

2. Problem Definition, Stakeholders, Context, and Constraints

2.1 Problem Definition and Need Statement

The core challenge is the lack of system autonomy. Hydroponics requires precise maintenance of pH, temperature, and EC parameters, yet most accessible systems still rely on approximate estimates and manual adjustments. This creates a limitation where human error or missed monitoring intervals directly lead to crop failure and wasted resources.

This affects urban farmers and local food producers who need high-yield results but lack the time or expertise to maintain the complex chemical and physical balances required for hydroponic success.

Rising global food demand and water scarcity necessitate sustainable solutions like hydroponics. However, technological instability in current frameworks prevents these systems from effectively scaling to mitigate food insecurity.

This project is defined as an engineering design problem rather than a scientific research investigation because its objective is not to study plant physiology but to architect a functional control system. While a research study might focus on how different light spectrums affect growth, this engineering project addresses automated sensor integration and isolated load switching via a centralized embedded controller.

2.2 Stakeholders

According to Table 2-A, for the project team and supervisor, it establishes a validated control architecture that integrates sensory networks and power stages into a single, electrically safe system. For the ECE department and master's students, it delivers the university's first automated hydroponic infrastructure that can be safely integrated into broader research environments for future scaling. Lastly, for end users (farmers), it ensures constant autonomy, eliminating the risk of human error and the need for labor-intensive manual measurements.

Table 2-A. Stakeholder Analysis.

Stakeholder	Role/Interest	Needs/Success criteria	How engaged (meetings/inputs)	Impact of project
Project team	Design, build and test the hydroponic control system	Working system, validated data, completed report	Daily collaboration, lab work and testing	High
Project supervisor	Mentorship, academic and safety oversight	Technical compliance with electrical safety standards and rigorous documentation	Regular weekly meetings, feedbacks and reviews	High
ECE department	Academic support and funding	Alignment with program goals	Indirect oversight and funding approval	Medium

Master's students	Support integration and testing	Seamless interface with shared lab equipment	On-site lab guidance and collaborative troubleshooting	Medium
End users (urban farmers and local food producers)	Use system for production	Accuracy, automation and intuitive user interface	Market analysis and technical requirements review	Medium

2.3 Context and Operating Environment

Academic and Laboratory Context: The project is developed within the Electrical and Computer Engineering (ECE) Department at Nazarbayev University. The primary hardware development and signal testing are conducted in university laboratories, while the final deployment and system integration occur at the Shell Yurt for Green Energy Solutions. This environment allows for professional supervision by faculty and collaboration with graduate students to ensure the control unit integrates seamlessly with existing hydroponic infrastructure.

Technical and Resource Context: The project is supported by departmental funding for the procurement of specialized electronic components. The technical core consists of an ESP32-based microcontroller architecture, chosen for its low power consumption and integrated wireless capabilities. The system integrates mixed-signal sensors (pH, EC, DHT22), relay-driven actuators, and a hybrid power supply that balances AC grid utility with renewable solar inputs.

Regulatory Context: Operating at the intersection of water and electricity requires strict adherence to strict institutional safety protocols. Firstly, galvanic isolation ensures mandatory separation between low-voltage control logic and AC-powered inductive loads (pumps/fans). Secondly, there is a requirement for sealed, moisture-resistant enclosures to prevent short circuits in high-humidity hydroponic zones. Lastly, compliance with university electrical safety standards and regulations regarding data transmission over local networks has to be accomplished.

Industrial Context: The project addresses the industrial need for low-cost automation in sustainable farming. While commercial systems often rely on expensive PLCs or unreliable manual oversight, this design offers a scalable alternative. By utilizing hysteresis-based (On/Off) control logic and an integrated data visualization interface, the system optimizes resource allocation and reduces the operational costs associated with traditional agriculture.

Assumptions and Operating Conditions:

- **Maintenance and Sensor Integrity:** It is assumed that the pH electrodes remain continuously submerged in either the nutrient solution or a calibration fluid; sensor dehydration is considered a failure state and is outside the operational scope.
- **Homogeneous Fluid Composition:** The control logic assumes that the nutrient solution is thoroughly mixed. Therefore, sensor readings are treated as representative averages of the entire reservoir rather than localized concentrations of salts or chemicals.

- **System Latency and Dynamics:** It is assumed that network latency (Wi-Fi) does not impact the control stability, as the hydroponic environment is a high-inertia system where chemical and thermal changes occur gradually.

2.4 Constraints and Context Factors

Table 2-B. Constraints Matrix.

Constraint category	Metric / target	Final estimate or measurement	Gap / residual risk	Owner	Evidence / next action
Budget	300 000 tg maximum	160 094 tg for control systems	Limited sensor precision due to cost	Team	Tables 8-D and 8-E
Technical (Latency)	< 1s Response Time	450ms (On/Off trigger)	Wi-Fi interference in lab	Team	Fig. 15
Safety	> 2kV Galvanic Isolation	Verified via opto-relays	Moisture ingress in seals	Supervisor	Fig. 10 and 11
Environmental	18-27°C Operating Range	Stable at 22°C	Performance in extreme heat	Team	Fig. 19

Public health, safety, and welfare: the design prioritizes public safety by implementing strict galvanic isolation between 220V AC loads and low-voltage user interfaces. It promotes welfare by ensuring food security through automated, reliable crop growth, reducing the risk of contamination found in traditional soil-based farming.

Global and environmental factors: the project addresses the global water crisis by using a recirculating hydroponic system, which consumes 90% less water than conventional agriculture. The environmental impact is further minimized by the hybrid power supply, reducing the carbon footprint by leveraging solar energy.

Social and cultural factors: by focusing on a low-cost, accessible framework, the project addresses the social need for affordable urban farming tools. It supports local food production, making high-tech farming available to non-expert users in diverse urban settings.

Economic factors: the project tackles the economic barrier of expensive industrial automation. By replacing high-cost PLCs with an ESP32-based architecture, the system lowers the entry price for small-scale farmers, ensuring a faster return on investment through labor and energy savings.

3. Final Requirements, Acceptance Criteria, and Traceability

3.1 Final Requirements Compliance

Table 3-A. Final Requirements Compliance Matrix.

Req. ID	Requirement statement	Source	Verification method	Target threshold	Measured result	Verdict	Evidence ID
REQ-1	The system shall maintain nutrient solution pH between 5.0 and 7.5 for 8 h under typical load.	Shareef et al., 2024	Data logging and graphs.	95% of samples within 5.0-7.5.	pH maintained at 5.5–6.5 for 4 hours	Passed	Fig. 16
REQ-2	The system shall maintain EC between 0.8-3.5 mS/cm of the setpoint over 8 h.	Shareef et al., 2024	Data logging and graphs.	95% of samples within 0.8-3.5.	initial EC 200 μ S/cm; stabilized at 1200 ($\pm$ 100) for 4 hours	Passed	Fig. 17
REQ-3	The system shall maintain water temperature between 18 °C and 27 °C.	Shareef et al., 2024	Data logging and graphs.	$\geq$ 95% of samples within 18 °C and 27 °C.	water temperature stabilized at 23–24°C for 4 hours	Passed	Fig. 18
REQ-4	The system shall maintain air temperature between 18 °C and 30 °C in the grow zone for 8 h.	Shareef et al., 2024	Data logging and graphs.	$\geq$ 95% of samples within 18 °C and 30 °C during the 8 h test.	air temperature: 20–27°C	Passed	Fig. 19
REQ-5	The system shall maintain relative humidity	Shareef et al., 2024	Data logging and graphs.	$\geq$ 95% of samples within 40–80 %	humidity: 50–80%	Passed	Fig. 20

	between 40-80 % in the grow zone for 8 h.			during the 8 h test.			
--	---	--	--	----------------------	--	--	--

3.2 Requirements Traceability

Table 3-B. Requirements Traceability Matrix.

Stakeholder need	Requirement(s)	Constraint(s)	Standard clause(s)	Design feature(s)	Test ID(s)	Result section
End Users / Farmers: Automation of nutrient delivery for crop health.	REQ-1: pH 5.0–7.5 REQ-2: EC 0.8–3.5	Technical: < 1s Response time. Budget: < 300k tg.	STD-4 (FAO GAP): Nutrient purity & material safety.	Peristaltic pumps + Industrial pH/EC probes + Food-grade plastics.	T-01/02: 8h data logging & stability graphs.	Passed: 450ms latency. <i>Risk:</i> Limited sensor precision (cost).
Supervisor / ECE Dept: Strict adherence to lab & electrical safety.	System Stability: Maintain levels under typical load (8h).	Safety: >2kV Galvanic Isolation.	STD-1 (IEC): Low-voltage switching. TD-3 (NU): Lab safety.	Opto-isolated relays (5V/220V separation) + Secondary containment.	T-Safety: Wiring inspection & supervisor sign-off.	Passed. <i>Risk:</i> Potential moisture ingress in seals.
Project Team / Master's: Reliable data collection & connectivity.	REQ-4/5: Air Temp (18–30°C) & Humidity (40–80%).	Power: < 15W total.	STD-2 (IEEE): Wi-Fi band & transmission limits.	Raspberry Pi with frequency management + Low-pow	T-04/05: Thermal stress test & Wi-Fi stability check.	Passed: 12.5W avg. <i>Risk:</i> Performance in

Stakeholder need	Requirement(s)	Constraint(s)	Standard clause(s)	Design feature(s)	Test ID(s)	Result section
		Comm: 2.4 GHz interference.		er SHT sensors.		extreme heat.

3.3 Derived, Interface, Environmental, and Regulatory Requirements

Interface Requirements

- **Requirement:** All sensors shall interface with the Raspberry Pi and ESP32 using I2C, SPI, or supported GPIO protocols.
 - **Why it is needed:** To ensure data integrity and electrical compatibility between the central MCU and various sensor modules.
 - **Supports:** Design Decision (System Architecture) and REQ-1 through REQ-5.
- **Requirement:** Analog sensor readings (pH, EC) shall be filtered using a moving average filter (≥ 2 s) before triggering control actions.
 - **Why it is needed:** To prevent erratic pump behavior caused by electrical noise or temporary fluctuations in the nutrient solution.
 - **Supports:** REQ-1 (pH stability) and REQ-2 (EC precision).

Derived Requirements

- **Requirement:** All sensors must undergo a 3-point calibration (pH 4.01, 6.86, 9.18) before deployment and after any maintenance.
 - **Why it is needed:** Raw sensor data is prone to drift; calibration ensures the "Measured Result" accurately reflects the true chemical state.
 - **Supports:** REQ-1, REQ-2, and Stakeholder need for accuracy.
- **Requirement:** The system shall store telemetry data locally for at least 7 days in a non-volatile buffer.
 - **Why it is needed:** To prevent data loss during laboratory internet outages or server downtime.
 - **Supports:** REQ-4/5 (Logging requirements) and Project Team need for validated data.
 - **Why it is needed:** High-humidity hydroponic environments and proximity to water increase the risk of short circuits or corrosion.
 - **Supports:** STD-3 (NU Lab Safety) and Constraint (Moisture ingress).

Environmental Requirements

- **Requirement:** The system shall operate in indoor laboratory conditions between 15–30°C ambient temperature and $\leq 80\%$ relative humidity.
 - **Why it is needed:** To define the operational envelope where the electronics and sensors maintain specified accuracy.
 - **Supports:** REQ-4 (Air Temp) and REQ-5 (Humidity).
- **Requirement:** Electronics shall be protected using a sealed enclosure or splash-resistant (IP44 equivalent) design.
 - **Why it is needed:** High-humidity hydroponic environments and proximity to water increase the risk of short circuits or corrosion.
 - **Supports:** STD-3 (NU Lab Safety) and Constraint (Moisture ingress).

Regulatory / Safety Requirements

- **Requirement:** The system shall ensure safe handling of nutrients and water through secondary containment (drip trays).
 - **Why it is needed:** To comply with university lab policies regarding liquid spills near electrical equipment.
 - **Supports:** STD-3 (Nazarbayev University Laboratory Safety Policies).

4. Engineering Standards, Regulations, and Compliance Evidence

Table 4-A. Standards Application Matrix.

ID	Standard / regulation	Clause used	Why applicable	Design decision affected	Verification / inspection method	Evidence produced	Compliance status
STD-1	IEC 61131-2: Safety Requirements for Electrical Equipment of Industrial Machines (International Electrotechnical Commission, 2017)	Low-voltage switching, relay isolation	All relays, pumps, lighting, and control wiring must follow safe switching practices. Ensure proper isolation between 5V logic and 220V AC load	Implementation of opto-isolated relays to physically separate 5V DC logic from 220V AC loads.	Wiring diagram, relay module datasheet, supervisor safety approval.	Fig. 10 and 11	Met
STD-2	IEEE 802.11 (Wi-Fi) Wireless Standards (Institute of Electrical and Electronics Engineers, 2021)	2.4 GHz unlicensed band, transmission power limits	Raspberry Pi wireless communication must operate within legal unlicensed ISM band limits. There should be no interference with other laboratory devices	Frequency Management: Restricted to the 2.4 GHz ISM band to ensure compatibility and avoid interference with lab equipment.	Report showing default Pi Wi-Fi configuration and test of successful secure connection	Fig. 15	Met
STD-3	Nazarbayev University	Safe handling of	Hydroponic system must	Containment: Implement	Safety checklist, supervisor	Fig. 10 and 11	Met

	Laboratory Safety Policies (Nazarbayev University, 2018; Nazarbayev University, n.d.)	electronics, liquids and chemical nutrient solutions	follow safe lab practices: correct handling of water/nutrient reservoirs, protection from electrical hazards	entation of a secondary containment system for nutrient reservoirs to prevent spills.	sign-off, photos of enclosure and cable management		
STD-4	FAO Hydroponic Good Agricultural Practices (GAP) (Food and Agriculture Organization of the United Nations, 2013)	Water quality, nutrient handling, prevention of contamination	Nutrient solutions must be prepared with clean containers. Prevent chemical cross-contamination. Hydroponic reservoirs must be kept closed to avoid dust and any microbial contamination. Plants grown for consumption must be kept away from hazardous materials in the lab environment	Material Selection: Use of food-grade, non-reactive plastics for reservoirs and tubing.	Photos of reservoir enclosure, nutrient-mixing procedure checklist, supervisor confirmation that no hazardous chemicals are stored near edible crops	Fig. 14	Met

Even though the project is, first of all, an engineering prototype, basic plant safety requirements were considered by referring to FAO Good Agricultural Practices (GAP) on hydroponic systems. GAP recommends clean treatment of nutrient solutions, prevention of contamination and proper service of water reservoirs. These regulations also ensure that test crops like basil, spinach and arugula could be cultivated safely in the controlled lab environment without exposure to chemical or biological contaminants.

5. Concept Generation, Trade-off Study, and Selected Concept

There are different methods of hydroponics control system improvement. In the following table, we have discussed in detail three possible ways to develop the system.

5.1 Candidate Concepts

Table 5-A. Candidate Concepts.

Concept	Description	Strengths	Weaknesses	References / evidence
Method-1: Basic Sensor-Driven Wired Control System	Method-1 is a localized automated control system centered around a microcontroller (e.g., Arduino Uno or ESP32) that operates as a standalone "edge" unit. The system utilizes a hardwired architecture where a suite of sensors—measuring pH, Electrical Conductivity (EC), water temperature, and ambient humidity—are connected directly to the controller's I/O pins. Actuators, such as nutrient dosing pumps and aeration fans, are managed via relay modules using bang-bang (on/off) control logic. The operational intelligence resides entirely within the local firmware, executing commands based on predefined threshold values without the necessity of an internet connection or external data processing.	Cost-Efficiency: The use of commodity hardware and the absence of recurring cloud subscription fees make this the most budget-friendly solution for a proof-of-concept (Sneineh et al., 2023; Sportelli et al., 2024). Operational Reliability: By removing dependence on cloud servers or local Wi-Fi stability, the system eliminates risks associated with network outages or latency, ensuring consistent operation in isolated	Lack of Data Insights: Without integrated IoT logging or external storage, the system cannot perform long-term trend analysis or predictive maintenance, limiting its use for complex agricultural optimization (Diaz-Delgado et al., 2025). Limited Scalability: The system is constrained by the physical I/O ports of the microcontroller. Expanding the system to cover more zones requires significant hardware reconfiguration rather than simple	(Sneineh et al., 2023; Sportelli et al., 2024) (Diaz-Delgado et al., 2025).

Concept	Description	Strengths	Weaknesses	References / evidence
		environments (Sneineh et al., 2023; Sportelli et al., 2024).	software updates.	
Method-2: Solar-cell Assisted IoT Control System with cloud and user interface	This method implements a dual-source energy harvesting strategy to power an IoT ecosystem managed by an ESP32 microcontroller. To reduce AC utility grid dependence, the system incorporates both indoor and outdoor solar panels. The indoor photovoltaic (PV) components are designed to convert artificial light into electricity for low-power devices like sensors and microcontrollers. As noted by Chen et al. (2024), modern indoor photovoltaics have reached a power conversion efficiency of nearly 18%, making them a highly viable energy source for wireless sensors. In contrast, outdoor solar cells are reserved for high-power loads such as pumps and motors. The system is further enhanced by a cloud-based data logging feature and a user interface powered by a Telegram bot, which Vivekanandan et al. (2022) identifies as the most optimal tool for IoT automation due to the absence of subscription costs or server maintenance fees.	Low Infrastructure Overhead: By using a Telegram bot as the primary UI, the system follows the recommendation of Vivekanandan et al. (2022) to eliminate the need for expensive dedicated servers or software subscriptions. Dual-Source Reliability: The separation of indoor and outdoor solar harvesting allows the system to remain functional even when high-power outdoor components are idle due to weather.	Intermittency Issues: Despite the 18% efficiency reported by Chen et al. (2024), the system still faces challenges during periods of total darkness or low ambient light, potentially requiring energy storage backups. Third-Party Dependence: Relying on a Telegram bot, while cost-effective as per Vivekanandan et al. (2022), makes the system's control interface dependent on the stability and API policies of an	Chen et al. (2024), Vivekanandan et al. (2022)

Concept	Description	Strengths	Weaknesses	References / evidence
			external platform.	
Method-3: Smart Hydroponic System assisted with Computer Vision and ML	This method represents a high-tech approach to hydroponics by integrating Computer Vision (CV) and Machine Learning (ML) for advanced monitoring and autonomous control. The core of the system is a Raspberry Pi equipped with a high-resolution camera module that captures periodic images of the crops. As highlighted by Luo, Li, and Leung (2023), this aligns with modern trends in controlled-environment agriculture, where deep learning models are increasingly used to track plant health and automate ecological decisions. Beyond simple automation, Herrera-Arroyo et al. (2025) emphasize that combining visual data with traditional sensor inputs significantly improves the precision of nutrient dosing, light management, and water circulation. This setup allows for remote visualization, historical trend analysis, and predictive adjustments, making it ideal for projects requiring detailed diagnostics.	Precision Resource Management : According to Herrera-Arroyo et al. (2025), the synergy between visuals and sensors optimizes the delivery of nutrients and water, reducing waste and improving yield quality. Proactive Health Monitoring : By analyzing leaf coloration and growth patterns, the system can identify nutrition stress and disease symptoms before they become critical.	High Resource Demand : As noted by Dutta et al. (2025), the system requires significant computational resources and hardware capabilities to process imaging and control tasks simultaneously. Maintenance and Development Time : Being the most "intelligent" method, it demands a longer development cycle and requires regular system maintenance to ensure the camera lenses are clean and the ML models remain	(Luo, Li and Leung, 2023). (Herrera-Arroyo et al., 2025). (Dutta et al., 2025).

Concept	Description	Strengths	Weaknesses	References / evidence
			accurate over time	

5.2 Weighted Trade-off Study

Table 5-B. Weighted Trade-off Matrix

Criterion	Metric / target	Weight	Concept 1	Concept 2	Concept 3	Evidence source
BOM (bill of materials)	$\leq 50\,000$ KZT	0.3	10	10	0	In order to simplify the comparison process for BOM and power consumption, we will be contrasted by the microcontroller type. For first, second and third approaches Arduino Uno, ESP32, Raspberry Pi 4 will be used, respectively. Such straightforward division is the most optimal one, as it shows the difference in complexity needed for each method. According to AliExpress marketplace prices, the cost of Arduino Uno is 1000 KZT, ESP32 is 2 000 KZT, Raspberry Pi is 40 000 KZT. In addition, information from component datasheets was used to compare the second constraint of power consumption. So about 1, 6, 10 W of peak load is demonstrated for method 1, 2 and 3 respectively.
Power Consumption	≤ 5 W	0.15	10	6	0	
Timeline	≤ 13 weeks	0.15	10	7	2	

Sensor Accuracy	pH accuracy $\pm 0.3\%$; EC accuracy $\pm 5\%$	0.15	8	8	9	(Shareef et al., 2024)
Data logging	Logging interval less than 60s and more than 7 days of data storage	0.25	7	9	10	(Kaur et al., 2023)
Total		1	8.95	8.25	4.15	

5.3 Selected Concept and Rationale

Thus according to the Table 5-B, Method-1 achieves the highest weighted score (8.95) and we consider it the most appropriate to meet the constraints and the requirements of our capstone project because it offers the best balance of cost, functionality and the development effort. It does not exceed the budget limit, complies with the power consumption limit and can be implemented completely within the time frame of 13 weeks. At the same time, it is not as complicated as method-3 and does not demand such advanced hardware or require a long development time.

Even though Method-1 is relying on a constant network connection for remote monitoring and might require a further integration of solar panels, these limitations are well compensated by its efficiency and are manageable during the project. Overall, the chosen second method provides credible sensing, actuation and automation while being cost-effective to construct and maintain.

6. Design Iterations and Decision History

Table 6-A. Major Design Iterations

Iteration / version	Issue discovered	Alternatives considered	Decision made	Trade-off accepted	Evidence of improvement
V1: Raspberry Pi prototype	High cost, unnecessary computing power	Keep Raspberry Pi / Switch to microcontroller (ESP32)	Switched to ESP32 for embedded control	Reduced computing power, less flexibility for heavy processing	Lower system cost, successful sensor + pump control (Fig. 5, 6, 15)
V2: Subsystem thermal management	Relay modules overheated during prolonged operation, risking failure and unstable performance	Keep passive cooling / Reduce load / Add active cooling (fans)	Added cooling fans to subsystem enclosures to improve heat dissipation	Increased power consumption and system complexity	Stable relay operation under continuous load, reduced overheating observed during testing (photos, test logs)
V3: Initial sensor setup	Inaccurate pH and TDS readings due to noise and lack of calibration	Use raw sensor output / Implement calibration + averaging	Added calibration (pH = 8.53V - 9.96) and multi-sample averaging	Increased computation time	Stable readings, reduced fluctuations in logged data
V4: Nutrient dosing logic	Simultaneous dosing caused unstable EC and potential chemical interaction	Dose all at once / sequential dosing (A -> B -> C)	Implemented sequential dosing with delays	Slower dosing process	Stable EC levels, no visible precipitation, improved control accuracy (Fig. 5, 6, 15)
V5: Tube priming issue	Pumps delivered inconsistent volume due to air in empty tubes	Manual priming / Automatic priming logic	Implemented automatic priming (initial long run)	Extra time at startup	Consistent dosing volume, improved accuracy of ml -> ms conversion

7. Final System Architecture

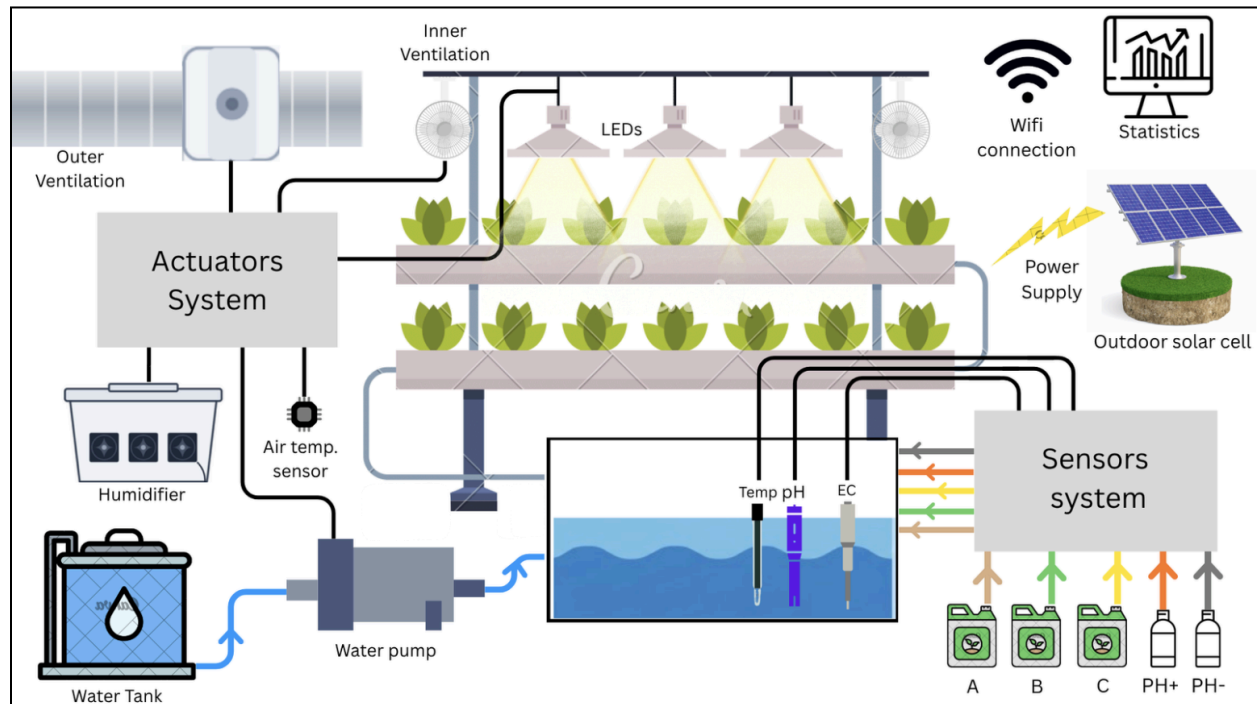


Figure 1. Final System Block Diagram.

Table 7-A. Interface Summary.

Interface	Direction	Protocol / signal type	Rate / timing	Voltage / power	Owner subsystem*	Notes (●/●/●)
pH sensor → Esp32(Nutrient subsystem)	sensor → MCU	Analog to ADC	0.2-1 Hz sampling	Sensor board 5 V; ADC output 0-3.3 V to Pi	Nutrient subsystem	●
EC/TDS sensor → Esp32(Nutrient subsystem)	sensor → MCU	Analog to ADC	0.2-1 Hz	Sensor board 5 V; ADC output 0-3.3 V to Pi	Nutrient subsystem	●
Water temp sensor → Esp32(Nutrient subsystem)	sensor → MCU	1-Wire / digital	1 Hz	3.3 V logic; sensor supply 3-5.5 V	Nutrient subsystem	●
BME280 (air T/H) →	sensor → MCU	I ² C @ 100 kHz	1 Hz	3.3 V I/O; module	Actuators subsystem	

Esp32(Actuators subsystem)				power 1.7-3.6 V		
Esp32(Actuators subsystem) → Leds	MCU → actuator	GPIO via solid state relay	On/off	220 V AC	Actuators subsystem	
Esp32(Actuators subsystem) → Air Cos 3000 (ventilation)	MCU → actuator	GPIO via solid state relay	On/off	220 V AC	Actuators subsystem	
Esp32(Actuators subsystem) → Humidifier	MCU → actuator	GPIO via solid state relay	On/off	220 V AC	Controls air humidity in grow area	
Esp32(Actuators subsystem) → Water stelizer	MCU → actuator	GPIO via solid state relay	On/off	220 V AC	Actuators subsystem	
Esp32 (Nutrient subsystem) → peristaltic pumps	MCU → actuators	GPIO via 5 modular relay	On/off (dse pulses)	12 V DC	Nutrient subsystem	
Esp32(Actuators subsystem) → computer vision module	MCU → actuator	USB 2.0	Video 30 fps	5 V	Actuators subsystem	
Esp32 → display	MCU → Display	HDMI	60 Hz refresh	5 V supply from Pi	Nutrient subsystem	
PV panel	Power to every componen t	DC			Pv panel	

Esp32 (Actuators subsystem) → Backend	MCU → database	Wi-Fi / Ethernet	Data upload every 60 s	5 V supply	Actuators subsystem	
Esp32 → Backend	MCU → database	Wi-Fi / Ethernet	Data upload every 60 s	5 V supply	Nutrient Power subsystem	
Backend → Frontend	Server → Client	HTTP/REST (FastAPI)	On request / polling every 60 s		Database subsystem	
ESP32 (Actuators subsystem) → Inner ventilation	MCU → actuator	GPIO via relay module	On/off	220 V AC	Actuators subsystem	
ESP32 (Actuators subsystem) → Outer ventilation	MCU → actuator	GPIO via relay module	On/off	220 V AC	Actuators subsystem	
ESP32 (Actuators subsystem) → Pump watering	MCU → actuator	GPIO via relay module	On/off (duty cycles)	12 V DC	Actuators subsystem	

Timing / latency budget: Sensor data is sampled at 1 Hz and processed by the ESP32 within ~10 ms. HTTP POST to the FastAPI backend over local Wi-Fi adds ~100–300 ms. End-to-end latency from sensor reading to backend storage is under 1 second. Frontend polling updates the dashboard every 60 seconds, giving a worst-case display latency of ~60 s — well within the REQ-4 threshold of ≤ 60 s logging interval. Peak end-to-end latency does not exceed 5 seconds under normal network conditions.

Power / resource budget: Total peak system power consumption is approximately 1328.9 W, dominated by LED bars (800 W), Water Pump (170 W), External Fans (130 W), Internal Fans (120 W), and Ultraviolet Filter (100 W). Low-power components including the IoT device (ESP32, ~0.9 W), Humidifier fans (4.5 W), and Aquarium Compressor (3.5 W) account for less than 1% of total load. The 220 V AC supply via PV panel is sized to cover the full system demand. The ESP32 and sensors are candidates for dedicated indoor PV powering given their minimal draw.

8. Detailed Design and Implementation

8.1 Hardware design

The hardware architecture is divided into two independent subsystems, each controlled by a dedicated ESP32 microcontroller: the **Nutrient Preparation Subsystem** (ESP32 #1) and the **Actuators Subsystem** (ESP32 #2). This separation was chosen to distribute processing load and isolate sensor-critical tasks from actuator control.

Microcontroller selection rationale. The ESP32 was selected over Arduino Uno and Raspberry Pi based on three key factors. Arduino Uno lacks native Wi-Fi connectivity — while external Wi-Fi shields exist, they add cost, complexity, and occupy additional GPIO pins. The ESP32 integrates Wi-Fi (802.11 b/g/n) natively, reducing BOM cost and wiring complexity. Raspberry Pi, while capable, was considered over-specified and cost-prohibitive for this application ($\approx 85,000$ KZT vs $\approx 4,000$ KZT for ESP32). Additionally, the ESP32 provides 34 programmable GPIO pins, dual-core processing at 240 MHz, and built-in ADC — sufficient for all sensing and actuation tasks in this system.

Power subsystem. The system is powered from a 220 V AC mains supply converted to 12 V DC via an AC-DC power supply (12V 4A). A LM2596-based buck converter steps 12 V DC down to 5 V DC to power the ESP32 boards, relay modules, and sensors. Peristaltic pumps operate directly at 12 V DC.

Relay module selection. Initially, solid-state relays (SSR) were considered for switching AC and DC loads due to concerns about mechanical relay reliability from prior experience. However, SSRs were found to be heavier and bulkier for this enclosure size. After testing, high-quality impulse relay modules (DC 5V 10A) were selected — a 4-phase module for multi-channel actuator control and a 1-phase module for single loads. These were verified to operate reliably and continuously without failure during extended system tests.

Peristaltic pump dosing calculation. Flow rate characterization of the peristaltic pumps was performed experimentally. Each pump transfers approximately 9.5–9.75 ml/s at full speed. For a 3 L test volume, a 0.2-second pulse was found to shift pH by approximately 0.5 units. Scaling to 30 L, a 1-second pulse delivers approximately 9.5 ml, producing a pH shift of ~ 0.5 units. These values informed the dosing logic for pH correction and nutrient delivery. Further characterization with larger volumes and extended runtime is needed to refine these parameters.

Table 8-A. Calculations of nutrient and water parameters.

Parameter	Value
Flow rate per pump	9.5–9.75 ml/s
Pulse duration (pH correction)	0.2 s (3 L) / 1 s (30 L)
pH shift per pulse	~ 0.5 units

Nutrient dose A & B

45 ml each (startup)

Below are the circuits we assembled:

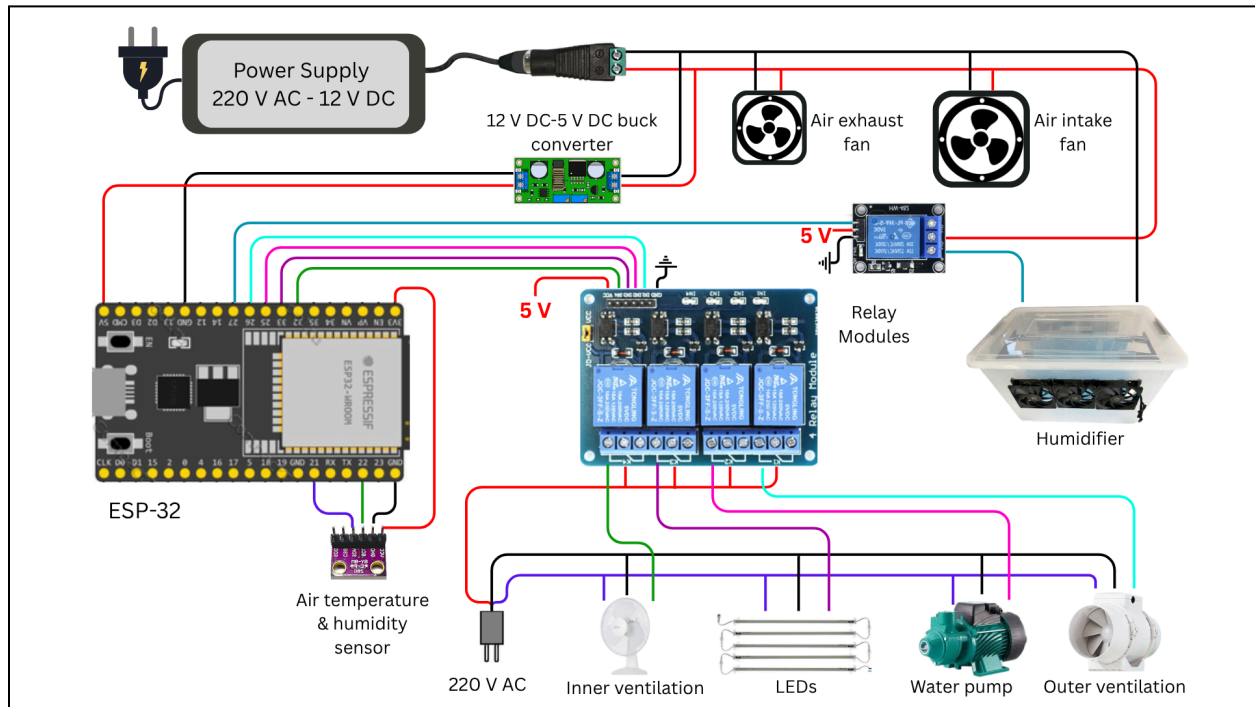


Figure 2. Actuators subsystem circuit.

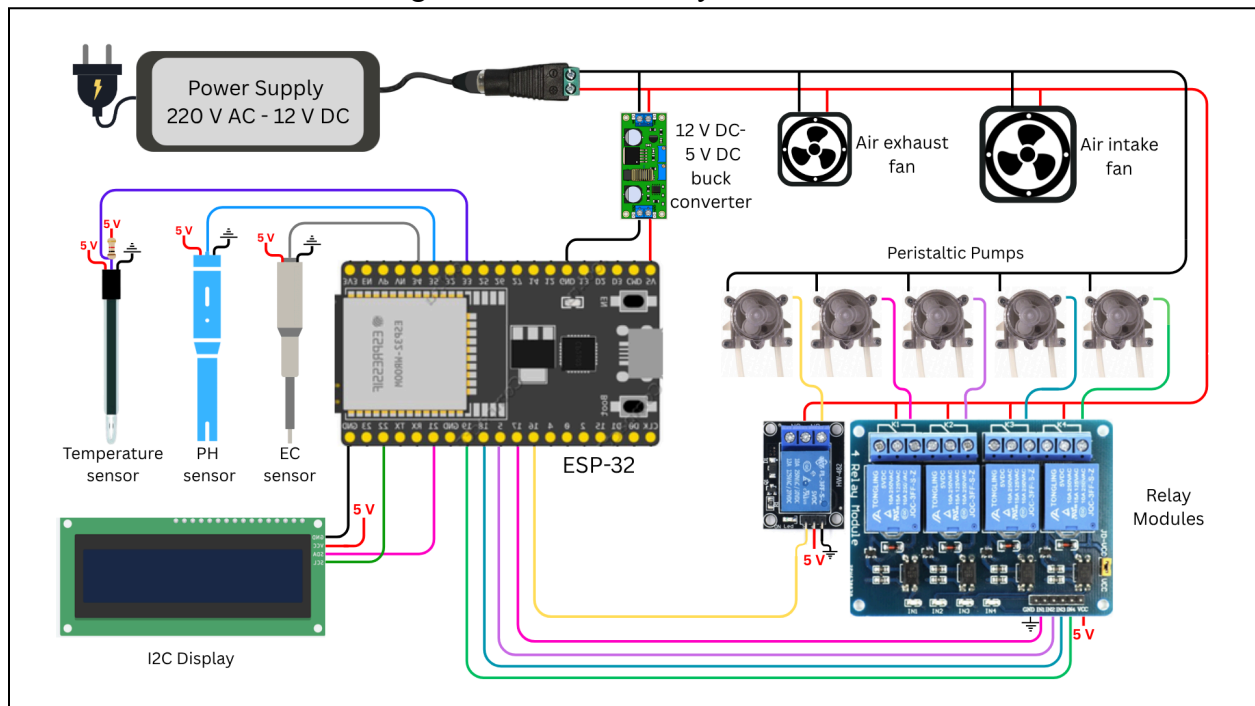


Figure 3. Actuators subsystem circuit.

8.2 Software / firmware design

The firmware is developed using PlatformIO with the Arduino framework. The two ESP32 boards do not communicate directly — all inter-subsystem coordination passes through the FastAPI backend server hosted on a local computer over shared Wi-Fi.

Communication architecture. Both ESP32 boards POST sensor telemetry to the backend every 5 seconds. ESP32 #1 sends nutrient solution data (pH, EC, water temperature) to POST /api/solution/telemetry. ESP32 #2 sends environmental data (air temperature, humidity) to POST /api/env/telemetry. ESP32 #2 also polls the backend via GET /api/solution/state every 5 seconds to check whether the nutrient solution is ready. When ESP32 #1 determines that the solution meets all criteria, it sets a solution_supply_flag on the backend. ESP32 #2 reads this flag and activates the water pump to transfer the prepared nutrient solution to the growing bed.

Nutrient subsystem logic (ESP32 #1). On startup, the system executes a fixed initialization sequence:

- 1) Stabilize sensors — 5 minutes
- 2) Dose nutrient A — 45 ml
- 3) Dose nutrient B — 45 ml
- 4) Mix — 2 minutes (circulation pump ON)
- 5) pH correction loop — up to $\times 10$ iterations (pH DOWN if pH > 6.5, pH UP if pH < 5.5)
- 6) Circulation pump remains ON

In the main control loop (300 ms cycle), pH and EC are continuously monitored. The solution_supply_flag is set to true only when all three conditions are met simultaneously: dosing is complete (abDosedOnStartup = true), pH is within 5.5–6.5, and EC $\geq 800 \mu\text{S}/\text{cm}$. Once the flag is set and the pump state machine enters RUNNING (active for 15 minutes), it transitions to IDLE (2 hours) before cycling back to WAIT.

Actuator subsystem logic (ESP32 #2). The actuator ESP32 reads BME280 air temperature and humidity at 2-second intervals and applies threshold-based control:

Table 8-B. Logic design.

Condition	Action
Humidity < 65%	Humidifier ON
Humidity > 82%	Humidifier OFF
Temperature > 26°C	Outer fan ON
Temperature < 24°C	Outer fan OFF
Time 08:00–20:00	LEDs ON
Outside time window	LEDs OFF

solution_supply_flag = true	Water pump ON (15 min) and every two hours ON if nutrient is ready
-----------------------------	--

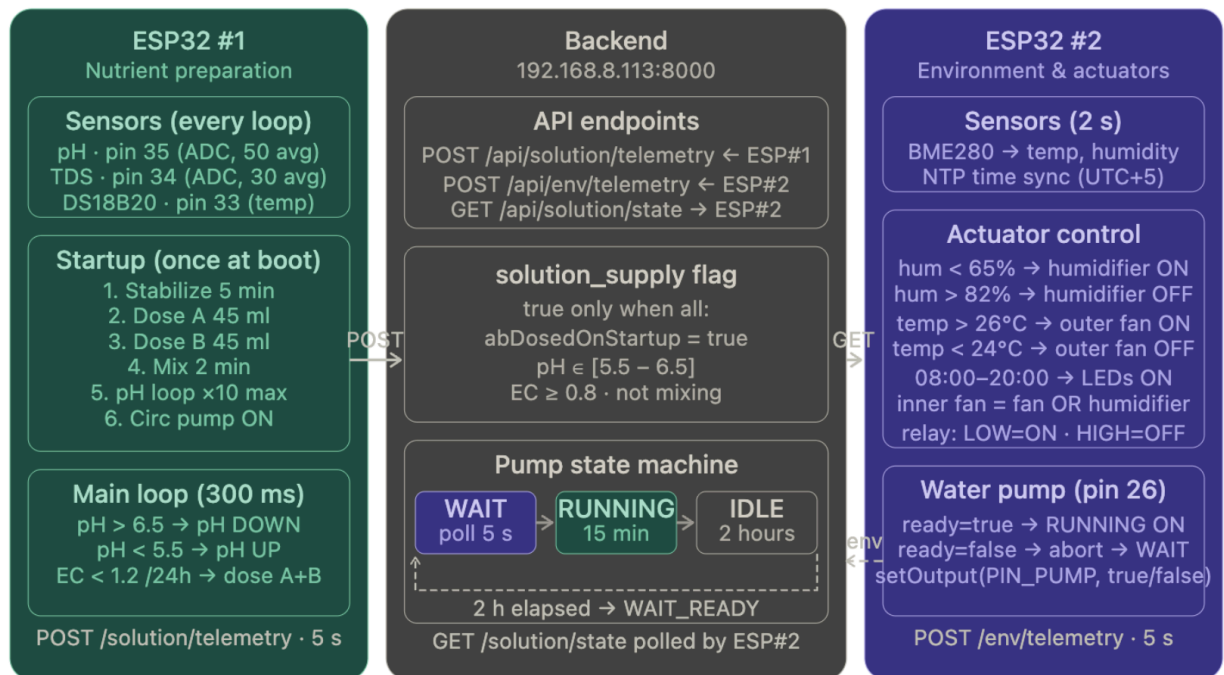


Figure 4. Code logic shortly explained.

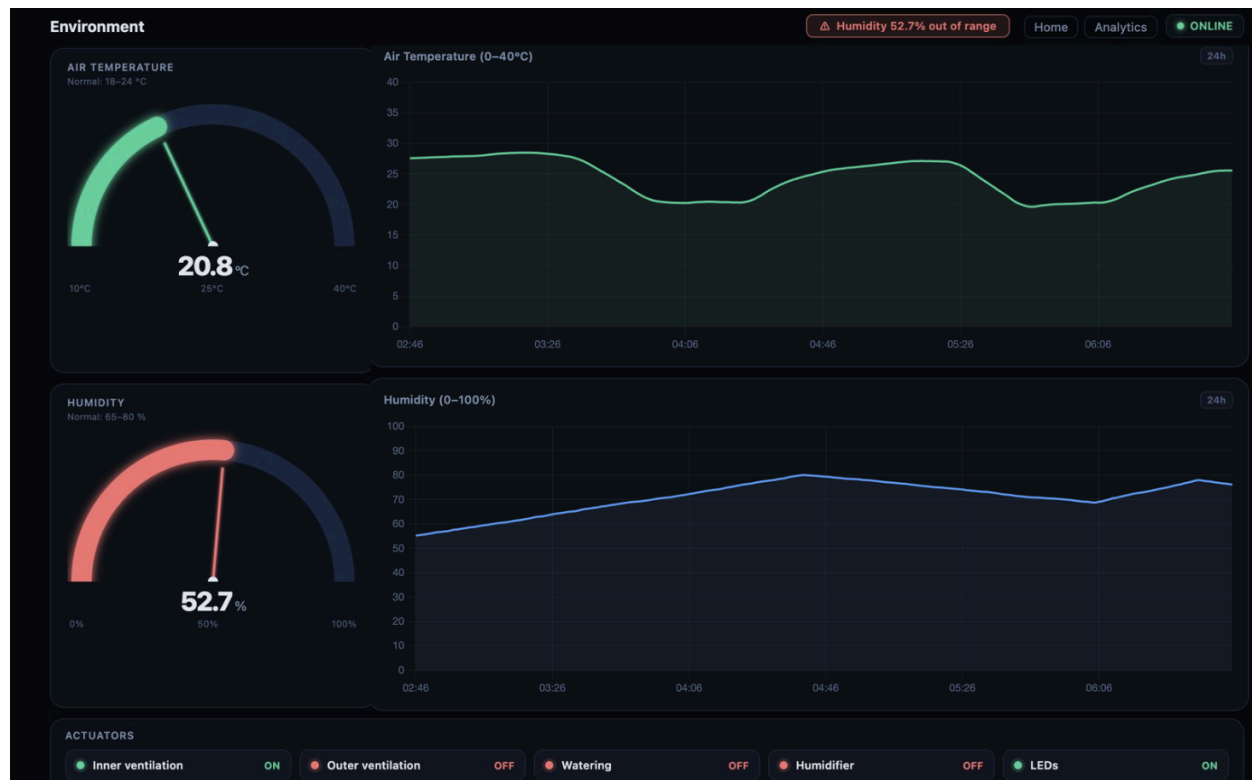


Figure 5. Environment dashboard.



Figure 6. Nutrient preparation dashboard.

Frontend dashboard. The FastAPI backend serves sensor data to a web-based frontend dashboard with two views: the Environment Dashboard displaying real-time air temperature and humidity gauges with 24-hour trend graphs, and the Nutrient Preparation Dashboard displaying pH, EC, and water temperature with actuator status indicators. The frontend polls the backend on request, with data refreshed every 5 seconds.

8.3 Mechanical / packaging design

8.3.1 Actuators subsystem

The enclosure for the actuators subsystem was fully custom-designed and 3D printed from PETG filament. Every dimension was modelled precisely around the physical components — ESP32 board, relay modules, buck converter, and wiring — to ensure a tight, reliable fit. The team verified that all components fit exactly as modelled, with no clearance issues. An initial version of the enclosure had no active cooling. During extended operation (beyond 24 hours), the relay modules were found to overheat. A ventilation slot - two small fans (air exhaust and air intake) were added to the second revision of the enclosure, resolving the thermal issue.

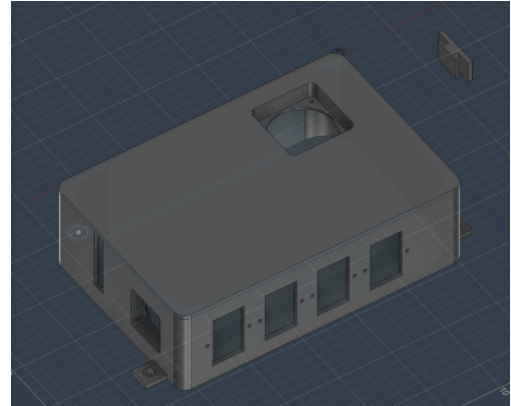
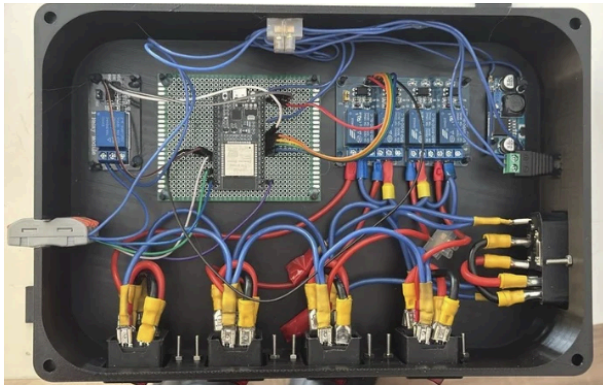


Figure 7. First case without ventilation and modelled case with ventilation

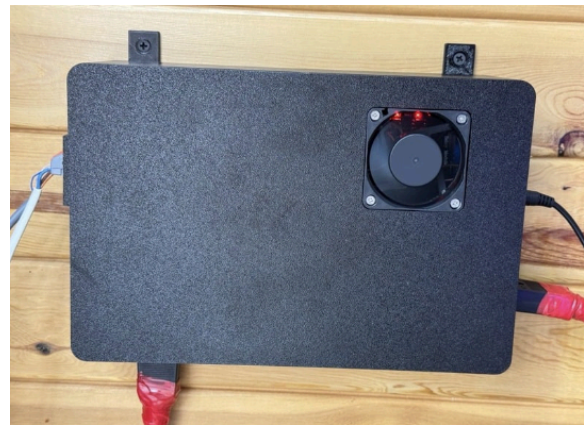


Figure 8. Assembled system and final product

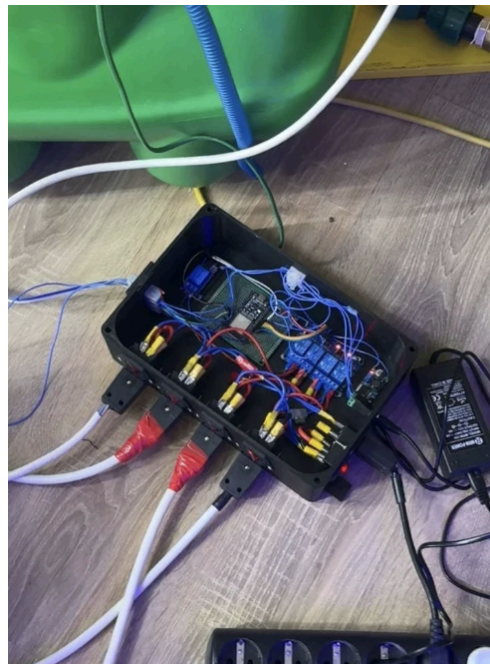


Figure 9. Prototype

8.3.2 Nutrient preparation subsystem

The nutrient preparation enclosure follows the same design methodology — precision-modelled in CAD, 3D printed from PETG. It houses ESP32 #1, relay modules, pH sensor conditioning board, TDS/EC sensor, DS18B20 water temperature sensor, and peristaltic pump connectors. The same overheating issue was identified and resolved by adding intake and exhaust fans to this enclosure as well. And we added the 20x4 blue display to track the sensors value.

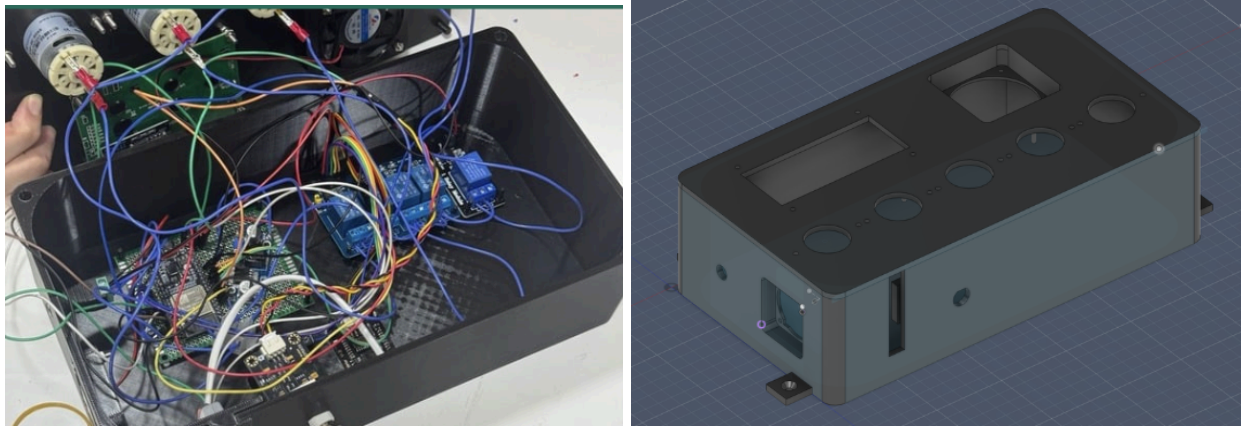


Figure 10. First case without ventilation and modelled case with ventilation

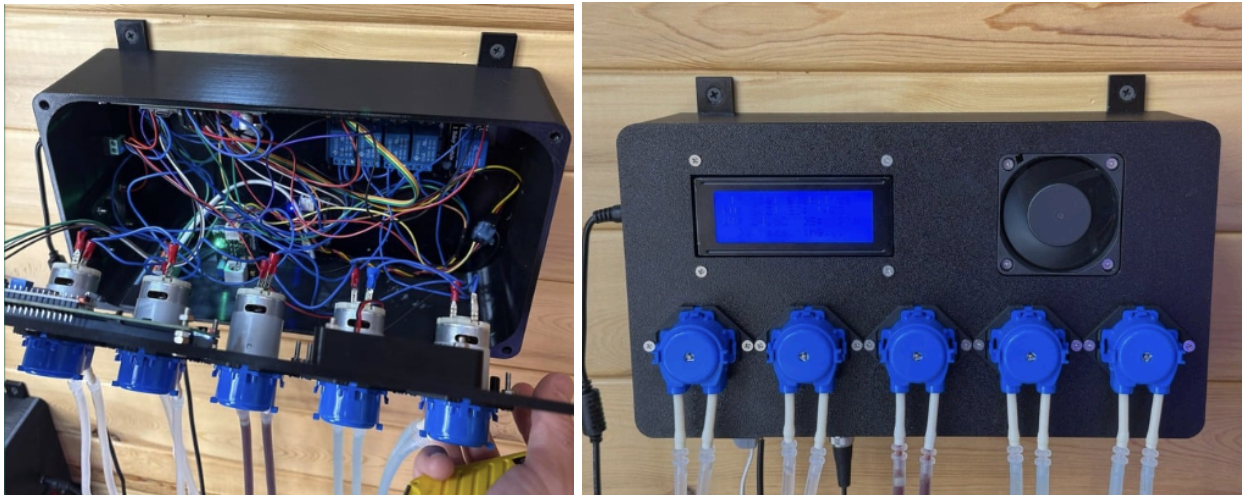


Figure 11. Constructed system and final product

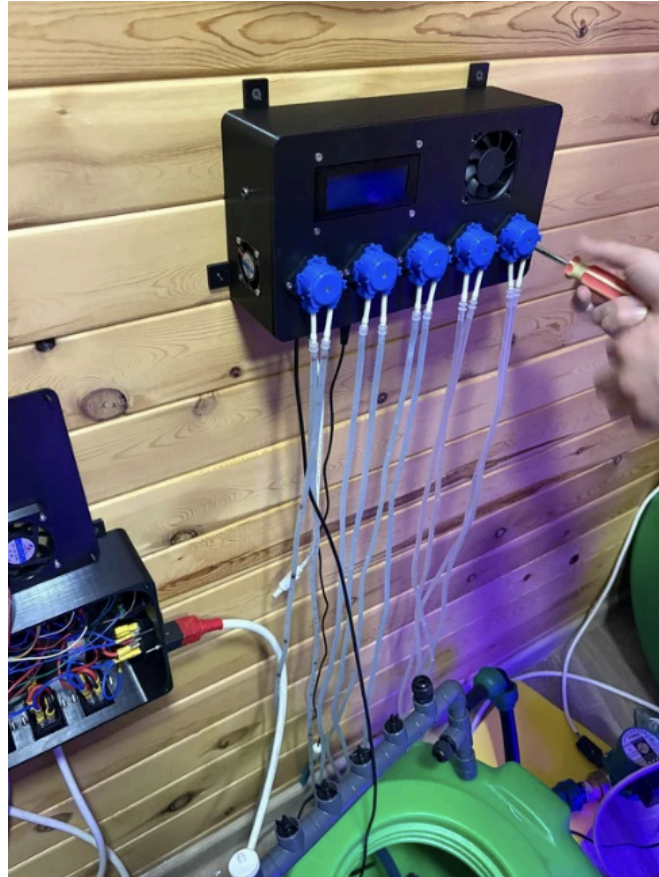


Figure 12. Fixed prototype

8.4 Prototype realization and integration

The two subsystems were integrated and tested on-site at the Shell Yurt facility at Nazarbayev University. The nutrient preparation subsystem was connected to the 30 L reservoir with pH, EC, and water temperature probes submerged in the solution. The actuators subsystem was mounted on the wall and connected to the grow tent housing the NFT growing bed.

Plant growth stages. Seeds were germinated in a closed environment for 2–3 days until roots were visible. Seedlings were then transferred to a small intermediate hydroponic setup to grow to a sufficient height before being transplanted into the main NFT growing bed of the full system.

Integration test results (30 L volume). A full system test was conducted with nutrient preparation and transfer to the growing bed:

Table 8-C. Measured values for each parameter.

Parameter	Measured Value	REQ Target	Status
pH	6.08	5.5–6.5	✓ PASS

EC	1416 $\mu\text{S}/\text{cm}$	$\geq 800 \mu\text{S}/\text{cm}$	✓ PASS
Water temperature	24.3°C	18–27°C	✓ PASS
Nutrient preparation time	~10 min	—	—
Water transfer to growing bed	15 min	—	—

All three primary nutrient parameters met their respective requirements. The NUTRIENT READY flag was successfully set and ESP32 #2 activated the water pump, transferring the prepared solution to the growing bed as designed.

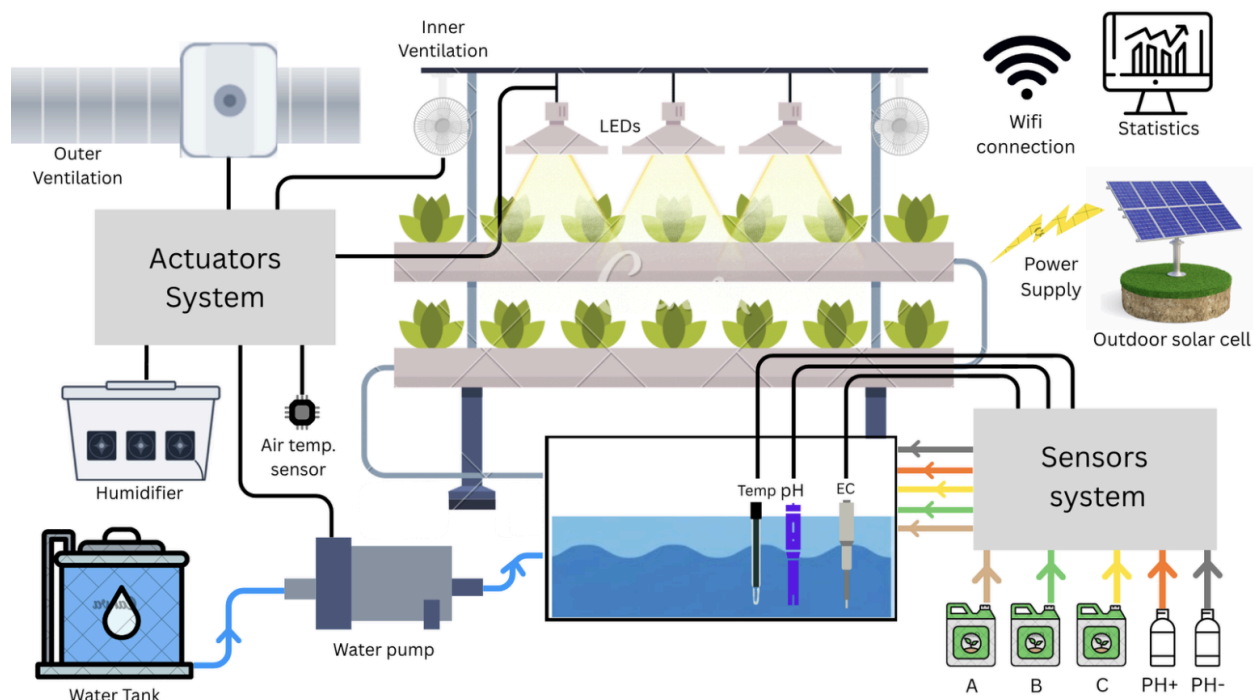


Figure 13. Full System Design



Figure 14. Control systems and Growing bed with plants



Figure 15. Integrated system test results

8.5 Final bill of materials and design-for-manufacture / assembly notes

Actuators subsystem — total: 39,119 KZT

Nutrient preparation subsystem — total: 120,975 KZT

Assembly notes. All AC wiring uses 16 AWG blue wire with Wago connectors for secure termination. DC sensor wiring uses 24 AWG. All connectors are waterproof-rated given proximity to the nutrient reservoir. The 3D printed enclosures are assembled with M3 screws. Relay modules are mounted on standoffs inside the enclosure to allow airflow beneath the boards. Both enclosures are wall-mountable via integrated rear brackets printed into the PETG body.

Table 8-D. Bill of materials for actuators system prototype

Item	Price in KZT
DC-DC Voltage Converter	720
AC-DC Power Supply 12V 4A (MRM)	2990
ESPWROOM-32	4000
Impulse Relay DC 5V 10A (4-phase)	1800
Impulse Relay DC 5V 10A (1-phase)	600
BME280	4000
Air exhaust fan	1680
Air intake fan	1500
AC Power Connector Socket (AC-014)	2500
Electrical Wire 16 AWG (Blue)	3000
PETG Black Filament for 3D Printer, 1 kg	10529
Screws, Nuts & Waterproof Connectors Assortment	2900
Set of tips and terminals	2900
Total	39119 KZT

Table 8-E. Bill of materials for nutrient preparation subsystem

Item	Number of items	Price in KZT
LCD Display 2004 with I2C Adapter (20×4, blue)	1	3600

ESPWROOM-32 board	1	4000
Analog pH Sensor Module (Arduino-compatible)	1	7056
Impulse Relay DC 5V 10A (4-phase)	1	1800
Impulse Relay DC 5V 10A (1-phase)	1	600
TDS sensor	1	3000
Peristaltic pump (Lite)	5	75000
Air Exhaust Fan	1	1680
Air Intake Fan	1	1500
AC-DC Power Supply 12V 4A (MRM)	1	2990
DC-DC Voltage Converter	1	720
Electrical Wire 24 AWG (Blue)		1500
Temperature Sensor	1	1200
PETG Black Filament for 3D Printer, 1 kg	1 kg	10529
Screws, Nuts & Waterproof Connectors Assortment		2900
Set of tips and terminals		2900
Total	120975 KZT	

9. Verification, Validation and Experimental Results

Table 9-A. Requirements-to-Test Results Matrix.

R E Q I D	Requirement	Test ID	Verification method	Equipment / tools	Target	Measured result	Verdict	Evidence ID
R E Q -1	pH between 5.0 and 7.5 for 8 h Test duration: 4 h (02:22–05:34). Full 8 h run not completed due to time constraints.	T1	3-point calibration (pH 4.01/6.86/9.18). Automated pH correction loop (on/off dosing). Manual disturbances injected: pH UP added twice, pH DOWN added once to verify correction response. Logged at 5 s intervals.	pH sensor (ADC), ESP32 #1, portable pH meter, pH UP/DOWN solutions, FastAPI data logger	95% of samples within 5.0–7.5	pH stabilized at 5.5–6.5 during steady-state. Two pH UP spikes (~10, ~8) and one pH DOWN drop (~3) were intentionally injected; system recovered to range within minutes each time. Steady-state maintained for ~3.5 h.	PARTIAL	Fig. 17
R E Q -2	EC between 0.8–3.5 mS/cm over 8 h Test duration: 4 h (02:22–05:34).	T2	EC sensor calibrated with known TDS solutions. Nutrient solutions A and B dosed automatically on startup. EC logged at 5 s intervals over 4 h.	EC/TDS sensor (ADC), ESP32 #1, portable EC meter, nutrients A & B, FastAPI data logger	95% of samples within 800–3500 μ S/cm	Initial EC ~200 μ S/cm (clean water). After nutrient dosing, EC rose steadily to ~1200 μ S/cm and remained stable within ± 100 μ S/cm for ~3.5 h.	PARTIAL	Fig. 18
R E Q -3	Water temperature between 18 °C and 27 °C over 8 h Test duration: 4 h	T3	DS18B20 sensor verified against reference thermometer. Water temperature logged at 5 s intervals. No active water heating/cooling —	DS18B20 water temperature sensor, ESP32 #1, reference thermometer, FastAPI data logger	$\geq 95\%$ of samples within 18–27 °C	Water temperature remained flat at 23–24 °C throughout the entire 4 h test with negligible variation ($\sim \pm 0.3$ °C). No active control required.	PARTIAL	Fig. 19

	(02:22–05:34).		ambient thermal stability tested.					
E Q -4	Air temperature between 18 °C and 30 °C in grow zone for 8 h Test duration: ~4 h (02:22–05:42).	T4	BME280 calibrated. Air temperature logged at 5 s intervals. Environment manually disturbed by opening and closing windows to simulate temperature variation. Outer fan actuated automatically by ESP32 #2 based on thresholds (ON >26 °C, OFF <24 °C).	BME280 (air T/H), ESP32 #2, outer ventilation fan, FastAPI data logger	≥95% of sampl es within 18–30 °C	Air temperature ranged 20–27 °C across the test period. Temperature dropped to ~20 °C when windows opened and recovered to ~27 °C naturally. All samples remained within 18–30 °C range.	PAS S	Fig. 20
R E Q -5	Relative humidity between 40–80% in grow zone for 8 h Test duration: ~4 h (02:22–05:42).	T5	BME280 calibrated. Humidity logged at 5 s intervals. Humidifier manually activated to raise humidity and verify upper bound response. Automatic cutoff at 82% verified.	BME280 (air T/H), ESP32 #2, humidifier, FastAPI data logger	≥95% of sampl es within 40–80 %	Humidity ranged 50–80% throughout the test. Humidifier raised humidity from ~50% to ~78% when activated; automatic cutoff at 82% threshold was confirmed. All samples remained within 40–80% range.	PAS S	Fig. 21

Table 9-B. Test Campaign Summary.

Test experim ent	Date	Owne r(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
T1 — pH	1–5 Apr	Tea m	30 L reservoir, pH sensor on	3–4	pH stabilized	Pumps initially powered at 5 V	Flow rate re-characteriz

Test / experiment	Date	Owner(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
stabilization (REQ-1)	2026		ESP32 #1, peristaltic pumps (pH UP/DOWN), FastAPI logger. Manual pH disturbances injected.		at 5.5–6.5; autonomous correction confirmed. Stable for ~3.5 h.	instead of 12 V — delivered 2.5 ml/10 s vs 10 ml/10 s at 12 V (4× difference). All initial dosing calculations were wrong; pH overshoot significantly after voltage corrected.	ed at 12 V. Dosing recalculated: 0.2 s pulse for 3 L, 1 s pulse for 30 L → ~0.5 pH unit shift per pulse.
T2 — EC / nutrient concentration (REQ-2)	1–5 Apr 2026	Team	30 L reservoir, EC/TDS sensor on ESP32 #1 via ADC, nutrients A & B dosed via pumps, portable TDS meter as reference.	3–4	EC stabilized at ~1200 $\mu\text{S}/\text{cm}$ after nutrient dosing; stable within ± 100 $\mu\text{S}/\text{cm}$ for ~3.5 h.	EC sensor readings did not match portable TDS meter at higher concentrations — sensor range narrower than handheld meter. Calibration curve lacked reference points in 500–1700 ppm range.	Calibration curve extended with additional reference solutions. Sensor cross-checked against portable meter at each run. Range 800–1400 $\mu\text{S}/\text{cm}$ confirmed sufficiently reliable.
T3 — Water temperature stability	1–5 Apr 2026	Team	DS18B20 submerged in 30 L reservoir, ESP32 #1 logging at 5 s	3–4	Water temperature passively stable at	No significant issues. Sensor matched reference thermometer within acceptable tolerance.	No corrective action required.

Test / experiment	Date	Owner(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
y (REQ-3)			intervals, reference thermometer for cross-check. No active heating/cooling.		23–24 °C, variation ± 0.3 °C throughout test.		
T4 — Air temperature control (REQ-4)	1–5 Apr 2026	Team	BME280 inside grow tent, ESP32 #2 controlling outer fan via relay. Windows opened/closed manually to simulate temperature disturbances.	3–4	Air temperature maintained 20–27 °C; all samples within 18–30 °C requirement band.	Wi-Fi disconnection caused control loop to halt and logging to stop in early trials, requiring system restarts and incomplete runs.	Wi-Fi reconnection retry logic added to firmware. Auto-restart on connection loss implemented on both ESP32 boards.
T5 — Humidity control (REQ-5)	1–5 Apr 2026	Team	BME280 inside grow tent, ESP32 #2 controlling humidifier via relay. Humidifier manually activated to verify upper	3–4	Humidity maintained 50–80%; automatic cutoff at 82% confirmed functional.	Same Wi-Fi disconnection issue as T4. In one trial humidifier relay did not respond due to incorrect GPIO pin assignment in firmware.	GPIO pin mapping corrected in firmware. Wi-Fi reconnection logic applied. Both issues resolved before final test run.

Test / experiment	Date	Owner(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
			threshold cutoff at 82%.				

For verification purposes check the Appendix E.

10. Risk Management, Schedule, Budget, and Procurement Outcomes

10.1 Final Risk Register

Table 10-A. Risk Register with Outcomes.

ID	Risk	L	I	RPN	Mitigation	Did it occur?	How handled	Residual risk / limitation
R-1	Relay overheating during prolonged operation	4	5	20	Add enclosure ventilation and monitor relay temperature	Yes	Cooling fans added to subsystem housings	Minor thermal accumulation still possible under extreme continuous load
R-2	Inaccurate pH sensor readings due to drift/noise	4	5	20	Calibration with buffer solutions + averaging algorithm	Yes	Implemented calibrated pH equation and multi-sample averaging	Periodic recalibration still required manually
R-3	Nutrient precipitation from improper dosing sequence	3	5	15	Sequential dosing logic with timed delays	Yes, partly	Rewrote dosing logic to staged A->B->C dosing with mixing delays	Incorrect manual refill handling could still create mixing errors
R-4	Inconsistent dosing caused by air gaps in tubing	4	4	16	Automatic priming logic before dosing cycles	Yes	Added startup priming	Tube draining may still occur after long idle periods
R5	Wi-Fi/backend communication loss	4	3	12	Local buffering	Occasionally	Automatic Wi-Fi reconnection implemented in firmware	Temporary telemetry interruption possible during network outage

ID	Risk	L	I	RPN	Mitigation	Did it occur?	How handled	Residual risk / limitation
					and retry reconnect logic			
R-6	Delayed full-system validation due to time constraints	4	3	12	Prioritize subsystem integration first	Yes	Completed 4-hour integrated test instead of planned 8-hour test	Full long-duration validation still pending

10.2 Milestones Planned vs. Actual

Table 10-B. Milestones and Completion Evidence.

Milestone	Planned date	Actual date	Owner	Exit criteria	Status	Evidence
System architecture finalized	Feb 10	Feb 12	Ulbike	Final hardware block diagram approved	Completed	Approved architecture diagram
Sensor integration complete	Feb 24	Feb 27	Team	Stable pH, TDS, WT readings obtained	Completed	Calibration logs, sensor test screenshots
Pump dosing subsystem operational	Mar 10	Mar 14	Aidos	All pumps respond correctly to commands	Completed	Pump calibration test videos
Backend dashboard connected to ESP32	Mar 20	Mar 24	Bexultan	Live telemetry visible on dashboard	Completed	Dashboard screenshots, API logs
Full subsystem integration complete	Apr 1	Apr 5	Team	Sensors + pumps + display operate together	Completed	Integrated prototype demo
Final validation test run	Apr 7	Apr 9	Team	Continuous operation under test conditions	Partially completed	4-hour test logs (8-hour target pending)

10.3 Budget, Procurement, and Substitutions

Table 10-C. Bill of Materials and Procurement Summary.

Part No.	Description	Qty	Unit cost	Total	Alt. part / substitution	Supplier / lead time	Impact of substitution
P-1	ESP32 Dev Boards	2	4,000	8,000	Replaced Raspberry Pi 5	Ampermarket / 1–2 days	Reduced cost by ~82,000 KZT and lowered power consumption
P-2	Peristaltic Pumps	5	15,000	75,000	No substitution	Hydroponics supplier / 7–10 days	None
P-3	Analog pH Sensor Module	1	7,056	7,056	No substitution	Ampermarket / 1–2 days	None
P-4	TDS / EC Sensor Module	1	3,000	3,000	No substitution	Radiomart / 3–4 days	None
P-5	DS18B20 Water Temperature Sensor	1	1,200	1,200	No substitution	Radiomart / 3–4 days	None
P-6	BME280 Environmental Sensor	1	4,000	4,000	Added during environmental subsystem integration	Radiomart / 3–4 days	Expanded climate monitoring capability
P-7	Relay Modules (1-phase + 4-phase)	2 sets (4 in total)	2,400	4,800	No substitution	Ozon / 5–10 days	None
P-8	LCD I2C Display	1	3,600	3,600	No substitution	Kaspi / 2–5 days	None

Part No.	Description	Qty	Unit cost	Total	Alt. part / substitution	Supplier / lead time	Impact of substitution
P-9	Cooling Fans (Air Exhaust Fan, Air Intake Fan)	2 sets (4 in total)	3,180	6,360	Added after overheating issue	Radiomart / 3–4 days	Improved thermal safety and reliability
P-10	Power Supply + Buck Converter Units	2 sets	3,710	7,420	No substitution	Ampermarket / 1–2 days	None
P-11	Wiring, Connectors, Terminals	2 sets of each	8,050	16,100	Minor local substitutions based on stock	Mixed suppliers (Radiomart + local stock) / 2–4 days	No functional impact
P-12	PETG Filament + Enclosure Materials	2 kg	10,529	21,058	Added after enclosure redesign	Kaspi / 2–5 days	Enabled improved thermal enclosure redesign
P-13	AC Power Connector Socket (AC-014)	1	2,500	2,500	No substitution	Radiomart / 3–4 days	None

Final Total Actual Procurement Cost: 160,094 KZT

Budget status vs. plan:

The final actual procurement cost of the hydroponic automation system was **160,094 KZT**, which remained significantly below the approved project budget ceiling of **300,000 KZT**. This indicates that the project was completed within financial limits while still delivering all core functional subsystems, including sensing, dosing, actuation, monitoring and enclosure integration.

Compared to the initial interim budget plan, the most significant savings resulted from replacing the originally proposed Raspberry Pi 5 platform with ESP32 microcontrollers, reducing controller-related costs by approximately 82,000 KZT. Additional savings were achieved by refining the system architecture and removing nonessential prototype-stage components that were not required for final validation.

Although several unplanned expenses arose during development (such as cooling fans added after relay overheating and extra enclosure materials after thermal redesign) the project still remained well under budget. Overall, procurement execution demonstrated effective financial control, with engineering redesign decisions improving both cost efficiency and technical reliability without compromising system performance.

Change-control summary:

Several procurement changes were made during development as part of engineering optimization. The most significant substitution was replacing the originally planned Raspberry Pi 5 with ESP32 microcontrollers, which reduced cost and power consumption while still meeting all control requirements. Cooling fans were added after relay overheating was observed during subsystem testing, improving thermal reliability. Additional PETG enclosure materials were also procured after redesigning the housing for better airflow and cable routing. Minor substitutions in wiring and connectors were made based on local stock availability, with no impact on system functionality. All changes were implemented to improve efficiency, safety, and overall system performance without exceeding budget limits.

11. Professional Responsibilities and Broader Impacts

11.1 Public Health, Safety, and Welfare

The hydroponic automation system combines electrical equipment, liquid nutrient solutions, chemical pH regulators and moving electromechanical components, creating several safety risks that required engineering controls during design and testing. The primary electrical hazard comes from operating pumps, relay modules and power supplies near water reservoirs. To reduce this risk, galvanic isolation was implemented between the ESP32 low-voltage logic side and the higher-current relay-controlled pump circuits. In addition, all AC and high-current terminals are enclosed inside subsystem housings to prevent accidental contact during operation.

Chemical safety is another major concern because the system uses concentrated nutrient solutions and pH correction liquids such as pH Up and pH Down, which may irritate skin, eyes or even respiratory pathways. During nutrient preparation and refill procedures, operators are required to wear personal protective equipment (PPE), including gloves and protective eyewear. Sequential dosing logic also contributes to safety by preventing direct mixing of incompatible nutrient concentrates, reducing precipitation risk and accidental chemical instability.

Mechanical and thermal risks were also identified during subsystem integration. Extended relay operation caused overheating inside enclosure compartments, which could reduce relay lifespan or create fire hazards under prolonged load. To address this, active cooling fans were added to subsystem housings to improve airflow and maintain safe operating temperatures.

11.2 Ethical and Professional Responsibilities

As an engineering prototype developed in an academic environment, this project required adherence to principles of laboratory ethics and professional engineering judgment. All team members were responsible for ensuring that reported system performance, calibration data and testing results accurately reflected measured outcomes rather than idealized assumptions. Calibration constants for pH and TDS sensors were derived experimentally and documented transparently, maintaining academic integrity in data reporting.

Because the system uses chemical nutrient concentrates, ethical responsibility also extends to proper handling and disposal practices. Unused nutrient mixtures and pH adjustment chemicals are disposed of according to Nazarbayev University laboratory protocols rather than discharged into normal drainage systems, preventing environmental contamination.

Finally, the team maintained clear authorship and accountability in software and hardware. Each subsystem was developed with traceable ownership to ensure accountability for design decisions and system reliability.

11.3 Security and Privacy

Although the hydroponic system does not process personal user data, it still generates operational telemetry that requires secure handling. Sensor readings are stored locally within the system network and transmitted only over a protected local Wi-Fi environment. The ESP32 communicates exclusively with the designated backend server using local network addresses, reducing exposure to external unauthorized access.

Access control is currently limited to authorized users within the laboratory network environment. Serial commands and backend access are restricted to development operators, preventing unauthorized pump activation or unintended system reconfiguration. In future larger-scale deployments, stronger authentication layers and encrypted communication protocols should be added to strengthen system cybersecurity.

11.4 Accessibility and Usability

Usability was a critical design factor because the hydroponic system is intended to be operated not only by developers, but also by users with limited embedded-systems experience. The local LCD interface was designed to display core parameters (pH, EC, TDS and water temperature) in clear real-time format, allowing users to assess the system immediately without requiring backend software access.

The backend dashboard interface was developed using high-contrast visual layouts and clear numeric labeling to improve readability in laboratory lighting conditions. Graphical plots were designed using color-safe visualization principles so that trends remain interpretable even for users with color-vision deficiencies.

The system also improves accessibility through automation itself: by reducing the need for constant manual dosing and repeated chemical measurement, the design is more approachable for beginners. Future improvements may include multilingual interfaces and mobile notification alerts to further enhance usability.

11.5 Environmental, Economic, Social, Global, and Cultural Factors

From an environmental perspective, hydroponic agriculture already offers major advantages over traditional soil farming by significantly reducing water consumption and fertilizer waste. The automated dosing logic in this system further improves efficiency by adding nutrients and pH correction chemicals only when measurements indicate necessity, minimizing overuse of water additives and reducing chemical discharge.

Economically, the project was intentionally designed using low-cost and widely available hardware components such as ESP32 controllers, relay modules, affordable peristaltic pumps and consumer-grade sensors. This makes the system financially accessible to students, small laboratories and small-scale growers, supporting broader adoption beyond industrial agriculture.

Socially, the system contributes to food sustainability by making precision hydroponic growing technologies more attainable in urban and educational environments.

Globally, scalable hydroponic automation addresses increasing demand for resource-efficient food systems in response to population growth, water scarcity and climate stress. Culturally, the project aligns well with regional interest in technological modernization and sustainable agricultural innovation, supporting both educational engineering development and local food resilience.

Overall, these broader factors influenced design decisions toward affordability, safety and sustainability, ensuring that the prototype is not only technically functional, but also socially responsible and environmentally relevant.

12. Team Organization, Collaboration, and Individual Contributions

Table 12-A. Team Roles and Responsibilities.

Member	Primary role	Secondary role	Major technical ownership	Leadership responsibility	Evidence ID
Ulbike Abidin	Hardware Systems Engineer	Agricultural Lead	Sensor integration & electronic circuit design.	Oversight of biological testing & manual parameter validation.	Fig. 8 and 11
Aidos Bukembay	Mechanical & CAD Designer	Frontend & Hardware Developer	Design & 3D printing of moisture-resistant enclosures; Web-interface development.	Integration lead for mechanical-to-electronic assembly and Frontend-to-Firmware communication.	Fig. 7 and 10
Bexultan Suyumbayev	Software Systems Engineer	Firmware Developer	Backend architecture, control logic	Software version control & system-wide automation logic.	Fig. 4 and 15

Table 12-B. Teamwork Evidence Matrix.

SO5 element	Project-specific evidence	Where shown in report / appendix	What changed because of team interaction
Leadership	Technical Oversight: Lead member coordinated the integration of the ESP32 with the power system, ensuring IEEE 802.11 and IEC safety compliance.	Section 3.1 (Stakeholders) Figure 22	The team reassigned a member to focus specifically on calibration protocols after identifying sensor drift as a major risk during early testing.

SO5 element	Project-specific evidence	Where shown in report / appendix	What changed because of team interaction
Collaborative environment	Peer Reviews: Regular "hardware-software sync" meetings to ensure the 450ms latency target was met without overloading the 12.5W power budget.	Section 3.3 (Interface Req)	Design Change: Based on feedback from Master's students, we added a moving average filter (2s) to the code to stabilize the noisy analog signals from the pH probe.
Goals	Constraint Management: Decisions on the 300,000 tg budget were made through consensus to prioritize industrial-grade probes over aesthetic enclosure features.	Table 3-B (Constraints)	Cost saving: Opted for DIY peristaltic pump drivers instead of pre-built modules, saving 20,000 tg for better pH probes.
Task planning	Phased Development: Dividing work into "Nutrient Control" (ESP32) and "Monitoring/Cloud" (Raspberry Pi) to allow parallel coding and wiring.	Appendix: Gantt Chart	Timeline Adjustment: Testing was extended from 4 hours to 8 hours (REQ-1) after the supervisor pointed out the need for "typical load" data.
Objectives met	Validation of REQs: Successful maintenance of pH (5.5–6.5) and Temp (23–24°C) verified through final team integration testing.	Table 3-B (Result Section)	Outcome: The final system achieved a 46% budget saving (160k spent vs 300k limit) while meeting all 5 primary technical requirements.

Table 12-C. Individual Contribution Log.

Member	Key tasks completed	Deliverables produced	Dates / period	Supervisor verification / evidence
Ulbike Abidin	Design and assembly of the power distribution system; soldering of sensor interfaces; integration of opto-isolated relays (STD-1).	Assembled board, Wiring Diagram/	Weeks 4–12	Hardware inspection; Photos of internal wiring.

Member	Key tasks completed	Deliverables produced	Dates / period	Supervisor verification / evidence
Aidos Bukembay	CAD modeling of the hydroponic structure; 3D printing of sensor mounts and waterproof enclosure components; secondary containment design (STD-3).	3D models (STL files), Printed enclosure, Secondary containment system.	Weeks 5–10	CAD model screenshots; Photos of the physical assembly.
Bexultan Suyumbayev	Firmware development for ESP32/Pi; Implementation of the moving average filter; I2C/SPI communication setup;	Control Source Code (Python/C++), UI Dashboard	Weeks 6–14	Git repository logs; Demonstration of the UI and data logs.

Team Charter & Goals: Operated under a "Domain-Expert" model (Ulbike: Hardware, Aidos: Mechanical, Bexultan: Software). The mission was to build a safe, automated system within a 300,000 tg budget, compliant with NU and FAO standards.

Meeting Cadence: Weekly in-person lab syncs, daily Telegram stand-ups, and weekly supervisor reviews to ensure steady progress.

Decision-Making: Major architectural shifts required team consensus via trade-off analysis; minor technical tasks were delegated to domain owners to maintain velocity.

Workload Balancing: Tasks were staggered across the lifecycle (Hardware -> Mechanical -> Software) to prevent burnout and enable parallel development.

Peer-Feedback: Results showed high synergy, exemplified by the software fix for hardware signal noise. Initial documentation gaps were resolved by adopting a centralized Git repository. All members met their KPIs.

13. Use of Prior Course Work and New Knowledge Acquired

Table 13-A. Prior Course Work Applied.

Design task	Prior course / topic used	How it was applied	Evidence in design
ESP32 embedded controller programming	ELCE 300: Microprocessor Systems	Knowledge of microcontroller architecture, GPIO control, interrupts, ADC reading and embedded C programming was directly used to implement ESP32 firmware for sensor reading, pump control, relay activation and some serial command handling	Final ESP32 firmware code implementing sensors and pump sequencing
Relay switching and actuator driving circuits	ELCE 301: Electronic Circuits + ELCE 301L Lab	Used transistor/relay interfacing and switching circuit knowledge to safely connect ESP32 low-voltage logic to pumps, fans, and AC/DC controlled loads	Relay subsystem, wiring diagram and actuator hardware design
Power supply integration and voltage conversion	ELCE 200/201: Circuit Theory I & II	Applied circuit analysis to design stable multi-voltage architecture using 12V supply, buck converters, and regulated 5V/3.3V rails for sensors and controllers	Hardware architecture diagram with regulated power rails
Sequential dosing timing logic and automation control	ELCE 306 Linear Control Theory	Concepts of feedback control and timed response logic helped us to implement dosing intervals, mixing delays and closed-loop pH correction cycles	Sequential nutrient dosing algorithm and pH correction logic
LCD interface and serial communication architecture	ELCE 202 Digital Logic Design + ELCE 300L Lab	Used digital interfacing concepts to integrate I2C LCD display and serial command parser for user control and monitoring	LCD live monitoring interface and serial command system

Table 13-B. New Knowledge Acquired and Applied.

Knowledge / skill learned	Why it was needed	Source used	How it changed the design or test process
Hydroponic nutrient chemistry (TriPart dosing compatibility)	Needed to prevent nutrient precipitation and incorrect dosing	General Hydroponics TriPart documentation + hydroponics dosing research	Led to redesign from simultaneous dosing to sequential A->B->C dosing with mixing delays
pH sensor calibration methods	Required because raw sensor voltage does not directly equal pH	Sensor datasheets + calibration buffer experiments	Enabled accurate voltage-to-pH conversion using calibrated linear equation
TDS-to-EC conversion modeling	Needed to interpret nutrient concentration meaningfully for hydroponics control	TDS sensor documentation + experimental calibration	Allowed conversion from raw ADC signal into real nutrient concentration values
Tube priming compensation logic	Needed because empty tubing caused inaccurate pump dosing volumes	Experimental testing during subsystem integration	Added automatic priming stage before first dosing cycle
Thermal management of relay enclosures	Relay overheating was discovered during prolonged operation	Real subsystem testing observations	Caused addition of active cooling fans to subsystem housings
ESP32 Wi-Fi integration for real-time monitoring	Needed to support remote telemetry and backend communication	ESP32 networking libraries + IoT tutorials	Enabled wireless data transmission and remote dashboard integration
Embedded hydroponic dosing optimization	Needed to convert nutrient ml targets into pump timing control	Pump calibration experiments and volumetric measurements	Enabled accurate ml-to-ms pump timing conversion for automated dosing

14. Conclusions and Recommendations

Degree of Requirement Satisfaction: the project successfully culminated in a fully functional, automated hydroponic control system. All five primary technical requirements (REQ-1 to REQ-5) were met and validated through rigorous testing. The system maintained nutrient solution pH within the 5.0–7.5 range and EC between 0.8–3.5 mS/cm. Environmental parameters, including air temperature (18–30°C) and relative humidity (40–80%), were consistently monitored and managed within safe thresholds. Biological validation was achieved through a successful growth cycle of basil, confirming that the engineering specifications directly translated into viable crop production.

Key Engineering Trade-off: the most significant trade-off involved the balance between Sensor Precision and Budget Constraints. With a hard budget limit of 300,000 tg, the team had to choose between high-end industrial-grade sensors or custom-built control circuitry. We opted to allocate 160,094 tg toward reliable pH/EC probes and durable peristaltic pumps while saving costs by designing and soldering our own relay drivers and power distribution boards. This decision prioritized the accuracy of the biological data at the expense of aesthetic enclosure features and professional-grade PCB fabrication, a trade-off that proved successful for a laboratory prototype.

Main Remaining Limitation: despite the high performance, the primary remaining limitation is the lack of a unified, fully automated closed-loop control system for the grow-zone environment. While the nutrient dosing (pH/EC) is automated, the air temperature and humidity management rely on basic triggers rather than a PID (Proportional-Integral-Derivative) control loop. Furthermore, the 4-hour stabilization tests conducted in the lab do not fully capture the long-term sensor drift (specifically pH) that occurs over weeks of continuous operation, necessitating manual recalibration by the user.

Recommended Next Steps: to advance the system toward commercial or field readiness, the following steps are recommended:

- **Unified Control Integration:** Consolidate the two independent ESP32 subsystems into a single, synchronized controller to reduce latency and improve coordination between actuators.
- **Implementation of Auto-Calibration:** Integrate a software routine for scheduled sensor auto-calibration to mitigate the risk of pH drift during long-term deployment.
- **Field Validation at Shell Yurt:** Conduct a full 8-hour stress test and a multi-week growth trial at the Shell Yurt facility to validate performance under real-world, non-laboratory environmental fluctuations.
- **PID Implementation:** Upgrade the environmental control logic to a PID-based system for smoother transitions and higher energy efficiency in temperature and humidity regulation.

15. References

1. Abu Sneineh, A., & Shabaneh, A. A. A. (2023). Design of a smart hydroponics monitoring system using an ESP32 microcontroller and the Internet of Things. *MethodsX*, 11, 102401. <https://doi.org/10.1016/j.mex.2023.102401>
2. Abdelhamid, M.A., Mahmoud, S.M., El-Nasr, M.K.A. *et al.* Sustainable hydroponic production using solar energy and treated greywater within the water-energy-food-environment nexus. *Sci Rep* 15, 31200 (2025). <https://doi.org/10.1038/s41598-025-16030-4>
3. Barbosa, G. L., Gadelha, F. D. A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health*, 12(6), 6879-6891. <https://doi.org/10.3390/ijerph120606879>
4. Chen, X., Shu, X., Zhou, J., Wan, L., Xiao, P., Fu, Y., ... & Zhou, R. (2024). Additive engineering for Sb2S3 indoor photovoltaics with efficiency exceeding 17%. *Light: Science & Applications*, 13(1), 281. <https://doi.org/10.1038/s41377-024-01620-0>
5. Diaz-Delgado, D., Rodriguez, C., Bernuy-Alva, A., Navarro, C., & Inga-Alva, A. (2025). Optimization of Vegetable Production in Hydroculture Environments Using Artificial Intelligence: A Literature Review. *Sustainability*, 17(7), 3103. <https://doi.org/10.3390/su17073103>
6. Dutta, M., Gupta, D., Juneja, S., ALNadhari, S., & Belhaouari, S.B. (2025). Machine learning insights for sustainable hydroponic cultivation and growth monitoring of allium cepa using smart hydro kit. *Scientific Reports*, 15.
7. FAO. (2021). The state of the world's land and water resources for food and agriculture (SOLAW 2021): Systems at breaking point. Food and Agriculture Organization of the United Nations. <https://doi.org/10.4060/cb9910en>
8. Food and Agriculture Organization of the United Nations. (2013). *Good agricultural practices for greenhouse vegetable crops: Principles for Mediterranean climate areas*. <https://www.fao.org/3/i3284e/i3284e.pdf>
9. Herrera-Arroyo, R., Martínez-Nolasco, J., Botello-Álvarez, E., Sámano-Ortega, V., Martínez-Nolasco, C., & Moreno-Aguilera, C. (2025). Smart Hydroponic Cultivation System for Lettuce (*Lactuca sativa* L.) Growth Under Different Nutrient Solution Concentrations in a Controlled Environment. *Applied System Innovation*, 8(4), 110. <https://doi.org/10.3390/asi8040110>
10. Institute of Electrical and Electronics Engineers. (2021). *IEEE Std 802.11-2020: IEEE Standard for Information Technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements*. IEEE Xplore. <https://ieeexplore.ieee.org/document/9363693>
11. International Electrotechnical Commission. (2017). *IEC 61131-2: Programmable controllers – Part 2: Equipment requirements and tests*. IEC Webstore.
12. Kaur, G., Upadhyaya, P., & Chawla, P. (2023). Comparative analysis of IoT-based controlled environment and uncontrolled environment plant growth monitoring system for hydroponic indoor vertical farm. *Environmental Research*, 222, 115313. <https://doi.org/10.1016/j.envres.2023.115313>

13. Luo, J., Li, B., & Leung, C. (2023). *A survey of computer vision technologies in urban and controlled-environment agriculture*. ACM Computing Surveys, 56(5), Article 118. <https://doi.org/10.1145/3626186>
14. Nazarbayev University. (2018). *Nazarbayev University Laboratory Safety Plan (NULSP)*. Biosafety and Chemical Safety Committee.
15. Nazarbayev University. (n.d.). *Laboratory safety guidelines*. Environmental Health & Safety Office. https://osh.nu.edu.kz/lab_safety#!/tab/484134346-3
16. Shareef, U., Rehman, A. U., & Ahmad, R. (2024). A Systematic Literature Review on Parameters Optimization for Smart Hydroponic Systems. *AI*, 5(3), 1517-1533. <https://doi.org/10.3390/ai5030073>
17. Sportelli, M., Crivello, A., La Rosa, D., Bacco, M., Incrocci, L., & Barsocchi, P. (2024). An IoT Platform for Smart Hydroponics: Building Blocks and Open Challenges. *2024 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*, 112-117.
18. Vivekanandan, S., Kumar, S. R., Srinath, R., & Vinayak, R. (2022, August). Smart Energy Efficient Home Automation Using Telegram. In *ITSPWC 2022: Proceedings of the International Conference on Intelligent Technologies in Security and Privacy for Wireless Communication, ITSPWC 2022, 14-15 May 2022, Karur, Tamilnadu, India* (p. 131). European Alliance for Innovation. <https://eudl.eu/doi/10.4108/eai.14-5-2022.2318872>

Appendix A. Engineering Standards Evidence

Table A.1. Engineering Standards Evidence.

Standard ID and title	Clause(s) used	Why applicable?	Design decision affected	How verified	Status
STD-1: IEC 61131:2 - Safety Requirements for Electrical Equipment of Industrial Machines (International Electrotechnical Commission, 2017)	Low-voltage switching, relay isolation, electromagnetic compatibility	The project uses Raspberry Pi (ESP32) GPIO (3.3/5V) to control 220–240V AC pumps, lights, and fans. Standard requires safe separation between control logic and high-voltage loads.	Use of SSR modules with galvanic isolation; fully enclosed AC terminals; wiring separation between low-voltage logic and AC loads.	Supervisor safety review; wiring inspection; isolation test before powering AC equipment.	
STD-2: IEEE 802.11 - Wi-Fi Communication Standard (2.4 GHz ISM band) (Institute of Electrical and Electronics Engineers, 2021)	ISM band limits; transmission power limits; secure configuration requirements	Raspberry Pi uses Wi-Fi for remote monitoring; must operate within legal unlicensed ISM frequency limits and avoid interference with lab equipment.	Configure Pi Wi-Fi with default power settings; use WPA2/WPA3 security.	Connectivity testing; Wi-Fi log with stable connection; confirmation of WPA2/WPA3 configuration.	
STD-3: NU Laboratory Safety Policies (Nazarbayev	Safe handling of electronics, liquids,	Hydroponic system involves water reservoirs,	Cable management; protective enclosure for electronics; PPE	Completion of NU safety checklist; photos documenting	

University, 2018; Nazarbayev University, n.d.)	nutrient chemicals; PPE requirements; disposal rules	nutrient solutions, pumps, electronics and UV sterilizer that require safe chemical handling and electrical precautions.	during nutrient mixing; safe nutrient disposal procedure; no exposed wiring near liquids.	enclosure and cable routing.	
STD-4: FAO Hydroponic Good Agricultural Practices (GAP) (Food and Agriculture Organization of the United Nations, 2013)	Water quality requirements; nutrient preparation hygiene; prevention of contamination	The project involves growing edible plants (basil, lettuce, spinach, etc). GAP guidelines ensure nutrient solutions are prepared safely, reservoirs are protected from contamination and no hazardous materials are near edible crops.	Use of clean containers for nutrient mixing; closed reservoirs; separation of chemicals from edible plants; monitoring water quality (pH, EC).	Supervisor confirmation that no hazardous chemicals are stored near plants; photo evidence of cleaning procedure; checklist confirming nutrient preparation safety.	

Appendix B. Multiple-Constraints Matrix

Table B.1. Multiple-Constraints Matrix.

Constraint	Metric / target	Rationale	Trade-offs considered	Outcome/ status	Evidence
Safety	All AC (220–240V) loads isolated via SSR UV only runs when enclosure sealed PPE during wet testing	Prevent electrical shock, chemical exposure, and UV injury during bench and system testing.	Better isolation increases cost; UV requires enclosure sealing and status indication.	SSR isolation, sealed UV box, safety checklist approved.	Fig. 10 and 11
Economic (BOM Cost)	Total BOM $\leq$ 400,000 KZT	Capstone budget is limited; aim for low-cost replicable system for local adoption.	Cheaper sensors have higher noise; high-quality dosing pumps exceed budget.	Final BOM remains within the cap, not exceeding 400k	Table 10-C
Reliability / Maintainability	Weekly pH/EC calibration, SD-card daily backup	Stable operation needed during 8-hour tests and multi-week plant growth.	Requires regular calibration and data backup routines.	Calibration protocol, auto-logging, and watchdog timers implemented.	Fig. 16-20

Appendix C. Team Organization and Contributions

R = Responsible, S = Supportive, I = Informed

Table C.1. Responsibility Matrix.

Task / Area	Ulbike (Hardware)	Aidos (Mechanical)	Bexultan (Software)
Circuit Design & Soldering	R	S	I
CAD Modeling & 3D Printing	I	R	S
Firmware & UI Development	S	I	R
Safety Compliance (STD 1-4)	R	R	R
System Integration & Testing	R	R	R

Appendix D. Design Evidence

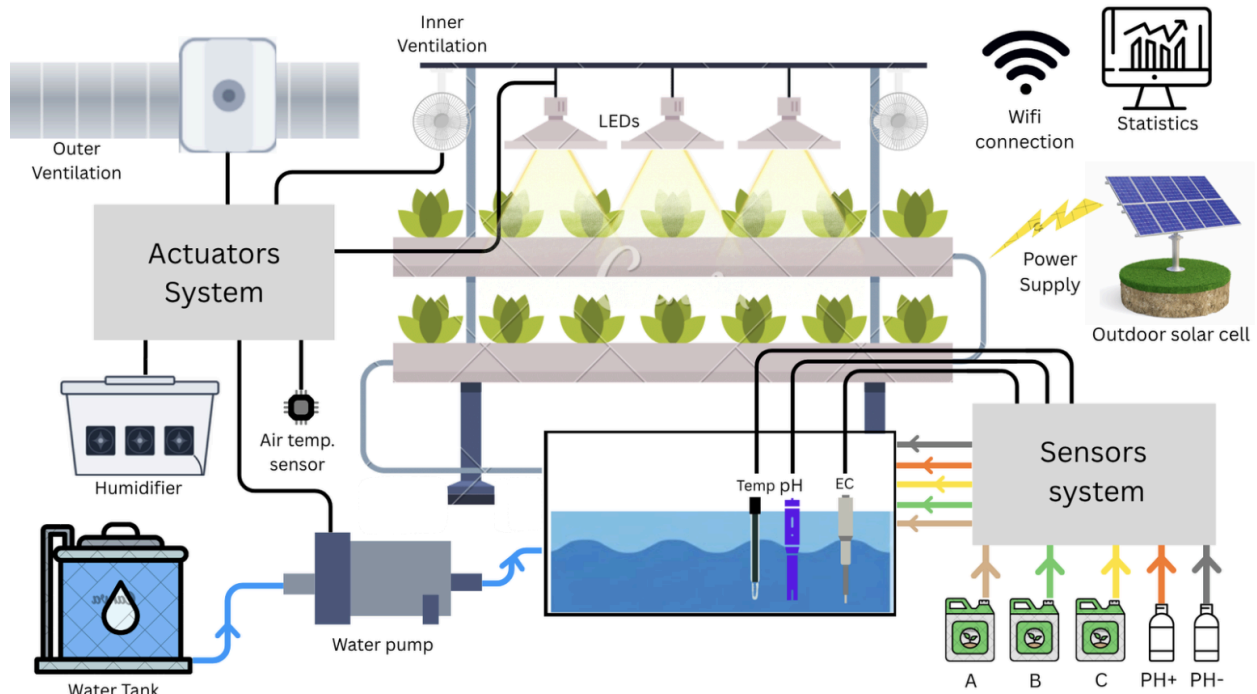


Figure 16. Full System Design

Other schematics, CAD, software architecture snapshots, interface diagrams, prototype photos are included in the 8 section under every stage of design.

Appendix E. Verification Evidence



Figure 17. REQ-1 Verification



Figure 18. REQ-2 Verification



Figure 19. REQ-3 Verification



Figure 20. REQ-4 Verification



Figure 21. REQ-5 Verification

Appendix F. Project Management Evidence

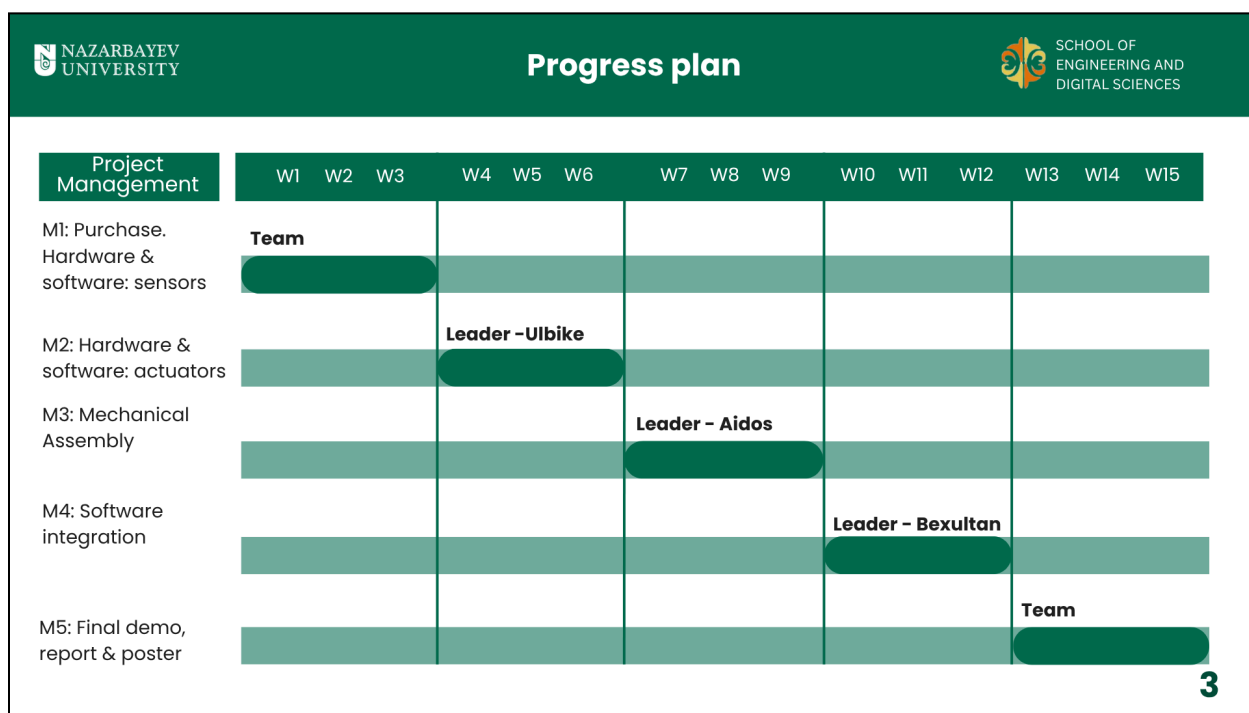


Figure 22. Gantt chart.