

MODULAR SMART IRRIGATION SYSTEM

Design and Experimental Evaluation of a Low Cost,
Servo Controlled Three Zone Irrigation System

*Water Distribution, Soil Moisture Monitoring,
and Irrigation Emitter Optimization*

THREE ZONE PRECISION IRRIGATION PROTOTYPE

Fusion 360 Design | 3D Printing | ESP32 Control | Experimental Validation



Prepared by

MELIKE MUSDAL

2026

ABSTRACT

This project presents the design, manufacturing, and experimental evaluation of a low cost modular smart irrigation system developed to reduce unnecessary water consumption and provide controlled irrigation for multiple plants. The system uses a single water pump and a servo controlled rotary manifold to distribute water between three separate irrigation zones. Each zone can be selected by rotating the internal distribution mechanism to calibrated angular positions of 0° , 90° , and 180° .

The mechanical components, including the rotary manifold and two alternative irrigation emitters, were designed using **Autodesk Fusion 360** and manufactured using additive manufacturing. A single outlet emitter and a multi outlet emitter were developed and experimentally compared. Flow rate measurements showed that the single outlet emitter delivered approximately 12.83 mL/s, whereas the multi outlet emitter delivered approximately 17.50 mL/s under the same pump operating conditions.

An **ESP32** microcontroller was used to control the servo motor, water pump, MOSFET switching module, and soil moisture sensors. Three soil moisture sensing channels were assigned to the irrigation zones. Sensor readings were processed by averaging multiple samples in order to reduce measurement noise and short term fluctuations.

The completed prototype successfully directed water toward three different outlets without visible leakage between the selected channels. The developed system demonstrates that a modular and zone based irrigation mechanism can be constructed using low cost components, 3D printed parts, and an ESP32 controller. The design also provides a foundation for future Wi-Fi based data recording, remote monitoring, and automatic irrigation according to individual plant requirements.

Keywords: *Smart irrigation, ESP32, soil moisture sensor, servo motor, rotary manifold, water distribution, 3D printing, modular irrigation.*

TABLE OF CONTENTS

Front Matter

- Abstract
- Table of Contents
- List of Abbreviations

Chapter 1 – Introduction

- 1.1 Project Background
- 1.2 Problem Definition
- 1.3 Project Aim and Objectives
- 1.4 Project Scope and Design Requirements

Chapter 2 – Mechanical Design

- 2.1 General Design Concept
- 2.2 Irrigation Emitter Design Requirements
- 2.3 Single Outlet Emitter Design
- 2.4 Multi Outlet Emitter Design
- 2.5 Manifold and Rotary Valve Design
 - 2.5.1 Manifold Body
 - 2.5.2 Internal Rotor
 - 2.5.2.1 O-Ring Sealing System
 - 2.5.3 Top Cover
 - 2.5.4 MG996R Servo Motor
 - 2.5.5 Assembly Operation and Calibration
 - 2.5.6 Dimensional Specification
- 2.6 Fusion 360 Modelling Process
- 2.7 3D Printing and Design Iterations

Chapter 3 – Electronic System

- 3.1 Electronic System Architecture
- 3.2 ESP32 and Pin Connections
- 3.3 Servo Motor System
- 3.4 Pump and MOSFET Control
- 3.5 Power Distribution and Protection
- 3.6 Soil Moisture Sensors

Chapter 4 – Software and Control

- 4.1 Progressive Firmware Development and Component Tests
- 4.2 Servo Position Test and Three Zone Mapping
- 4.3 Moisture Sensor Acquisition and Signal Processing
- 4.4 Integration of Moisture Detection and Servo Selection
- 4.5 Integrated Development Firmware
- 4.6 Final Closed Loop Irrigation Algorithm
- 4.7 Software Design Outcome

Chapter 5 – Experimental Evaluation

- 5.1 Emitter Flow Rate Measurement and Selection
- 5.2 Equal Volume Irrigation Test
 - 5.2.1 Common Experimental Conditions
- 5.3 Soil Wetting Distribution Experiment
 - 5.3.1 Single-Outlet Emitter Results
 - 5.3.2 Single Outlet Spatial Moisture Sensor Readings

- 5.3.3 Multi Outlet Emitter Results
- 5.3.4 Multi Outlet Spatial Moisture Sensor Readings
- 5.4 Results and Discussion
 - 5.4.1 Moisture Response and Distribution Uniformity

Chapter 6 – Final Prototype Functional Validation

- 6.1 Test Objective and Arrangement
- 6.2 Three Zone Water Routing Procedure
- 6.3 Observed Functional Results
- 6.4 Engineering Interpretation and Water Saving Assessment
- 6.5 Challenges and Engineering Decisions
- 6.6 Cost and Sustainability
- 6.7 Scope and Limitations
- 6.8 Practical and Societal Significance
- 6.9 30 Day Operational Evaluation
- 6.10 Chapter Summary

Chapter 7 – Future Development and Final Remarks

- 7.1 Plant Specific Moisture Control
- 7.2 Connected Monitoring and Data Logging
- 7.3 Environmental Sensing and Predictive Irrigation
- 7.4 Manifold Reliability and Hydraulic Development
- 7.5 Electrical and Hardware Reliability
- 7.6 Scalability and Wider Application
- 7.7 Long Term Experimental Validation
- 7.8 Final Project Perspective

Closing Remarks

References

LIST OF ABBREVIATIONS

Abbreviation	Definition
A	Ampere (unit of electric current)
ADC	Analog to Digital Converter
AO	Analog Output
BOM	Bill of Materials
CAD	Computer Aided Design
DC	Direct Current
ESP32	Espressif 32 bit Microcontroller
FDM	Fused Deposition Modelling
GND	Ground
GPIO	General Purpose Input/Output
IoT	Internet of Things
mL	Millilitre
mL/min	Millilitres per Minute
mL/s	Millilitres per Second
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
STL	Standard Tessellation Language
V	Volt (unit of electric potential difference)
Wi-Fi	Wireless networking technology

CHAPTER 1 – INTRODUCTION

1.1 Project Background

Fresh water is a limited natural resource, and irrigation is a major component of water use in agricultural, domestic, and small scale plant growing applications. In conventional irrigation, several plants are often watered for the same duration even though their soil conditions, root structures, pot sizes, and water requirements may be different. This approach can produce inconsistent results: one plant may receive excessive water while another remains comparatively dry.

Excessive irrigation may cause surface pooling, drainage from the bottom of a container, unnecessary soil saturation, and water loss. Insufficient irrigation may restrict plant development and reduce plant health. A more controlled approach is therefore required to deliver water to the zone that needs it, at a suitable time and in a repeatable amount.

Commercial multi zone irrigation systems commonly use a separate pump or electrically operated valve for each zone. Although effective, this arrangement increases cost, wiring complexity, power requirements, and the number of components that may require maintenance. The project presented in this report investigates a lower cost alternative based on one DC pump and one servo controlled rotary manifold. The manifold directs the supplied water to one of three plant zones while the other outlets remain inactive.

Water for the prototype is stored in a reusable 5 L water reservoir (water bottle/container), which acts as the common source for all three irrigation zones. During the final validation, the reservoir was filled to approximately 2.5 L. The R385 pump draws water directly from this reservoir and transfers it through the main hose to the servo controlled manifold, where the flow is routed to the selected plant zone. Using one shared reservoir together with one pump and one manifold keeps the hydraulic arrangement compact and allows the effect of demand based irrigation on total water consumption to be observed directly.

The system combines mechanical design, additive manufacturing, electronic control, software development, and experimental evaluation. The manifold, internal rotor, and alternative irrigation emitters were modelled in Autodesk Fusion 360 and manufactured by 3D printing. An ESP32 microcontroller controls the rotary mechanism and pump, while three soil moisture sensing channels provide relative information about the condition of the three irrigation zones.

1.2 Problem Definition

Small scale irrigation systems frequently distribute an equal amount of water to every plant without considering the actual condition of the soil. However, plants may require different irrigation amounts because of differences in species, soil composition, container geometry, environmental exposure, and previous watering. A fixed irrigation cycle can therefore cause overwatering in one zone and underwatering in another.

Providing every zone with an individual pump or solenoid valve would allow independent control, but it would also increase the cost and complexity of the installation. The central engineering problem addressed by this project is therefore:

How can a single pump be used to irrigate three plant zones independently through a low cost, modular, and electronically controlled water distribution mechanism?

A second engineering question concerns the final water delivery component. The geometry of an irrigation emitter influences flow rate, local water velocity, surface coverage, wetting depth, and the possibility of pooling. For this reason, a single outlet emitter and a multi outlet emitter were designed and compared experimentally under the same pump conditions.

1.3 Project Aim and Objectives

The primary aim of this project is to design, manufacture, and experimentally evaluate a low cost modular smart irrigation system capable of directing water to three separate plant zones using a single pump and a servo controlled rotary manifold. The system is designed to reduce unnecessary water use by enabling independent zone selection and by providing a foundation for irrigation decisions based on relative soil moisture measurements.

The objectives of the project are:

1. Design a compact rotary manifold capable of directing water toward three separate outlets.
2. Control the manifold with a servo motor at calibrated positions of 0°, 90°, and 180°.
3. Operate a DC water pump safely using an ESP32 and a MOSFET switching module.
4. Develop modular irrigation emitters using Autodesk Fusion 360.
5. Manufacture the designed mechanical components using 3D printing.
6. Compare the hydraulic behaviour of single outlet and multi outlet emitters.
7. Measure and compare the average flow rates of the two emitter designs.
8. Investigate soil wetting distribution under equal volume irrigation conditions.
9. Monitor the relative moisture condition of three irrigation zones using independent sensor channels.
10. Create a platform that can later support Wi-Fi monitoring and cloud based data logging.

1.4 Project Scope and Design Requirements

The scope of the project includes the mechanical design and manufacture of a three zone rotary water distribution mechanism, electronic integration of the ESP32, servo motor, pump driver, power distribution components and moisture sensors, development of the control software, and experimental comparison of two irrigation emitter geometries.

The completed prototype uses one water inlet, one pump, and three selectable outlets. Zone selection is achieved by aligning the internal rotor with the required outlet at servo commands of 0°, 90°, and 180°. The

servo control signal is assigned to GPIO26, the MOSFET pump control signal to GPIO25, and the three analog moisture sensor outputs to GPIO32, GPIO33, and GPIO34.

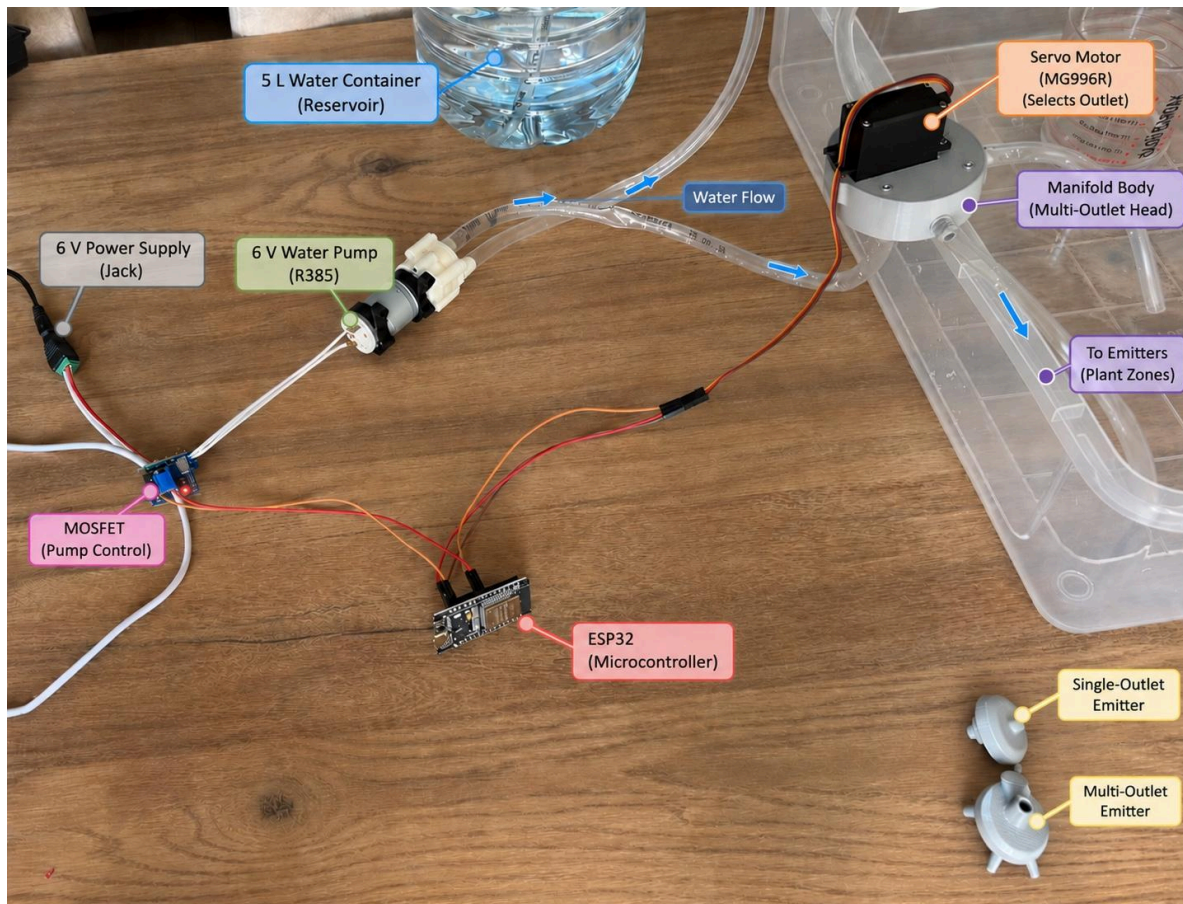


Figure 1.1. Annotated overview of the prototype architecture, showing the 5 L reservoir, 6 V pump supply, MOSFET controlled R385 pump, ESP32 controller, MG996R servo motor, rotary manifold body, water flow path, single outlet and multi outlet emitters.

The moisture sensors are used as relative indicators rather than laboratory grade instruments for absolute volumetric water content. Their readings can be affected by soil type, insertion depth, electrode contact, electrical noise, corrosion, and measurement drift. To reduce short term fluctuations, multiple analog samples are averaged before a value is displayed or used by the control logic.

The hydraulic scope also includes a reusable 5 L reservoir as the common water source. In the final prototype test it contained approximately 2.5 L of water, with the pump suction line placed in the reservoir and the pump discharge connected to the rotary manifold. The reservoir therefore forms the starting point of the complete hydraulic path: reservoir → pump → manifold → selected outlet → emitter → plant zone.

The current prototype validates three zone selection, pump control, water delivery through the selected channel, and emitter performance testing. Wi Fi communication, Supabase data storage, remote monitoring, and fully autonomous threshold based irrigation are defined as future extensions and are not presented as completed functions. Likewise, the design is intended to reduce unnecessary water use, but a precise percentage of water savings cannot be claimed without a long term comparison against a conventional irrigation method.

The principal design requirements are summarized in the following table:

Requirement	Target
Number of irrigation zones	3
Controller	ESP32
Number of pumps	1
Zone selection mechanism	Servo controlled rotary manifold
Servo positions	0°, 90°, 180°
Pump switching	MOSFET module
Moisture sensors	3 independent channels
Moisture sensor pins	GPIO32, GPIO33, GPIO34
Servo signal pin	GPIO26
Pump control pin	GPIO25
Mechanical design software	Autodesk Fusion 360
Manufacturing method	3D printing
Irrigation emitters	Single outlet and multi outlet
Design approach	Low cost and modular
Future connectivity	Wi-Fi and cloud database logging

CHAPTER 2 – MECHANICAL DESIGN

This chapter describes the mechanical development of the modular irrigation system, including the irrigation emitters, the three zone rotary manifold, the internal rotor, and the interfaces used to connect the printed parts to the pump, hoses, and servo motor. The components were designed in Autodesk Fusion 360 and manufactured using fused deposition modelling. The design process was iterative: dimensions, outlet geometry, rotor alignment, sealing behaviour, and assembly details were repeatedly tested and adjusted until water could be directed to each zone independently.

2.1 General Design Concept

The mechanical system was developed around a modular architecture. Instead of assigning a separate pump or valve to every plant, a single pump supplies water to a central rotary manifold. An internal rotor selects one of three outlets, and flexible hoses carry the water from the manifold to the irrigation emitters positioned in the plant containers. This arrangement reduces the number of active flow control components and allows the water distribution mechanism to be modified without redesigning the complete electronic system.

The complete water path can be described as follows: water is drawn from the reservoir by the DC pump, transferred through the inlet hose to the manifold, redirected by the internal rotor toward the selected outlet, and finally delivered to the soil through a removable emitter. The servo motor is mechanically coupled to the rotor. When the servo reaches a calibrated angular position, the rotor channel aligns with the corresponding outlet.

Three outlet positions were used in the final prototype. Zone 1 corresponds to 0° , Zone 2 to 90° , and Zone 3 to 180° . These values represent the final calibrated control positions rather than purely theoretical geometric assumptions. The success of the mechanism depends on both the electronic command and the physical relationship between the servo horn, rotor, and outlet openings.

The design was divided into replaceable functional modules: the manifold body, internal rotor, manifold cover, hose connections, irrigation hoses, and emitter heads. This modularity allows an individual part to be reprinted or redesigned while the remaining components are retained. It also enables alternative emitters to be evaluated using the same pump and manifold.

2.2 Mechanical Design Requirements

The mechanical design was required to satisfy several functional and manufacturing constraints. The most important requirement was selective distribution: water had to leave only the outlet associated with the commanded servo position. The nonselected channels had to remain inactive, and the transition between zones had to be repeatable.

The principal mechanical design criteria were:

- Compatibility with one inlet and three independently selectable outlets.
- Reliable rotor alignment at the calibrated servo positions.
- Minimal visible leakage from non selected channels.
- Compatibility with the selected flexible hose.
- Sufficient wall thickness for 3D printing and repeated assembly.
- A removable and replaceable irrigation emitter connection.
- Geometry that could be manufactured without unnecessarily complex support structures.
- Compact dimensions suitable for a small multi plant prototype.
- Low material use and straightforward replacement of failed parts.

Because the hose had an internal diameter of approximately 5 mm and an external diameter of approximately 8 mm, the connection features had to provide a secure fit without damaging the hose. The printed interfaces also had to tolerate small dimensional variations caused by printer calibration, material shrinkage, layer height, and surface roughness.

The design was not evaluated solely by whether water flowed through it. Alignment, sealing, printability, ease of assembly, resistance to blockage, and compatibility with the electronic control sequence were considered together. A mechanically successful part therefore had to operate repeatedly as part of the complete system rather than only in an isolated water test.

The irrigation emitter is the final component through which water enters the soil. Its geometry affects the flow rate, local water velocity, surface wetting pattern, and probability of water accumulation.

Two emitter concepts were designed:

- Single Outlet Emitter
- Multi Outlet Emitter

Both designs were produced using the same design and manufacturing approach so that their performances could be compared under controlled conditions.

2.3 Single Outlet Emitter Design

The single outlet emitter was developed as the simplest water delivery option considered in this project. Its function is to receive water from the irrigation hose and discharge it through one soil facing outlet, producing a concentrated wetting point and a relatively direct internal flow path.

The final emitter consists of a circular body with an external diameter of 30 mm and a main body thickness of 9 mm. Its overall axial length, measured between the ends of the hose connector and the soil facing outlet, is 28 mm. A concentric recessed region with a diameter of 27 mm was incorporated into the body to reduce unnecessary material while retaining sufficient structural support.

The ribbed hose connector has a maximum external diameter of 8.5 mm, a root diameter of 7 mm and an internal bore diameter of 5 mm. Circumferential retaining ribs improve the grip between the printed component and the flexible irrigation hose. On the opposite side, the soil facing outlet has a base diameter of 8.38 mm and projects 3.62 mm from the body. The section view confirms a continuous internal water path between the hose connection and the single discharge outlet.

The body was created from a dimensionally constrained circular sketch and converted into a three dimensional form using extrusion operations. The central recess and internal water passage were produced by removing material from the main body. The hose connector and soil facing outlet were positioned on opposing sides of the emitter so that a continuous water path was maintained through the component. Retaining ribs, tapered transitions and rounded external edges were then incorporated to improve hose attachment, handling and 3D printability. Fillet and chamfer features were also applied around the hose-barb transition and entry edges to remove sharp corners and create a smoother connection surface. This improved hose insertion and handling while reducing abrupt geometric transitions at the interface.

The single opening produces a concentrated discharge and provides a straightforward reference design for experimental testing. Its principal advantages are its simple geometry, relatively low manufacturing complexity, continuous internal flow path and reduced number of small openings that could become blocked. Its main limitation is that water may initially accumulate around a single point rather than being distributed across a wider soil surface. The resulting wetting pattern may therefore be influenced by soil properties, emitter placement and irrigation duration.

The single outlet emitter was retained as the baseline design for comparison with the multi outlet emitter. This allows the effect of distributed discharge geometry on flow rate, wetting area and soil moisture response to be evaluated under controlled experimental conditions.



Figure 2.1. Isometric view of the final single outlet emitter model developed in Autodesk Fusion 360.

2.3.1 Dimensional Specification

The principal dimensions of the final single outlet emitter are summarized below. These values define the external body, soil positioning spike, water outlet, and hose interface.

Parameter	Value	Verification status
External body diameter	30 mm	Final technical drawing
Recessed body diameter	27 mm	Final technical drawing
Main body thickness	9 mm	Final section view
Overall emitter length	28 mm	Final section view
Outlet-nozzle base diameter	8.38 mm	Final technical drawing
Outlet nozzle projection length	3.62 mm	Final technical drawing
Hose connector maximum diameter	8.5 mm	Final technical drawing

Hose connector root diameter	7 mm	Final technical drawing
Hose connector internal bore diameter	5 mm	Final technical drawing
Number of discharge outlets	1	Final CAD model
Radial wall thickness around recess	1.5 mm	Calculated from Ø30 mm and Ø27 mm

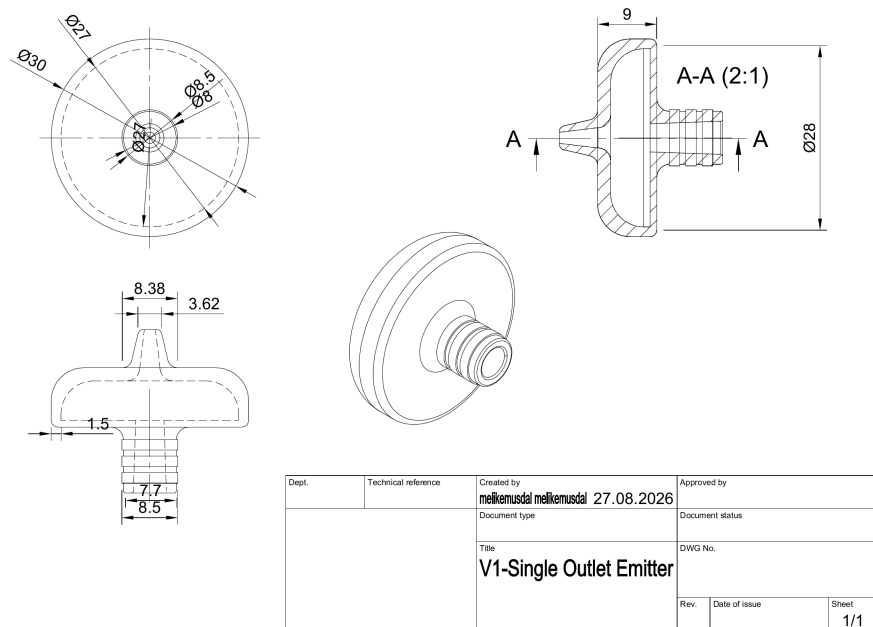


Figure 2.2. Dimensioned technical drawing and section view of the final single outlet emitter. All dimensions are in millimetres.

2.4 Multi Outlet Emitter Design

The multi outlet emitter was developed to distribute water through several smaller openings rather than one concentrated outlet. Water enters through the same type of hose connection and reaches an internal distribution region before leaving through multiple holes arranged around the emitter body. The objective was to increase the surface area exposed to irrigation and reduce the concentration of water at a single point. The final multi outlet emitter was designed with five separate water outlets, allowing water to be distributed through five individual channels from a single irrigation head.

The basic Fusion 360 workflow began with the main body and internal channel. After the first outlet feature was defined, the remaining outlet openings were positioned using a circular pattern operation. This approach maintained consistent spacing and reduced the need to sketch each hole independently. The outlet positions were checked in section view to confirm that every opening intersected the internal water passage.

The multi outlet concept introduces additional engineering considerations. Small printed holes may be affected by material accumulation, print orientation, dimensional tolerance, or soil particles. Water may also

favour the outlet with the lowest hydraulic resistance, producing unequal discharge. Consequently, the visual symmetry of the CAD model does not automatically guarantee equal flow from every opening.

Compared with the single outlet emitter, the multi outlet design produced a higher measured average flow rate under the same pump test conditions. The measured values were 12.83 mL/s for the single outlet emitter and 17.50 mL/s for the multi outlet emitter. This result demonstrates that emitter geometry influenced the hydraulic behaviour of the system. However, the final design decision must also consider wetting uniformity, surface pooling, penetration depth, leakage, and resistance to blockage.

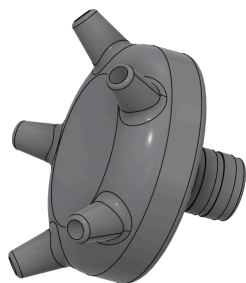


Figure 2.3. Isometric view of the final multi outlet emitter model developed in Autodesk Fusion 360.

2.4.1 Dimensional Specification

The final multi outlet emitter uses a 30 mm diameter body with five discharge outlets arranged around its perimeter. The hose barb connection was further refined using both fillet and chamfer features around the transition and entry edges. These features removed sharp corners, created a smoother contact path for the flexible hose, and made insertion and removal easier while reducing the risk of local damage at the connection interface. Each outlet has a 2.34 mm internal bore. The internal distribution chamber has a diameter of 5 mm, matching the internal bore of the hose connection and providing a continuous flow path from the inlet to the outlet distribution region. The completed technical drawing gives an overall height of 23.92 mm, a maximum span of 34.89 mm, a secondary span of 33.39 mm, an 8.2 mm hose connector outer diameter, a 5 mm hose connection internal bore, and an R2 transition fillet.

Parameter	Value	Verification status
External body diameter	30 mm	Final technical drawing
Overall emitter height	23.92 mm	Final technical drawing
Maximum overall span	34.89 mm	Final technical drawing
Secondary overall span	33.39 mm	Final technical drawing
Number of discharge outlets	5	Final CAD model
Individual outlet hole diameter	2.34 mm	Final technical drawing
Hose connector outer diameter	8.2 mm	Final technical drawing
Hose internal diameter	4 mm	Confirmed nominal hose size
Hose external diameter	6 mm	Confirmed nominal hose size
Hose connector internal bore	5 mm	Final technical drawing

Body to connector fillet radius	R2 mm	Final technical drawing
Internal distribution chamber diameter	5 mm	Final technical drawing

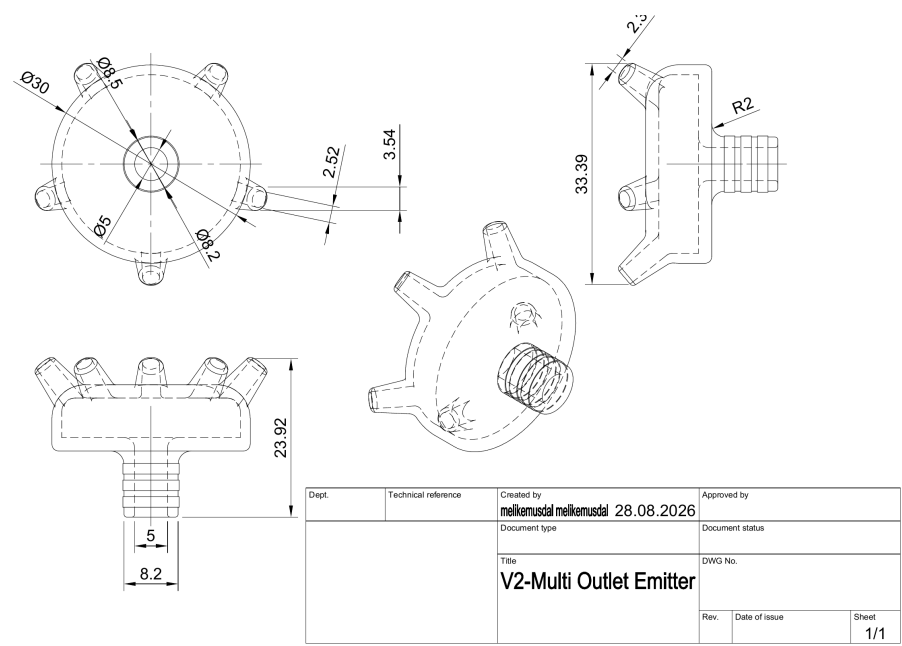


Figure 2.4. Dimensioned technical drawing of the final multi outlet emitter. All dimensions are in millimetres.

2.5 Rotary Manifold Assembly

The rotary manifold assembly is the central mechanical distribution unit of the irrigation system. It enables one pump to serve three irrigation zones by directing the inlet flow toward one selected outlet. The assembly consists of five principal components: the manifold body, internal rotor, top cover, MG996R servo motor, and MG996R servo horn/coupling disc.

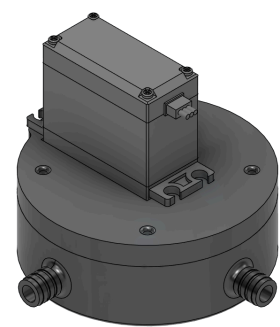


Figure 2.5. Isometric view of the complete rotary manifold assembly.



Figure 2.6. Exploded view of the rotary manifold assembly, showing the manifold body, internal rotor, top cover, and MG996R servo motor.

2.5.1 Manifold Body

The manifold body forms the stationary hydraulic housing of the flow selection mechanism. Water enters through the common hose barb inlet located at the bottom of the body and reaches the enclosed distribution chamber formed by the manifold body and the internal rotor. This chamber provides the necessary operating space and concentric guidance for the rotor to turn without contacting the surrounding walls excessively. Three radial outlet passages are incorporated into the manifold body, enabling water to be directed toward three separate irrigation zones. The rotor contains one active flow opening; as the MG996R servo rotates the rotor, this opening aligns with one of the three outlets according to the commanded angular position of 0°, 90°, or 180°. The aligned outlet is thereby connected to the inlet flow path, while the remaining outlets are isolated by the rotor surfaces and O-ring seals. The body to cover fastening arrangement maintains the relative position and concentric alignment of the manifold body, rotor, and top cover. In addition, the servo is secured to the top cover so that the servo housing remains stationary and only its output shaft and attached horn rotate, transmitting controlled angular motion to the rotor. The final manifold body has a circular housing radius of R35 mm (Ø70 mm). The main body height is 20 mm, while the overall axial height including the protruding hose barb connection is 30 mm. The maximum width across the opposing hose barb connections is 90 mm. The body incorporates four hose barb connections: one common water inlet and three selectable outlets. Each connection has a Ø5 mm internal water flow bore, a maximum outside diameter of Ø8 mm, and a projection height of 10 mm. Fillet and chamfer features were applied around the hose-barb connection transitions to remove sharp edges, create smoother geometric transitions, and make hose installation and removal easier while reducing local stress concentration at the connection region. The Ø1.9 mm manifold body screw holes are 7 mm deep, supporting repeatable cover alignment and secure assembly.

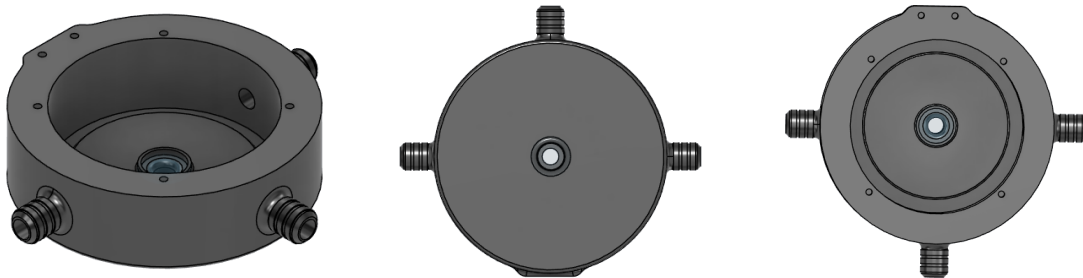


Figure 2.7. Final manifold body showing the common inlet, three selectable outlet connections, and central cavity for the internal rotor.

2.5.2 Internal Rotor

The internal rotor is the moving flow selection component and is seated concentrically within the central cavity of the manifold body. Its central channel connects directly to the common inlet and, together with the surrounding manifold body, forms an enclosed water distribution chamber. A single radial flow passage terminates at the outlet opening on the rotor perimeter. As the MG996R servo rotates the rotor, this opening aligns sequentially with the three outlet passages in the manifold body. Water is therefore

delivered only to the outlet corresponding to the commanded servo angle, while the remaining outlets stay outside the active flow path.

The finalized rotor has an outside diameter of $\varnothing 51.2$ mm and a front sealing diameter of $\varnothing 44.8$ mm, giving a radial outer wall thickness of 3.2 mm. Its overall height is 18.8 mm. The rotor water flow passage itself has a $\varnothing 6$ mm internal diameter. At the outer side of the rotor, where this $\varnothing 6$ mm passage opens toward the selected manifold outlet, a $\varnothing 9.6$ mm circular recess is provided for the local outlet O-ring. The O-ring used at this location has a 1.8 mm cross sectional thickness and is seated in a 1.8 mm deep recess around the $\varnothing 6$ mm water outlet. On the lower side of the rotor, where the rotor interfaces with the manifold body inlet, the water passage is again $\varnothing 6$ mm. The corresponding O-ring seating diameter is $\varnothing 7$ mm, providing the sealing region around this inlet interface. The same elastomeric O-ring type is used at this location; although the seating dimensions differ, the flexibility of the O-ring allows it to conform to the designed interface. A third circumferential sealing feature is located around the outer $\varnothing 51.2$ mm rotor region. This peripheral O-ring seat is defined by a 1.1 mm height and a 0.5 mm depth and is used to limit water escaping around the rotor while it rotates.

On the servo facing side, the rotor contains a $\varnothing 9$ mm central coupling hole. Directly beneath it, a circular recessed seat measuring $\varnothing 20.83$ mm in diameter and 2 mm in depth accommodates the round servo horn boss fitted to the motor shaft. This recessed seat centres the coupling and transfers servo rotation accurately to the rotor. The rotor clearance, water passage geometry, and sealing features were designed together because they directly influence leakage control, rotational friction, and positioning accuracy.

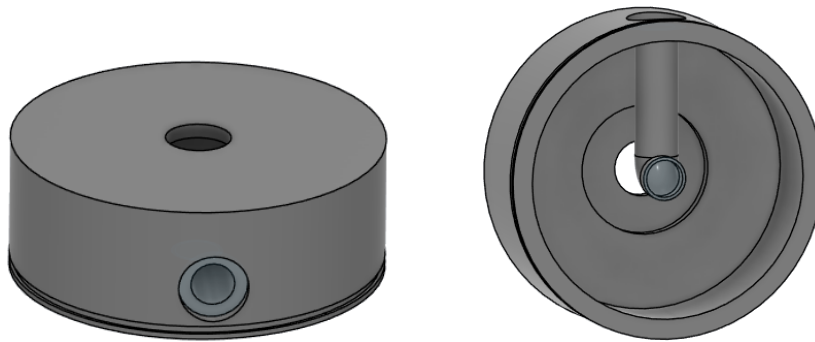


Figure 2.8. Final internal rotor geometry showing the central water passage, radial outlet, servo coupling region, and O-ring sealing features.

2.5.2.1 O-Ring Sealing System

An O-ring is a circular elastomeric sealing element used to restrict fluid leakage between mating mechanical surfaces. When compressed within a designed groove or seat, the elastomer deforms and fills small clearances between the rotating rotor and the stationary manifold body. This creates a flexible hydraulic seal while still allowing the rotor to rotate between the three irrigation positions. The internal rotor was designed with three dedicated O-ring locations rather than a single sealing point, and each seal performs a specific function within the rotary manifold.

The rotor uses sealing at both hydraulic connection interfaces. At the outer radial water outlet, the internal flow passage is $\varnothing 6$ mm and is surrounded by a $\varnothing 9.6$ mm O-ring recess. A 1.8 mm cross section O-ring is

seated to a depth of 1.8 mm at this location so that, when the rotor aligns with a selected manifold outlet, the interface is sealed around the active flow passage. On the lower rotor to manifold body inlet interface, the water passage is also Ø6 mm and the O-ring seating diameter is Ø7 mm. The same type of elastomeric O-ring is used despite the different seating geometry because its flexibility allows it to conform to the interface and maintain sealing contact.

The third O-ring provides circumferential sealing around the rotor body. It follows the outer Ø51.2 mm rotor region and is installed in a peripheral sealing feature with a height of 1.1 mm and a depth of 0.5 mm. Unlike the two local O-rings that seal the inlet and selected outlet water passages, this circumferential seal is intended primarily to reduce water escaping through the clearance between the rotating rotor and the stationary manifold body as the rotor moves between the 0°, 90°, and 180° positions.

Accordingly, the three O-rings perform distinct but complementary functions: one seals the Ø6 mm radial water outlet within its Ø9.6 mm, 1.8 mm deep seat; one seals the lower Ø6 mm rotor to body inlet interface within the Ø7 mm seating region; and the third seals circumferentially around the Ø51.2 mm rotor region using the 1.1 mm high and 0.5 mm deep peripheral feature. The elasticity of the O-ring material allows the same sealing element type to accommodate the different local seating geometries. Together, these seals restrict leakage at the inlet, selected outlet, and rotating rotor body interface while allowing the MG996R servo to rotate the rotor between the three irrigation positions.

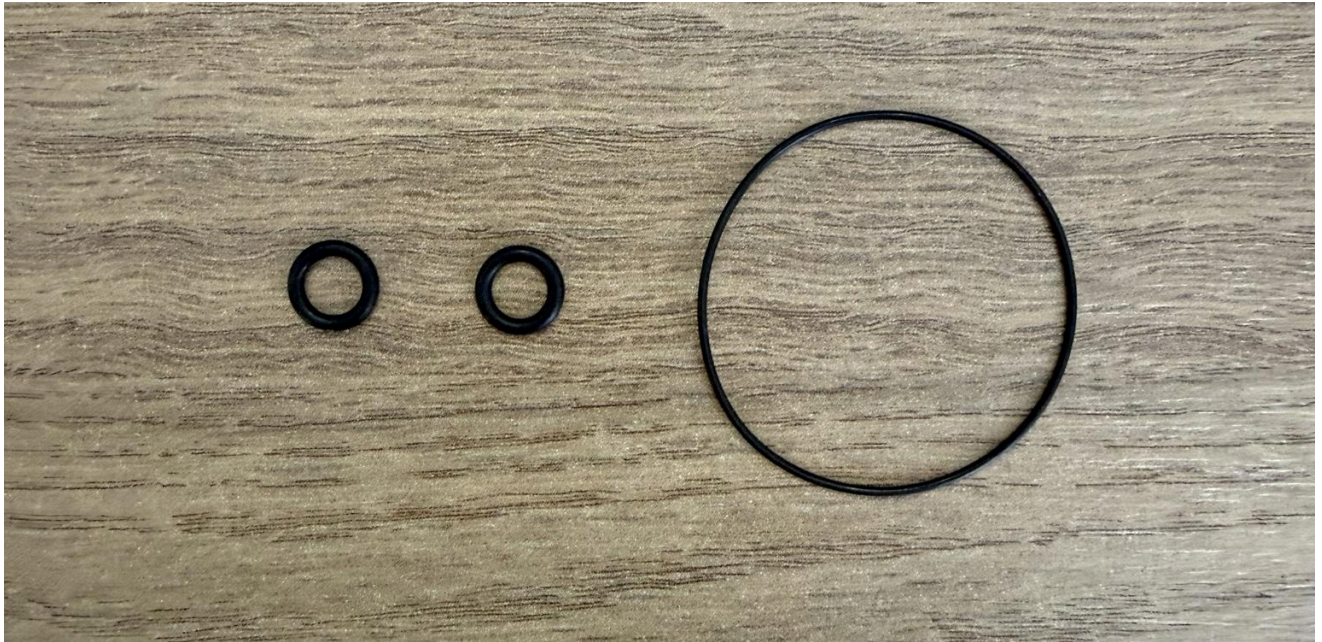


Figure 2.9. O-rings used in the rotary manifold sealing system, including the two local hydraulic seals and the larger circumferential rotor seal.

2.5.3 Top Cover

The top cover completes the upper boundary of the manifold and retains the internal rotor in its operating position. The MG996R servo motor is inserted from above into the rectangular mounting pocket, where its housing is secured against rotation. The servo output shaft passes through the central opening in the cover and engages the round servo horn seated in the rotor, allowing the commanded shaft rotation to be transmitted directly to the flow selection mechanism. The cover is fastened to the manifold body with screws, maintaining the concentric alignment of the body, rotor, servo horn, and motor shaft. Once

assembled, the top cover and manifold body enclose the rotor and form a closed hydraulic flow chamber that limits leakage and keeps the water confined to the intended inlet to outlet path. The main circular cover has an outer diameter of 70 mm and a total thickness of 7 mm; the small mounting projection increases the maximum external span to 70.9 mm. The centred servo mounting pocket is 40.2 mm long, with a 20.2 mm internal opening and a 13.2 mm central recessed region. The upper mounting lug is 23.71 mm wide (11.85 mm from the centreline to either side), and the pocket is positioned symmetrically about the cover centreline. Eight Ø1.9 mm screw holes, each 5 mm deep, are provided in total: four equally spaced cover to body fastener holes located on a Ø56 mm pitch circle diameter at 90° intervals, and four additional holes for mounting the MG996R servo motor. A 0.5 mm chamfer was applied to the entry edges of the top-cover screw holes to remove sharp circular edges, guide the screw tips more smoothly into the holes, and improve alignment and ease of assembly for both the cover-to-body and servo mounting connections. The cover must maintain rotor alignment without applying excessive axial pressure, because excessive constraint may increase friction, while insufficient retention may permit leakage or axial movement.

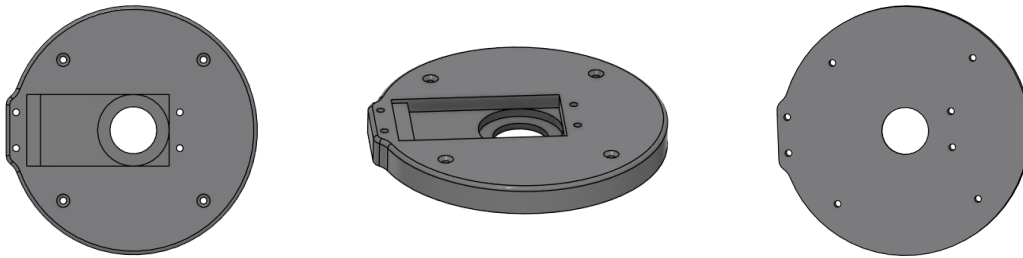


Figure 2.10. Final top cover design showing the central MG996R servo mounting pocket and screw fastening arrangement.

2.5.4 MG996R Servo Motor

The MG996R servo motor provides the controlled rotary motion required for irrigation zone selection. In this system, the servo is operated over a commanded angular range of 0° to 180°, and the manifold was designed around three indexed rotor positions at 0°, 90°, and 180°. These positions align the single rotor flow opening with the three corresponding outlet passages in the manifold body. A round servo horn with an outside diameter of Ø20.83 mm is fitted onto the splined output shaft and retained by the central fixing screw. The horn seats inside the matching recess in the internal rotor; consequently, rotation of the servo shaft turns the horn and directly rotates the rotor to the selected flow position. The servo has a three wire electrical interface. The ground wire, typically brown or black, is connected to the common ground shared by the servo power supply and ESP32. The positive supply wire, normally red, is connected to the regulated 5-6 V servo supply. The control wire, typically orange, yellow, or white, carries the PWM position command from the ESP32 control pin. The servo must be powered from the dedicated regulated supply rather than directly from the ESP32, while both circuits retain a common ground reference. The servo is treated as a commercial component; therefore, the project drawings focus on its mounting position, shaft alignment, electrical interface, and connection to the manifold rather than reproducing its internal construction. According to the manufacturer, the MG996R body measures 40.7 × 19.7 × 42.9 mm.

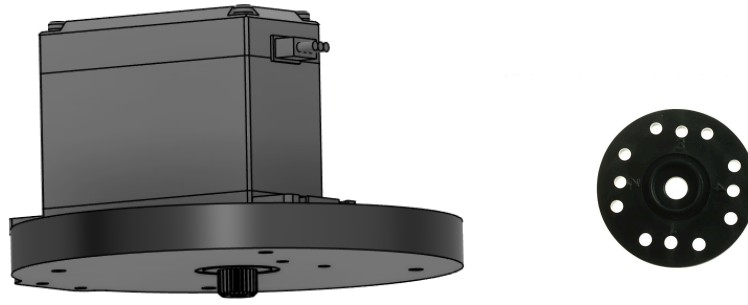


Figure 2.11. MG996R servo motor and round servo horn used to rotate the internal rotor between the three calibrated outlet positions.

2.5.5 Assembly Operation and Calibration

In the final closed configuration, the manifold body, internal rotor, top cover, round servo horn, and MG996R servo motor form a single compact flow selection assembly. Water entering through the common lower inlet reaches the internal rotor and is directed toward the outlet aligned with the rotor passage. The top cover retains the rotor inside the body, while the servo horn transfers rotation from the motor shaft to the rotor. Correct operation required both CAD accuracy and physical calibration. Because the installed orientation of the servo horn changed the mechanical reference position, the completed assembly was calibrated experimentally until the commanded 0° , 90° , and 180° positions corresponded to the three physical outlet channels. Sealing was evaluated by supplying water while observing all three outlets. Under the prototype operating conditions, the final assembly directed water through each selected channel without visible discharge from the inactive outlets. Repeated transitions between the three zones were also used to evaluate positioning repeatability. Sufficient travel time was allowed before pump activation, particularly during the longer return movement from 180° to 0° .



Figure 2.12. Final assembled rotary manifold showing the manifold body, internal rotor, top cover, and servo motor integrated as a three zone flow selection mechanism.

2.5.6 Dimensional Specification

The final closed manifold assembly has an outside diameter of Ø70 mm. The combined height of the manifold body and top cover is 27 mm, increasing to 37 mm when the lower inlet hose barb connection is included. The MG996R servo motor extends 33.05 mm above the upper surface of the top cover. The maximum width across the two opposing hose barb ends is 90 mm. Each hose barb connection has a Ø5 mm internal water flow bore, a maximum outside diameter of Ø8 mm, and a projection height of 10 mm. The top cover contains eight Ø1.9 mm screw holes, each 5 mm deep: four cover to body fastener holes and four MG996R servo mounting holes. The corresponding screw holes in the manifold body are 7 mm deep. The dimensional table below summarizes these confirmed assembly dimensions and mechanical interfaces; component specific technical drawings are presented separately for the manifold body, internal rotor, and top cover.

Parameter	Value	Verification status
Number of common inlets	1	Confirmed
Number of selectable outlets	3	Confirmed
Outlet reference positions	0°, 90°, 180°	Confirmed calibration
Inlet port bore diameter	Ø5 mm	Confirmed from final CAD drawing
Outlet port bore diameter	Ø5 mm	Confirmed from final CAD drawing
Hose barb maximum outside diameter	Ø8 mm	Confirmed from final CAD drawing
Closed manifold outside diameter	Ø70 mm	Confirmed from final CAD assembly
Combined manifold body and top cover height	27 mm	Confirmed from final closed assembly
Overall height including lower inlet	37 mm	Confirmed from final closed assembly
Maximum width across opposing hose barb ends	90 mm	Confirmed from final closed assembly
Total top cover through holes	8 × Ø1.9 mm	Four cover to body and four servo mounting holes
Hose barb projection height	10 mm	Applies to all four hose barb connections
Servo height above top cover surface	33.05 mm	Confirmed from final closed assembly
Top cover screw hole depth	5 mm	Applies to all eight Ø1.9 mm screw holes
Manifold body screw hole depth	7 mm	Confirmed from final manifold body drawing

2.6 Fusion 360 Modelling Process

Autodesk Fusion 360 was used to create the mechanical components as parametric solid models. Parametric modelling was selected because the dimensions of the hose interfaces, channels, outlet openings, and mating parts could be modified without recreating the entire geometry. The workflow combined sketches, dimensional constraints, extrusion, cut operations, hole features, fillets, patterns, section analysis, and assembly inspection.

The general modelling sequence was as follows:

1. Define the functional water path and identify the inlet, outlet, and mating interfaces.
2. Create a two dimensional base sketch on the most suitable reference plane.
3. Apply dimensional and geometric constraints to control the main profile.
4. Generate the primary solid body using Extrude or Revolve where appropriate.
5. Create the internal water passage using Extrude Cut, Hole, or combined body operations.
6. Add the hose connection and verify compatibility with the 5 mm internal and 8 mm external hose dimensions.
7. Create repeated outlet features with a pattern operation when required.
8. Use section analysis to verify internal continuity and wall thickness.
9. Inspect the relationship between the rotor opening and all three manifold outlets.
10. Assemble the parts digitally and check for interference or unintended gaps.
11. Export the completed bodies in STL format for additive manufacturing.

Sketch placement affected the efficiency of the modelling process. Each sketch plane was selected according to the feature being created: longitudinal features were easier to define from a side plane, while circular bodies and outlet distributions were more clearly constructed from a top or end plane. Construction lines and projected geometry were used to preserve alignment between connected features.

Section analysis was particularly important because many critical features were internal and could not be evaluated from an exterior view. Cross sectional inspection was used to confirm that the inlet reached the internal chamber, that emitter outlets opened into the water passage, and that the rotor channel could overlap the intended manifold outlets without creating excessively thin walls.

The CAD models should be documented using a consistent visual sequence in this report: dimensioned sketch, primary solid body, internal cut or section view, final isometric model, exploded assembly where applicable, and photograph of the manufactured component. This sequence allows the reader to understand both the modelling decisions and the relationship between the digital model and the physical prototype.

2.7 Additive Manufacturing and Design Iterations

After modelling, the parts were exported in STL format and prepared for fused deposition modelling. Print orientation was selected to balance dimensional accuracy, support requirements, surface quality, and the likelihood of obtaining open internal channels. Features such as small outlet holes and narrow water passages required particular attention because printed material could partially reduce their effective diameter. All custom 3D printed components used in the prototype were fabricated using grey PETG

(Polyethylene Terephthalate Glycol) filament. The manifold body, internal rotor, top cover, and both emitter designs were manufactured using the same grey PETG material. PETG was selected for the physical prototype because it is suitable for functional printed parts and provides the durability and moisture resistance required for repeated assembly and irrigation testing.

The first printed components were treated as engineering prototypes rather than final products. Each version was assembled, connected to the hose system, and tested with water. Observations from these tests were returned to the Fusion 360 models. This design manufacture test modify cycle was repeated until the parts met the required functional behaviour.

The principal issues identified during development included:

- Mismatch between theoretical servo angles and physical rotor alignment.
- Insufficient or excessive fit at hose and component interfaces.
- Partial restriction of small printed outlet holes.
- Leakage risk at mating surfaces and around the rotor.
- Rotor movement when the servo was not mechanically secured.
- Variation in the time required for short and long servo movements.
- The need to balance compact geometry with adequate printable wall thickness.

Several temporary angle references were tested during calibration before the physical rotor was correctly repositioned. After mechanical realignment, the final control references were established as 0°, 90°, and 180°. This distinction is important: the final angles became reliable only after the physical assembly and electronic commands were calibrated as one system.

The completed mechanical prototype demonstrated repeatable selection of three irrigation zones. During the final recorded test, the servo moved the rotor to all three positions, water emerged from the selected outlet, and no visible leakage occurred from the inactive outlets. These observations provided the mechanical basis for the electronic control and experimental evaluation described in the following chapters.

CHAPTER 3 – ELECTRONIC SYSTEM

This chapter describes the electronic architecture used to operate the three zone irrigation prototype. The electronic subsystem was designed to coordinate sensing, mechanical zone selection, and water delivery while keeping the high current pump and servo loads electrically separated from the low voltage control electronics. The ESP32 acts as the central controller, the MG996R servo rotates the internal manifold rotor, the R385 pump supplies water, and three capacitive soil moisture sensors provide independent feedback from the irrigation zones.

The system was developed through repeated wiring and functional tests. Particular attention was given to common grounding, voltage conversion, inductive load protection, and the order in which the servo and pump are activated. These considerations were necessary because the servo and pump can generate short current peaks and electrical noise that may disturb the ESP32 or damage switching components if the power system is not correctly arranged.

Electronic System Architecture (Three-Zone Precision Irrigation Controller)

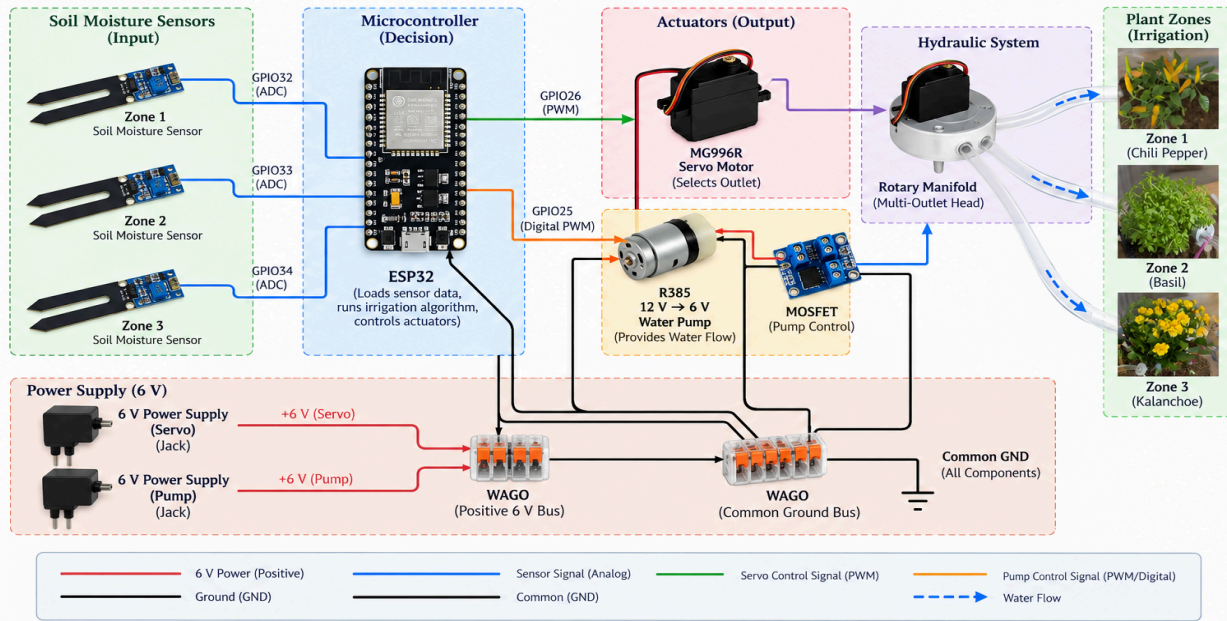


Figure 3.1. Electronic architecture and signal-flow diagram of the three-zone precision irrigation controller.

3.1 Electronic System Architecture

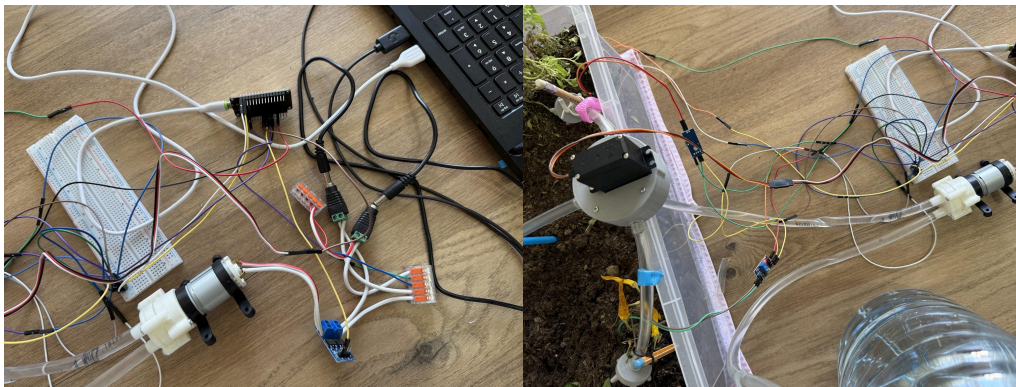
The electronic system follows a sensing decision actuation structure. Each plant zone is monitored by a dedicated capacitive soil moisture sensor. The ESP32 reads the three analogue sensor signals, processes multiple samples to reduce short term fluctuation, and identifies the zone requiring irrigation. The controller then commands the MG996R servo to rotate the manifold rotor to the calibrated position associated with that zone. After the rotor has reached and settled at the target angle, the ESP32 activates the water pump through a MOSFET switching stage.

The hydraulic and electronic functions are therefore coordinated as a sequence rather than operated simultaneously without control. Zone 1, Zone 2, and Zone 3 correspond to the final calibrated servo references of 0° , 90° , and 180° , respectively. At each position, the single radial passage in the internal rotor aligns with one outlet in the manifold body. The remaining two outlets stay isolated by the rotor geometry and O-ring sealing arrangement. This allows one pump and one servo controlled valve to serve three separate irrigation lines.

The architecture separates the system into three electrical domains. The control domain contains the ESP32 and sensor inputs. The actuator domain contains the servo motor and the pump driver. The power domain distributes the 6 V pump supply and the regulated low voltage supply required by the servo and control electronics. Although these domains use different voltage and current levels, their ground references are connected to a common ground so that the PWM and switching signals have a stable

electrical reference.

Figure 3.2. Prototype electronic and hydraulic integration during system testing.



3.2 ESP32 and Pin Connections

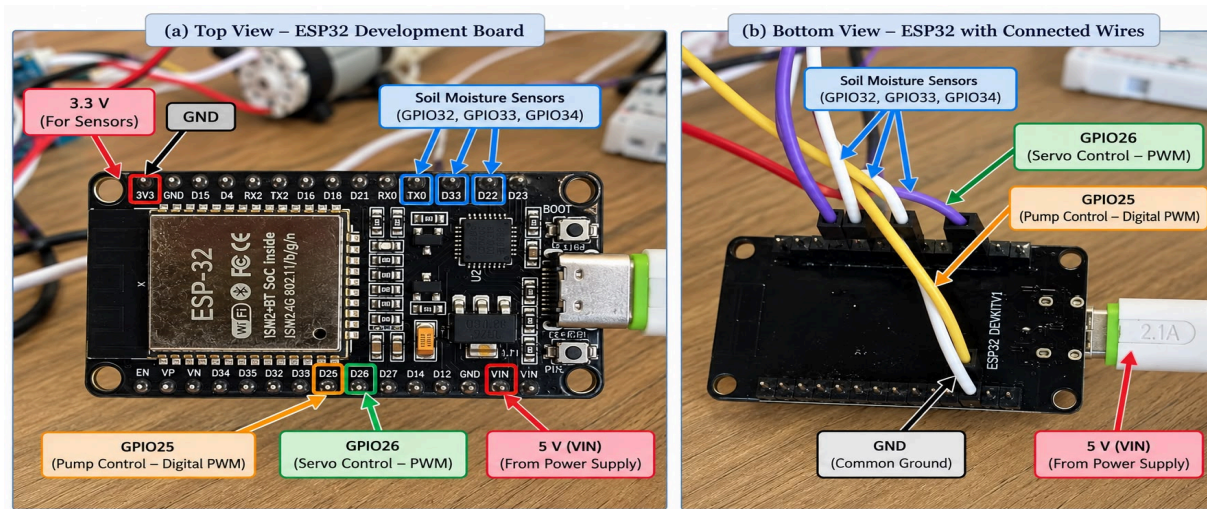


Figure 3.3. Final ESP32 pin allocation and physical wiring used in the prototype: GPIO25 for pump/MOSFET control, GPIO26 for MG996R servo PWM control, GPIO32-GPIO34 for the three capacitive soil moisture sensor signals, together with the 3.3 V sensor supply, 5 V/VIN input, and common ground connection.

The ESP32 was selected because it provides sufficient processing capability, multiple analogue to digital converter inputs, PWM capable digital outputs, and integrated Wi-Fi for future data logging. During prototype testing, serial communication was configured at 115200 baud so that sensor values, servo positions, pump states, and calibration messages could be observed from a computer. The current prototype performs the irrigation sequence locally; future Wi-Fi and database functions are intended for monitoring and logging rather than as a requirement for basic irrigation operation.

The MG996R servo control wire is connected to ESP32 GPIO 26. This pin carries the PWM control signal that defines the requested servo position. The servo is not powered directly from the ESP32 because its current demand is substantially higher than the current available from a microcontroller pin or the ESP32 regulator. Instead, only the control signal and common ground are shared with the ESP32, while the servo receives power from a dedicated regulated 5–6 V rail.

The pump is controlled through the MOSFET module from ESP32 GPIO25. This output provides the digital/PWM control signal used to switch the R385 pump. The three capacitive soil-moisture sensor analogue outputs are connected to the ESP32 ADC capable inputs GPIO32, GPIO33, and GPIO34, providing three independent measurement channels for the irrigation zones. Together with the MG996R servo control signal on GPIO26, the final functional pin allocation is therefore: GPIO25 for pump/MOSFET control, GPIO26 for servo PWM control, and GPIO32, GPIO33, and GPIO34 for the three soil moisture sensor inputs.

A common ground connection is essential. The negative terminals of the 6 V pump adapter, servo power adapter, MOSFET driver, pump circuit, sensors, and ESP32 share the same electrical reference through the negative WAGO connection. Without this common reference, the voltage levels of the servo PWM and MOSFET control signals can become undefined, causing unstable servo movement, failure of the pump switch, or intermittent controller resets.

3.3 Servo Motor System

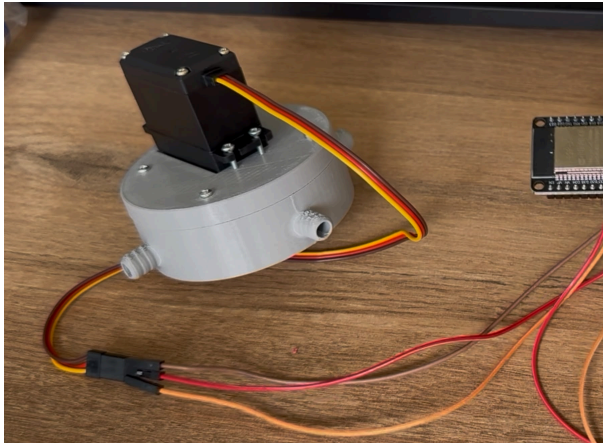


Figure 3.4. MG996R servo motor integrated with the rotary manifold during prototype testing.

The MG996R servo motor provides the angular motion required to select the irrigation outlet. The manifold operates from 0° to 180°, with indexed positions at 0°, 90°, and 180°. The servo shaft drives a round horn seated in the internal rotor, transferring rotation directly to the flow selection mechanism.

The servo uses ground, positive supply, and control connections. It is powered from the regulated 5–6 V supply, shares the common ground, and receives its position command from ESP32 GPIO 26.

Mechanical calibration was performed with the assembled manifold because the horn orientation affects the physical outlet alignment. The rotor and horn were repositioned and tested until the three commanded angles aligned reliably with the three manifold outlets. The servo is allowed to settle before pump activation.

Servo current peaks were treated as a power distribution issue rather than a software fault. Supplying the motor from the ESP32 or applying an incorrect voltage can overheat or permanently damage the servo. The dedicated regulated supply and common ground arrangement reduce this risk. A bulk capacitor placed close to the servo supply terminals can also reduce short voltage drops caused by rapid changes in servo load.

3.4 Pump and MOSFET Control

Water is supplied by an R385 6–12 V DC pump connected to the common inlet of the manifold. The pump is an inductive and comparatively high current load, so it cannot be connected directly to an ESP32 output. A 15 A MOSFET switching module is used as the electronic interface between the controller and the pump. The ESP32 drives the low current control input of the module, while the MOSFET switches the pump current from the 6 V supply.

The driver supports on/off operation and PWM power control. Early tests investigated low duty cycle operation because a low flow rate is desirable for precision irrigation and reduces leakage and surface pooling. However, the R385 pump did not start reliably at the tested low PWM levels. The final recorded operating sequence therefore used short full duty pulses: after the servo reached a zone, the system waited approximately 3 s, operated the pump at 100% duty for 1 s, and then allowed approximately 5 s before moving to the next zone. This produced a short and repeatable water delivery event without requiring continuous high pressure operation.



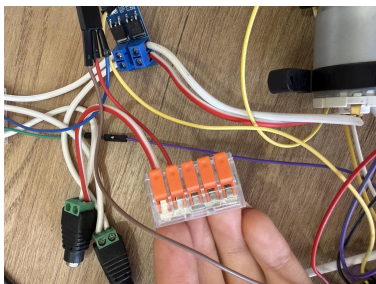
Figure 3.5. R385 DC pump connected to the MOSFET switching module during prototype wiring and functional testing.

The MOSFET module, pump, and power wiring must be sized for the actual motor current rather than for the ESP32 signal current. Loose ground connections, undersized conductors, or an incorrectly wired MOSFET can cause heating and switching failure. For this reason, the pump current path is kept separate from the breadboard signal path, while the ESP32 is connected only to the MOSFET control input and common ground.

An 8 x 10 mm flexible hose (8 mm internal diameter and 10 mm external diameter) was used for the main water transfer line. On the suction side, one end of the hose was placed in the 5 L water reservoir and connected to the inlet of the R385 pump, allowing the pump to draw water directly from the reservoir. On the discharge side, the pump outlet was connected through the hose to the servo controlled manifold. The manifold then routed the pumped water through the selected outlet line toward the corresponding plant and irrigation emitter. This arrangement created a continuous hydraulic path from the 5 L reservoir, through the pump and manifold, to the selected plant zone

3.5 Power Distribution and Protection

The prototype uses separate power inputs for the pump and servo motor. The R385 pump is supplied by a 6 V adapter and is connected through the MOSFET module, whereas the MG996R servo is powered from a separate adapter that provides the required 5–6 V supply. The servo supply is routed from its power adapter jack through the positive WAGO connection, while the negative terminals of both adapters are joined to the common ground bus.



The electrical distribution was organized using two WAGO lever connectors to avoid long and repetitive point to point cable runs. The positive WAGO serves only as the servo supply junction: it connects the positive lead from the servo power adapter jack to the positive lead that supplies the MG996R servo. It is therefore kept separate from the 6 V positive supply used by the pump. The negative WAGO forms the common ground bus and combines the ESP32 GND lead, the negative lead from the pump adapter jack, the negative lead from the servo adapter jack, the negative connection to the MOSFET module, and the negative lead of the servo motor. Connecting these return paths at a common WAGO terminal gives the ESP32 control signal, MOSFET driver, pump supply, and servo supply the same electrical reference. This arrangement shortens the wiring, keeps the positive and ground paths clearly identifiable, improves mechanical security, and simplifies continuity testing, fault isolation, and component replacement.

Figure 3.6. Positive WAGO power distribution connector used as the dedicated junction between the servo power adapter positive lead and the MG996R servo positive supply lead.

Testing is performed progressively. First, the output voltage and polarity of the dedicated servo adapter are verified without the servo connected. Second, the ESP32, servo, and pump driver signals are tested independently. Third, the servo and pump are operated together while the supply voltages and component temperatures are observed. This staged procedure reduces the probability that a wiring error will damage several components at the same time and makes it easier to identify whether a fault originates from power delivery, control logic, or the mechanical load.

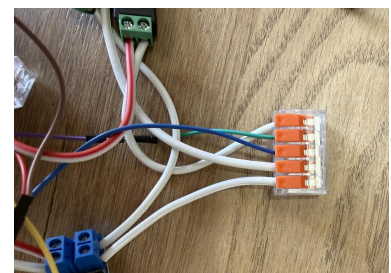


Figure 3.7. Negative WAGO common-ground connector combining the ESP32 GND, pump adapter negative, servo adapter negative, MOSFET negative, and MG996R servo ground connections.

3.6 Soil Moisture Sensors



Three capacitive soil moisture sensors are assigned to the three irrigation zones so that each plant can be monitored independently. Capacitive sensors were selected because the sensing element does not depend on exposed conductive probes in the same way as a basic resistive sensor, reducing corrosion during repeated use. Each sensor produces an analogue output that changes with the dielectric properties of the surrounding soil and is read by an ADC capable ESP32 input. The sensors must be calibrated individually because raw ADC values depend on sensor variation, supply voltage, insertion depth, soil type, compaction, and local water distribution. For each channel, reference readings are obtained under dry and wet conditions. The measured value can then be interpreted relative to these limits or converted into a normalized moisture percentage. The same physical insertion depth and orientation should be maintained during calibration and plant testing.

Figure 3.7. Soil moisture sensor module used during prototype testing.

The ESP32 uses a 12 bit analogue to digital converter, giving a raw ADC range from 0 to 4095. A reading close to the upper end of this range represents the dry end of the sensor response; during the soil-wetting experiments, pre irrigation readings reached approximately 4089-4094 ADC in very dry conditions. As water content increases, the sensor output decreases, so lower ADC values indicate wetter soil. Because the three sensors do not respond identically, their raw readings are also interpreted using sensor-specific dry and wet calibration references. A normalized moisture index can be calculated as $(ADC_dry - ADC_measured) / (ADC_dry - ADC_wet) \times 100$, where values approaching 0% represent the dry calibration condition and values approaching 100% represent the wet calibration condition.

For the final prototype control logic, ADC 2000 was selected as a common experimental moisture threshold. The controller interprets an averaged value of 2000 ADC or higher as DRY / IRRIGATION REQUIRED, whereas an averaged value below 2000 ADC is classified as SUFFICIENTLY WET and the pump remains off. This threshold is applied to the mean of 50 consecutive sensor readings rather than to a single instantaneous measurement. The 2000 ADC boundary is an experiment specific control reference for this prototype, not a universal soil moisture value; future versions can use individually calibrated plant specific percentage thresholds.

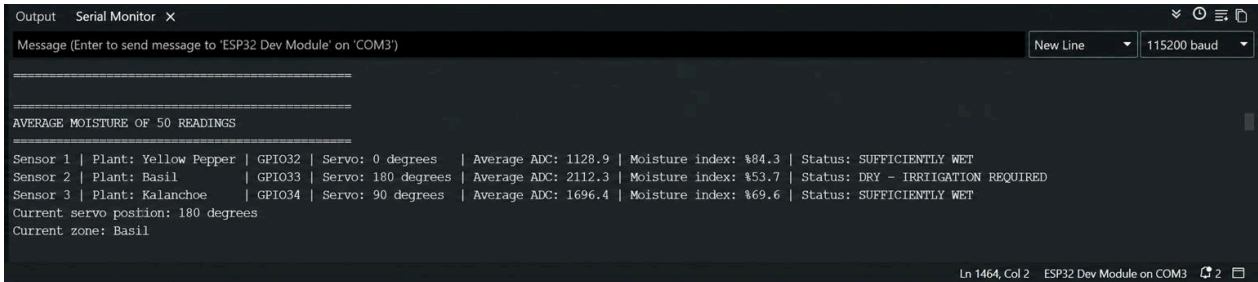


Figure 3.8. Serial Monitor output showing the mean of 50 moisture readings for the three plant zones, including sensor-specific ADC values, moisture indices, servo positions, and the resulting irrigation status classification.

To reduce noise and short term fluctuations, the ESP32 processes several consecutive samples rather than making an irrigation decision from a single reading. The samples are averaged before comparison with the moisture threshold. Separate channel variables are maintained for Zone 1, Zone 2, and Zone 3, allowing different plant requirements or thresholds to be implemented later without changing the manifold hardware

The intended automatic sequence is local and autonomous: read the three sensors, identify a zone below its moisture threshold, rotate the servo to the corresponding calibrated angle, wait for mechanical settling, activate the pump for the defined pulse, and then recheck the sensors after an appropriate absorption period. Future Wi-Fi connectivity and Supabase logging can record timestamped moisture values, active zone, servo position, pump state, power level, and irrigation duration, but loss of the network must not prevent the ESP32 from performing the basic irrigation decision locally.

Figure 3.9. Sensor 1 installed in the Yellow Pepper zone, showing the capacitive soil moisture sensor positioned in the soil adjacent to the irrigation emitter.



Electrical sensor placement is also important. Sensor leads should be routed away from the pump motor and high current wiring where practical, and the analogue supply should remain stable. If switching noise affects the measurements, additional averaging, short delays after actuator operation, decoupling capacitors, or separated cable routing can be used. These measures ensure that the control decision represents soil condition rather than electrical disturbance from the pump or servo.

CHAPTER 4 – SOFTWARE AND CONTROL

This chapter describes the software development process used to transform the individual electronic and mechanical components into a closed loop three zone irrigation controller. The firmware was developed in the Arduino programming environment for the ESP32 and evolved progressively from short component verification sketches to an integrated control program. This staged approach was important because pump operation, water delivery, servo positioning, sensor acquisition, and irrigation decisions could be verified independently before they were combined into the final system.

Rather than writing the complete controller at the beginning, the software was built through repeated test observe modify cycles. Early programs answered simple engineering questions such as whether the pump could be switched reliably, whether water reached the emitter, whether the manifold could move between its three outlet positions, and whether the moisture sensors produced stable and meaningful ADC values. The final development firmware grew to approximately 1000 lines as calibration routines, serial diagnostics, 50 sample averaging, zone mapping, servo movement, pump timing, repeated moisture checks, and safety oriented sequencing were combined.

4.1 Progressive Firmware Development and Component Tests

The first Arduino sketches were intentionally short and isolated. Their purpose was not autonomous irrigation but hardware verification. A basic pump test switched the MOSFET control signal ON for a defined interval and then OFF again. Several operating levels and durations were investigated during development, including low PWM duty cycle tests and short timed pulses. These tests confirmed the electrical control path from the ESP32 to the MOSFET and pump and made it possible to observe whether the R385 pump started consistently.

The pump tests were also hydraulic tests. With the reservoir, hose, manifold, and emitter connected, short activation commands were used to confirm that the pump could draw water, that the tubing remained connected, and that water emerged from the intended emitter. This was particularly useful after changes to the hose connections, manifold sealing, MOSFET wiring, or emitter geometry because the water path could be checked without running the complete automatic program.

Early low output tests showed that the R385 pump did not start reliably at the lowest PWM levels. Although reduced pump power was initially attractive for gentle irrigation, repeatability was more important for the experimental prototype. Later control therefore relied on short full duty activations rather than assuming that a low PWM command always produced a predictable flow. This software decision was based directly on observed pump behaviour.

4.2 Servo Position Test and Three Zone Mapping

After basic pump operation had been verified, a separate servo control sketch was used to test the rotary manifold. The MG996R control signal was generated by the ESP32 on GPIO26. The test program commanded the servo to the three principal reference angles and allowed sufficient time for each movement to finish before the next command was issued.

```
0 degrees:
Sensor 1 / Yellow Pepper

90 degrees:
Sensor 3 / Kalanchoe

180 degrees:
Sensor 2 / Basil

4. If no zone needs irrigation, the servo remains at its last position.
*/

// Move to the required zone if it is still dry, with priority given first.
if (irrigationNeeded[moveToZone]) {
    return moveToZone;
}

// 0 -> 90 -> 180 degree order

const int zoneAngles[3] = {
    0,    // Sensor 1 = 0 degrees
    90,   // Sensor 3 = 90 degrees
    180   // Sensor 2 = 180 degrees
};

for (int i = 0; i < 3; i++) {
    int zone = zoneAngles[i];
```

The basic sequence was conceptually simple: move to 0°, wait, move to 90°, wait, move to 180°, wait, and then return to the starting position. This short program was important because the electronic command angle and the physical water outlet alignment were not automatically identical. The servo horn, rotor, and manifold had to be treated as one mechanical system. During development, temporary angular references were tested and the horn/rotor relationship was adjusted until repeatable physical alignment was achieved.

The final manifold mapping used in the completed prototype was Zone 1 / Yellow Pepper at 0°, Zone 3 / Kalanchoe at 90°, and Zone 2 / Basil at 180°. The software therefore did not assume that numerical zone order had to be the same as increasing servo angle. Instead, each plant zone was explicitly associated with its calibrated servo position. This mapping was retained in the final controller so that a moisture decision for a specific plant always produced the correct physical outlet selection.

Figure 4.1. Firmware excerpt showing the final three zone servo mapping and priority order: 0° = Sensor 1 / Yellow Pepper, 90° = Sensor 3 / Kalanchoe, and 180° = Sensor 2 / Basil. The code also retains the current servo position when appropriate and checks zones in the 0° → 90° → 180° order.

The final servo position test code also defined an explicit priority order for cases in which more than one zone was classified as dry at the same time. The controller checked the zones in physical manifold order: 0° first for Sensor 1 / Yellow Pepper, 90° second for Sensor 3 / Kalanchoe, and 180° third for Sensor 2 / Basil. If the currently selected zone still required irrigation, the servo remained at that zone rather than moving unnecessarily. If no zone required irrigation, the servo remained at its last position. This position aware priority logic reduced unnecessary servo movement while preserving the calibrated plant to outlet mapping.

4.3 Moisture Sensor Acquisition and Signal Processing

The next development stage introduced the three capacitive soil moisture sensors. Each sensor was read independently through an ADC capable ESP32 input. Initial test sketches printed the raw ADC values to the Serial Monitor so that dry soil, wet soil, insertion depth, and short term fluctuation behaviour could be observed before the readings were allowed to control the pump.

A single instantaneous ADC reading was found to be unsuitable as the sole basis for an irrigation decision because sensor values can fluctuate because of electrical noise, soil contact, local water movement, and small changes in sensor position. The software was therefore expanded to collect multiple measurements and calculate an average. In the final implementation, each decision uses the mean of 50 ADC samples. This produces a more stable control value while still preserving the relative response of each zone.

The program maintains separate variables for the three sensor channels. Raw ADC values are retained for traceability, while calibrated dry and wet references can be used to calculate an approximate moisture

index for reporting. For the final functional validation, ADC 2000 was used as the common dry trigger: a value above 2000 was interpreted as requiring irrigation, while a value below 2000 was accepted as sufficiently wet for that control cycle. The threshold is a prototype control reference rather than a universal agronomic value.

```
Serial.println();
Serial.println("=====");
Serial.println("AVERAGE MOISTURE RESULTS FROM 50 MEASUREMENTS");
Serial.println("=====");

for (int i = 0; i < 3; i++) {
    sensorAverages[i] =
        sensorSums[i]
        / (float)SAMPLE_COUNT;

    // If ADC is 2000 or higher, irrigation is required.

    irrigationNeeded[i] =
        sensorAverages[i]
        >= DRY_THRESHOLD_ADC;

    float moisturePercent =
        calculateMoisturePercentage(
            sensorAverages[i],
            i
        );

    Serial.print("Sensor ");
    Serial.print(i + 1);

    Serial.print(" | Plant: ");
    Serial.print(PLANT_NAMES[i]);

    Serial.print(" | GPIO");
    Serial.print(SENSOR_PINS[i]);
```

Figure 4.2. Firmware excerpt showing 50 sample moisture averaging and the ADC 2000 irrigation threshold used for sensor-based control.

4.4 Integration of Moisture Detection and Servo Selection

The major software transition occurred when sensor measurement and manifold positioning were combined. At this stage, the controller no longer moved the servo according to a fixed demonstration sequence only. Instead, the measured condition of each plant determined whether its corresponding outlet had to be selected.

The integrated logic follows a sensing decision actuation sequence. First, the ESP32 obtains the averaged moisture value for a zone. Second, the value is compared with the control threshold. If irrigation is required, the program determines the servo angle associated with that zone and commands the MG996R to rotate the internal manifold rotor. A settling delay is then applied so that the rotor can reach the correct outlet before the pump is switched on. Only after this mechanical alignment is the pump permitted to deliver water.



Figure 4.3. Integrated three zone prototype used for moisture guided servo selection, showing the Yellow Pepper, Basil, and Kalanchoe irrigation zones connected to the servo-controlled rotary manifold.

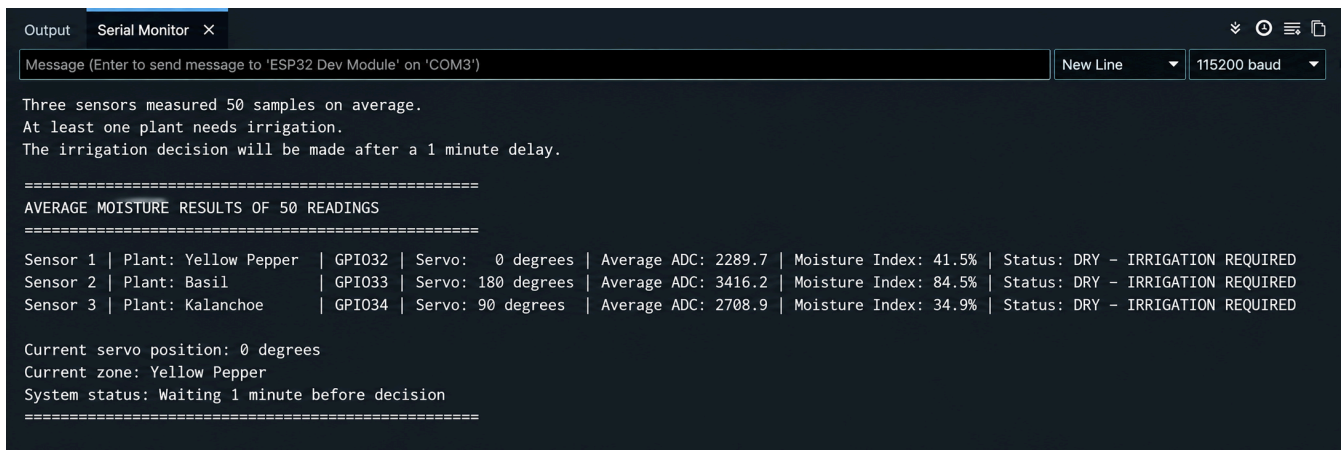
This ordering is a central feature of the software. Activating the pump while the rotor is still moving could pressurise the manifold between outlets and increase the risk of unintended discharge or leakage. The firmware therefore coordinates sensing, rotation, settling, and pumping as separate sequential states rather than operating the actuators simultaneously without timing control.

4.5 Integrated Development Firmware

As the project progressed, the separate test routines were combined into a much larger Arduino/ESP32 program of approximately 1000 lines. The length of this development firmware resulted from integration and diagnostic requirements rather than from one single algorithm. It contained sensor reading routines, averaging, calibration variables, serial output, zone to angle mapping, servo commands, pump commands, timing intervals, repeated threshold checks, stored state information, and test functions used while the hardware was being tuned.

The long development program was particularly valuable during debugging. Serial messages at 115200 baud made it possible to observe which sensor was being read, the averaged ADC value, whether the

zone was classified as dry or sufficiently wet, the requested servo position, and whether the pump was ON or OFF. When a physical result did not match the expected behaviour, these messages helped distinguish a software decision from a wiring, power, sensor, servo, or hydraulic problem.



```
Output Serial Monitor X
Message (Enter to send message to 'ESP32 Dev Module' on 'COM3') New Line 115200 baud

Three sensors measured 50 samples on average.
At least one plant needs irrigation.
The irrigation decision will be made after a 1 minute delay.

=====
AVERAGE MOISTURE RESULTS OF 50 READINGS
=====
Sensor 1 | Plant: Yellow Pepper | GPIO32 | Servo: 0 degrees | Average ADC: 2289.7 | Moisture Index: 41.5% | Status: DRY - IRRIGATION REQUIRED
Sensor 2 | Plant: Basil | GPIO33 | Servo: 180 degrees | Average ADC: 3416.2 | Moisture Index: 84.5% | Status: DRY - IRRIGATION REQUIRED
Sensor 3 | Plant: Kalanchoe | GPIO34 | Servo: 90 degrees | Average ADC: 2708.9 | Moisture Index: 34.9% | Status: DRY - IRRIGATION REQUIRED

Current servo position: 0 degrees
Current zone: Yellow Pepper
System status: Waiting 1 minute before decision
=====
```

Figure 4.4. Example Serial Monitor output showing averaged moisture readings, plant specific zone mapping, servo position and irrigation decision during firmware validation.

The firmware also evolved with the mechanical prototype. Earlier calibration experiments used temporary servo references while the manifold and horn were being aligned. These intermediate values were not treated as final design specifications. Once the mechanical assembly was repositioned and validated, the control program was standardized around the final physical references of 0°, 90°, and 180° and the actual plant to outlet mapping.

4.6 Final Closed Loop Irrigation Algorithm

The final control strategy replaced fixed duration watering with repeated short irrigation pulses. For each zone, the ESP32 calculates a 50 reading moisture average and compares it with the ADC 2000 dry threshold. If the value is above the threshold, the controller selects the corresponding manifold outlet and activates the pump for exactly 1 second. The pump then stops, water is allowed to infiltrate, and a new 50 reading average is calculated.

If the new reading is still above the threshold, the same zone receives another 1-second pulse. The process therefore continues as 1 s + recheck + 1 s + recheck + 1 s, for as long as the measured soil condition requires. As soon as the averaged reading falls below the threshold, irrigation for that zone stops and the controller proceeds to evaluate the remaining zones. If a zone is already sufficiently wet when checked, the pump remains OFF for that zone.

This feedback structure is fundamentally different from an equal scheduled irrigation routine. The controller does not predetermine that all three plants must receive the same pump duration. A relatively wet zone may receive no pulse or only one pulse, while a drier zone may receive several pulses. The software therefore converts independent soil moisture measurements directly into differentiated water delivery.

The controller also stores or tracks the current/previous servo position during the operating sequence. This allows unnecessary movements to be avoided and makes the physical routing sequence more efficient. When movement is required, a suitable settling interval is applied before pump activation. Longer movements, particularly transitions spanning a large angular range, are given sufficient time before water delivery begins.

4.7 Software Design Outcome

The software development process progressed through three clear levels: component verification, coordinated actuator control, and closed loop irrigation. Short Arduino sketches first confirmed that the pump, MOSFET, tubing, and emitter could deliver water and that the servo could reach the required manifold positions. Sensor focused programs then established stable ADC acquisition and 50 sample averaging. Finally, these functions were combined into the integrated ESP32 controller in which soil condition determines zone selection and irrigation duration.

The resulting firmware is locally autonomous. The essential sequence measure moisture, identify a dry zone, rotate the manifold, wait for alignment, apply a 1 second water pulse, remeasure, and stop or repeat runs on the ESP32 itself and does not depend on an internet connection. This architecture is also compatible with the planned future Wi-Fi and Supabase data logging extension: cloud connectivity can record measurements and irrigation events without becoming a dependency for the basic watering decision.

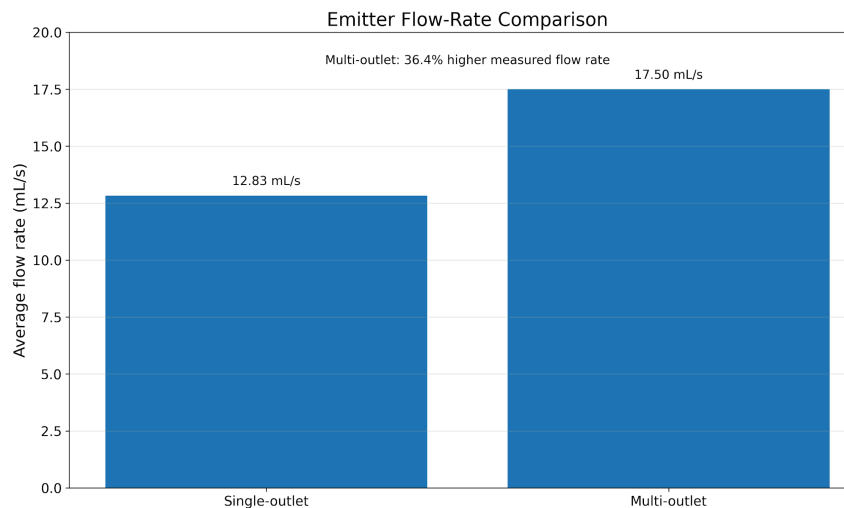
The final software therefore provides the control layer that connects the mechanical manifold, electronic hardware, and soil moisture measurements into one functional precision irrigation system. Its most important contribution is not simply automatic pump switching, but feedback based allocation of water: each zone is measured independently, physically selected through the servo driven manifold, and irrigated only for as long as its measured condition requires.

CHAPTER 5 – EXPERIMENTAL EVALUATION

This chapter experimentally evaluates the two irrigation emitter geometries developed for the prototype. The comparison was organised in three stages: flow rate measurement, equal volume irrigation, and spatial soil wetting assessment. Using nearly identical delivered volumes allowed the effect of emitter geometry to be separated from the effect of irrigation quantity. The results were then used to select the emitter incorporated into the final three zone prototype.

5.1 Emitter Flow Rate Measurement and Selection

The flow rate of each emitter was determined from three repeated water collection trials using $Q = V/t$, where Q is flow rate, V is collected volume, and t is pump operating time.



The single outlet emitter produced an average flow rate of 12.83 mL/s (approximately 769.8 mL/min), whereas the multi outlet emitter produced 17.50 mL/s (1050 mL/min). The multi outlet design therefore delivered 4.67 mL/s more water, corresponding to a 36.4% higher measured flow rate. For the equal volume comparison used in the following sections, a 100 mL target required 7.79 s of operation for the single outlet emitter and approximately 5.71 s for the multi outlet emitter; 5.70 s was used experimentally.

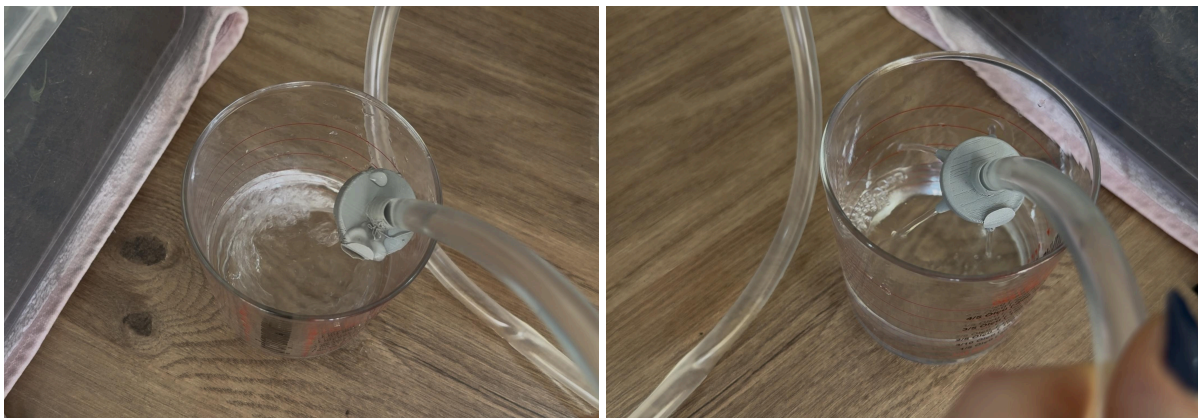


Figure 5.1. Emitter flow rate comparison. Average measured flow rate was 12.83 mL/s for the single outlet emitter and 17.50 mL/s for the multi outlet emitter, a 36.4% increase.

5.2 Equal Volume Irrigation Test



To compare the two emitter geometries fairly, both were tested using an approximately 100 mL equal volume dose. The single outlet emitter was operated for 7.79 s, delivering approximately 99.95 mL, while the multi outlet emitter was operated for 5.70 s, delivering approximately 99.75 mL. The 0.20 mL difference was only about 0.2%, so subsequent differences in wetting behaviour can be attributed primarily to emitter geometry rather than unequal irrigation volume.

Figure 5.2. Equal volume irrigation test arrangement for the single outlet (Cup A) and multi outlet (Cup B) emitter geometries under comparable soil and sensor conditions.

5.2.1 Common Experimental Conditions

Both tests were performed in separate but geometrically identical containers under the same initial conditions. Each emitter was positioned at the centre of the soil surface, the pump was operated at 100% output from a 6 V supply, and the target dose was 100 mL. Surface wetting, qualitative water behaviour, and soil moisture response were recorded immediately after irrigation and after 5 and 15 min. The initial dry soil reference reading was 3569 ADC counts.

Table 5.1. Common experimental conditions for the single and multi outlet tests

Parameter	Value
Container diameter	16 cm
Container height	6.5 cm
Soil mass	0.85027 kg (approximately 850 g)
Soil depth	3.5 cm
Initial soil condition and raw ADC	Dry; 3569 ADC
Emitter position	Centre of container
Target irrigation volume	100 mL
Pump operating condition	100% output at 6 V
Single outlet pump duration	7.79 s
Multi outlet pump duration	5.70 s

5.3 Soil Wetting Distribution Experiment

Surface wetting was quantified from the right-left and front-back wetting diameters. The mean diameter was calculated as $D_{avg} = (D_{RL} + D_{FB})/2$. Because the measured wetting footprint was not perfectly circular, the final wetted area was calculated using the elliptical approximation $A = \pi D_{RL} D_{FB}/4$. Spatial moisture was evaluated independently using three capacitive sensors positioned 2, 4, and 6 cm from the emitter centre, with every reported sensor value based on the mean of 50 ADC samples.

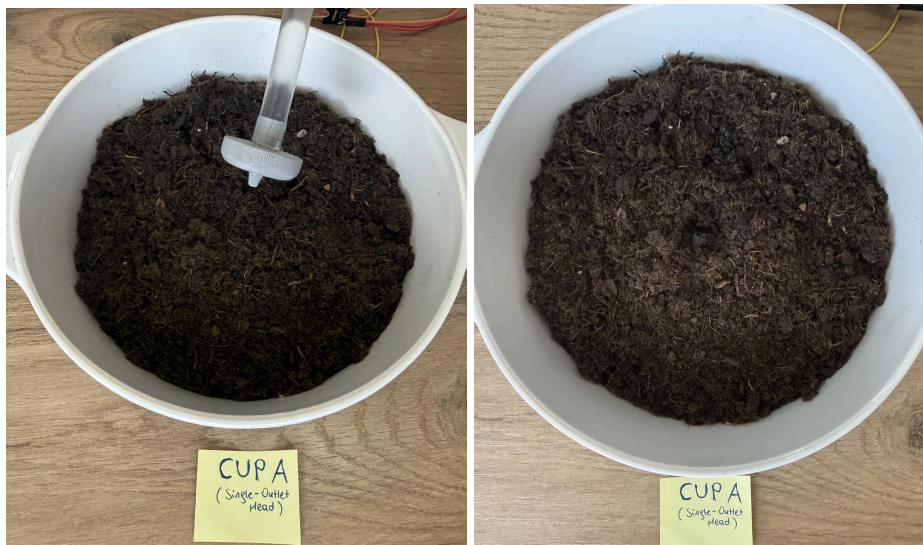


Figure 5.3. Soil wetting test setup for comparing the two emitter geometries.

5.3.1 Single Outlet Emitter Results

Table 5.2. Quantitative single outlet soil wetting measurements

Time	Right-left diameter (cm)	Front-back diameter (cm)	Mean diameter (cm)	Elliptical wet area (cm ²)	Raw ADC
Immediately after irrigation	4.00	2.00	3.00	6.28	1150
5 min	3.00	1.50	2.25	3.53	1325
15 min	3.00	1.00	2.00	2.36	1229

The single outlet measurements provide the baseline for the comparison. Its concentrated discharge produced a relatively localised wetting pattern, and the raw ADC measurements showed increasing spatial variation with distance from the emitter. Qualitative observations of pooling, runoff, drainage, and infiltration are retained in Table 5.3.

Table 5.3. Qualitative single outlet water behaviour observations.

Time	Ponding	Surface runoff	Water at container edge	Bottom drainage	Leakage
Immediately after irrigation	None	Low	None	None	None
5 min	None	None	None	None	None
15 min	None	None	None	None	None

5.3.2 Single Outlet Spatial Moisture Sensor Readings

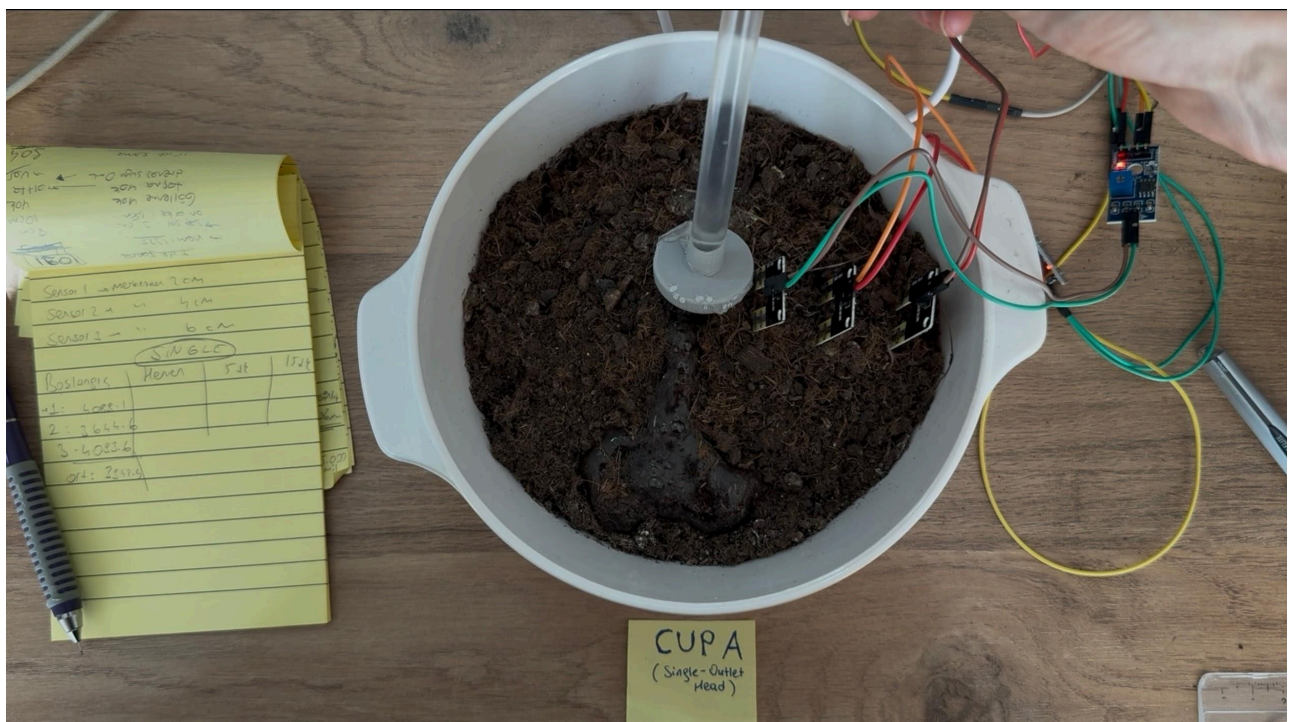


Figure 5.4. Single outlet spatial moisture sensor test at 2, 4, and 6 cm.

Three capacitive soil moisture sensors were positioned radially at 2 cm, 4 cm, and 6 cm from the emitter centre. Each reported value is the mean of 50 ADC samples, with lower raw ADC values indicating wetter soil. These raw measurements are retained for traceability and converted to sensor specific calibrated moisture indices in Section 5.4.

Table 5.4. Single outlet spatial soil moisture readings (mean of 50 samples)

Time	Sensor 1 (2 cm)	Sensor 2 (4 cm)	Sensor 3 (6 cm)	Mean raw ADC
Before irrigation	4089.1	3644.6	4093.6	3942.4
Immediately after irrigation	1453.1	3594.3	4091.3	3046.2
5 min	1679.3	1714.0	2700.4	2031.2
15 min	1469.1	1494.1	2414.8	1792.7

5.3.3 Multi Outlet Emitter Results



Figure 5.5. Multi outlet emitter wetting pattern during the equal volume test.

The multi outlet emitter was evaluated under the same geometry, soil, sensor positions, observation times, pump setting, and approximately 100 mL delivered volume. Its multiple discharge openings produced a much wider wetted footprint than the single outlet design. Although the continuous 100 mL application produced initial ponding, runoff, edge overflow, and bottom drainage, these effects diminished during infiltration and were absent after 15 min.

Table 5.5. Quantitative multi outlet soil wetting measurements

<i>Time</i>	<i>Right-left diameter (cm)</i>	<i>Front-back diameter (cm)</i>	<i>Mean diameter (cm)</i>	<i>Elliptical wet area (cm²)</i>	<i>Raw ADC</i>
<i>Immediately after irrigation</i>	10.00	11.00	10.50	86.39	1203
<i>5 min</i>	8.00	10.00	9.00	62.83	1091
<i>15 min</i>	6.00	5.00	5.50	23.56	904

Table 5.6. Qualitative multi outlet water behaviour observations

<i>Time</i>	<i>Ponding</i>	<i>Surf5.3.4 ace runoff</i>	<i>Water at container edge</i>	<i>Bottom drainage</i>	<i>Leakage</i>
<i>Immediately after irrigation</i>	<i>Present</i>	<i>Medium</i>	<i>Present</i>	<i>Present</i>	<i>None</i>
<i>5 min</i>	<i>None</i>	<i>Low</i>	<i>Lower side overflow present</i>	<i>Present</i>	<i>None</i>
<i>15 min</i>	<i>None</i>	<i>None</i>	<i>None</i>	<i>None</i>	<i>None</i>

5.3.4 Multi Outlet Spatial Moisture Sensor Readings

The three moisture sensors remained at the same 2, 4, and 6 cm radial positions used in the single outlet experiment. Each reported value is again the mean of 50 ADC samples. Keeping the sensor positions and delivered volume constant allowed the spatial response of the two emitter geometries to be compared directly.

Figure 5.6. Multi outlet spatial soil moisture response at 2, 4, and 6 cm.**Table 5.7.** Multi outlet spatial soil moisture readings (mean of 50 samples)

<i>Time</i>	<i>Sensor 1 (2 cm)</i>	<i>Sensor 2 (4 cm)</i>	<i>Sensor 3 (6 cm)</i>	<i>Mean raw ADC</i>
<i>Before irrigation</i>	<i>3562.0</i>	<i>3730.3</i>	<i>3949.9</i>	<i>3747.4</i>
<i>Immediately after irrigation</i>	<i>1968.7</i>	<i>3213.1</i>	<i>3591.5</i>	<i>2924.4</i>
<i>5 min</i>	<i>1798.7</i>	<i>1898.5</i>	<i>1978.3</i>	<i>1891.8</i>
<i>15 min</i>	<i>1688.2</i>	<i>1747.3</i>	<i>1808.2</i>	<i>1747.9</i>

5.4 Results and Discussion

The equal volume experiment showed a clear trade off between hydraulic capacity and spatial distribution. The multi outlet emitter had the higher measured flow rate (17.50 versus 12.83 mL/s) and produced a wetted area approximately 9.98–17.80 times larger than the single outlet design over the recorded observation periods. Because the applied volumes differed by only about 0.2%, this improvement cannot be explained by a larger irrigation dose.

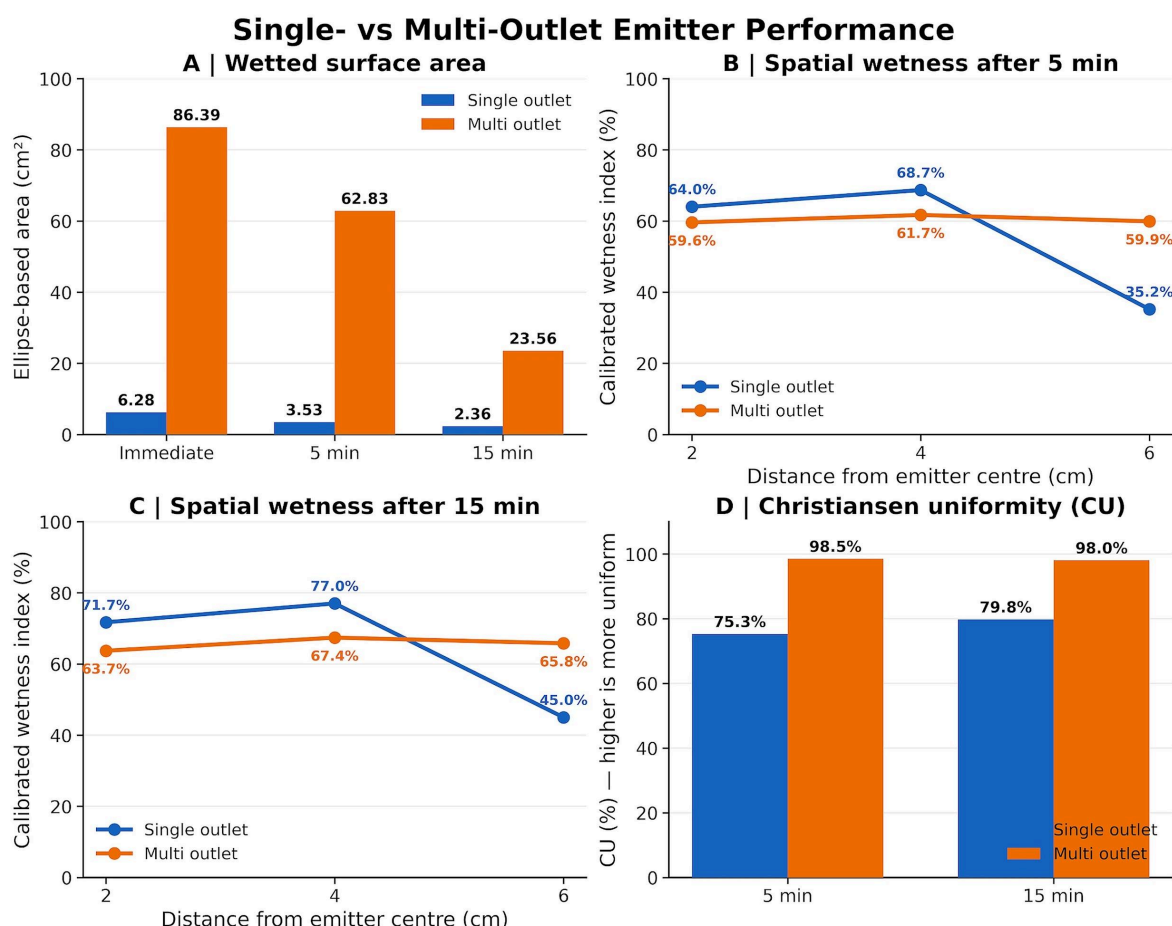


Figure 5.7. Spatial moisture distribution 15 min after equal volume irrigation, showing the more uniform multi outlet response.

The principal advantage of the multi outlet geometry was wetting uniformity. After sensor specific calibration, the single outlet moisture indices at 2, 4, and 6 cm were 64.0%, 68.7%, and 35.2% after 5 min and 71.7%, 77.0%, and 45.0% after 15 min. The corresponding multi outlet values were much closer together: 59.6%, 61.7%, and 59.9% after 5 min and 63.7%, 67.4%, and 65.8% after 15 min.

The multi outlet design therefore reduced the spatial moisture range from 33.5 to 2.2 percentage points at 5 min and from 32.0 to 3.8 percentage points at 15 min. Its Christiansen uniformity coefficients were 98.5% and 98.0%, confirming substantially more even water distribution. This result, rather than flow rate alone, was the main reason for selecting the multi outlet emitter for the final prototype.

The continuous 100 mL multi outlet test also revealed an important limitation: its higher flow and distributed discharge could initially produce ponding, runoff, container edge overflow, and drainage. The experimental conclusion was therefore not to use a smaller coverage emitter, but to retain the more uniform multi outlet

geometry and control the applied volume through short feedback based irrigation pulses. This finding directly informed the 1 second pulse and recheck strategy used in the final system.

5.4.1 Moisture Response and Distribution Uniformity

For quantitative comparison, each sensor was calibrated using its own dry and wet reference values. The calibrated moisture index was calculated as $(ADC_{dry} - ADC_{measured}) / (ADC_{dry} - ADC_{wet}) \times 100$, with values limited to 0–100%. Christiansen's coefficient of uniformity (CU) was calculated from the three calibrated indices. Immediate measurements were retained as transient observations but were not used as the principal uniformity comparison because water had not yet redistributed consistently to the middle and outer sensor positions.

The mean calibrated moisture levels of the two emitters became similar after infiltration, but their spatial consistency remained very different. At 15 min the single outlet readings ranged from 45.0% to 77.0%, whereas the multi outlet readings remained between 63.7% and 67.4%. The multi outlet emitter therefore achieved similar overall soil wetting while distributing that moisture much more evenly across the measured radius.

Table 5.8. Calibrated moisture index and spatial uniformity comparison

Time	Emitter	Mean index (%)	Sensor range (pp)	CU (%)
5 min	Single outlet	56.0	33.5	75.3
5 min	Multi outlet	60.4	2.2	98.5
15 min	Single outlet	64.6	32.0	79.8
15 min	Multi outlet	65.6	3.8	98.0

Taken together, the flow rate, wetted area, calibrated moisture, and CU results support the multi outlet emitter as the final design choice. It delivered water faster and over a wider area, while the 15 min spatial range decreased from 32.0 percentage points for the single outlet to only 3.8 percentage points for the multi outlet. The observed excess water during the continuous 100 mL trial also established why the final controller should avoid long uninterrupted irrigation and instead deliver short doses followed by moisture remeasurement.

CHAPTER 6 – FINAL PROTOTYPE FUNCTIONAL VALIDATION

This chapter presents the final functional validation of the completed three zone irrigation manifold. The purpose of this stage was to confirm that the servo driven rotor could align with each outlet and direct water independently to the selected zone. The assessment was treated as a functional demonstration of the mechanical routing mechanism; it was not used as a long term plant growth study or a repeated reliability test.

6.1 Test Objective and Arrangement

The final validation was conducted in a $34.8 \times 49.1 \times 17.2$ cm cultivation container with a nominal capacity of 20 L. Approximately 75% of the container was filled with soil. Three plants were installed as independent irrigation zones: Zone 1 contained the yellow pepper, Zone 2 contained basil, and Zone 3 contained Kalanchoe. A 5 L water bottle filled to approximately 2.5 L served as the test reservoir.

Water was supplied by an R385 pump rated for 6–12 V and operated from a 6 V adapter in the final system. With the selected multi-outlet emitter installed, the experimentally measured average flow rate was 17.50 mL/s, equivalent to approximately 1.05 L/min. Water was carried through tubing with an 8 mm internal diameter and a 10 mm external diameter to the servo controlled manifold and then to the selected plant zone.

The control and monitoring hardware comprised an ESP32, three capacitive soil moisture sensors, an MG996R servo motor, a MOSFET pump switching stage, WAGO power distribution connectors, a DC jack, a breadboard, and jumper wiring. Pencils and drinking straws were used only as temporary soil anchors to hold the hoses and emitters in stable positions during testing.

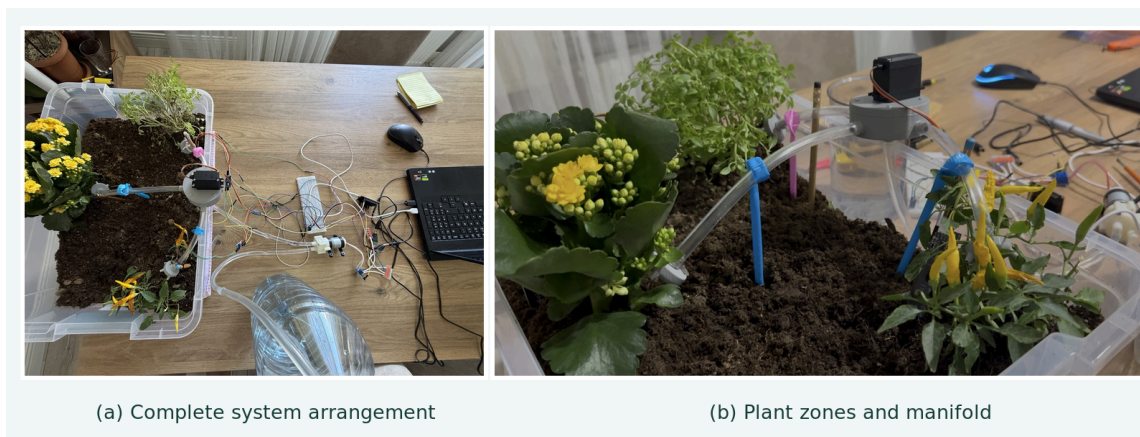


Figure 6.1. Final three zone irrigation test arrangement: (a) complete system arrangement and (b) planted zones with the servo controlled manifold.

The assembled manifold, internal rotor, top cover, MG996R servo motor, pump, and three outlet hoses were tested as one integrated system. The three manifold positions were assigned to Zone 1 at 0° , Zone 2

at 180°, and Zone 3 at 90°. During the recorded demonstration, the servo was commanded sequentially to each position while water flow at the corresponding outlet was observed.

ZONE 1 — YELLOW PEPPER



Sensor 1 • GPIO32 • Servo 0°

ZONE 2 — BASIL



Sensor 2 • GPIO33 • Servo 180°

ZONE 3 — KALANCHOE



Sensor 3 • GPIO34 • Servo 90°

Figure 6.2. Equal scale photographs of the three irrigation zones: Zone 1—Yellow Pepper, Zone 2—Basil, and Zone 3—Kalanchoe, with their assigned sensors and servo positions.

6.2 Three Zone Water Routing Procedure

The final routing test used the complete closed-loop control sequence rather than a fixed demonstration cycle. The ESP32 first calculated the mean of 50 readings from each soil-moisture sensor and compared the averaged value with the experimental ADC 2000 irrigation threshold. A zone with an averaged reading of 2000 ADC or higher was classified as requiring irrigation, whereas a reading below 2000 ADC was accepted as sufficiently wet and received no water.

When irrigation was required, the controller commanded the MG996R servo to the calibrated manifold position assigned to that plant: 0° for Zone 1 (Yellow Pepper), 90° for Zone 3 (Kalanchoe), and 180° for Zone 2 (Basil). After the servo movement, a settling interval was applied before pump activation so that the internal rotor could align fully with the selected outlet. Water delivery was then checked at the intended outlet while the two inactive outlets were observed for visible leakage or simultaneous discharge.

Irrigation was delivered as repeated 1 second pump pulses rather than as one continuous dose. After each pulse, the pump was switched off and the system allowed time for the applied water to infiltrate the soil. The controller then obtained a new 50 reading moisture average for the same zone. If the averaged value remained at or above ADC 2000, another 1 second pulse was delivered; if it fell below the threshold, irrigation for that zone stopped. The controller then proceeded to evaluate the remaining zones according to their own measured conditions.

This procedure made the validation both a hydraulic routing test and a closed loop control test. It verified the complete sequence of sensing → decision → zone selection → servo settling → 1 second water delivery → moisture remeasurement → stop or repeat. Consequently, the number of pulses was not predetermined or equal for all plants; it emerged from the measured moisture response of each zone. The resulting zone specific pulse counts and water volumes are reported in Section 6.3.

6.3 Observed Functional Results

A functional three zone water routing test was completed using the final manifold assembly. The calibrated routing was 0° for Zone 1 (Yellow Pepper), 90° for Zone 3 (Kalanchoe), and 180° for Zone 2 (Basil). At each commanded position, water was delivered through the selected outlet without visible external leakage or simultaneous discharge from the inactive outlets.

The closed loop validation used ADC 2000 as the experimental irrigation threshold, with lower ADC values indicating wetter soil. Every control decision was based on the mean of 50 sensor readings. When a zone measured 2000 ADC or higher, the pump delivered a 1 second pulse; the soil was then allowed to respond and the zone was re-evaluated. A reading below 2000 ADC required no irrigation.

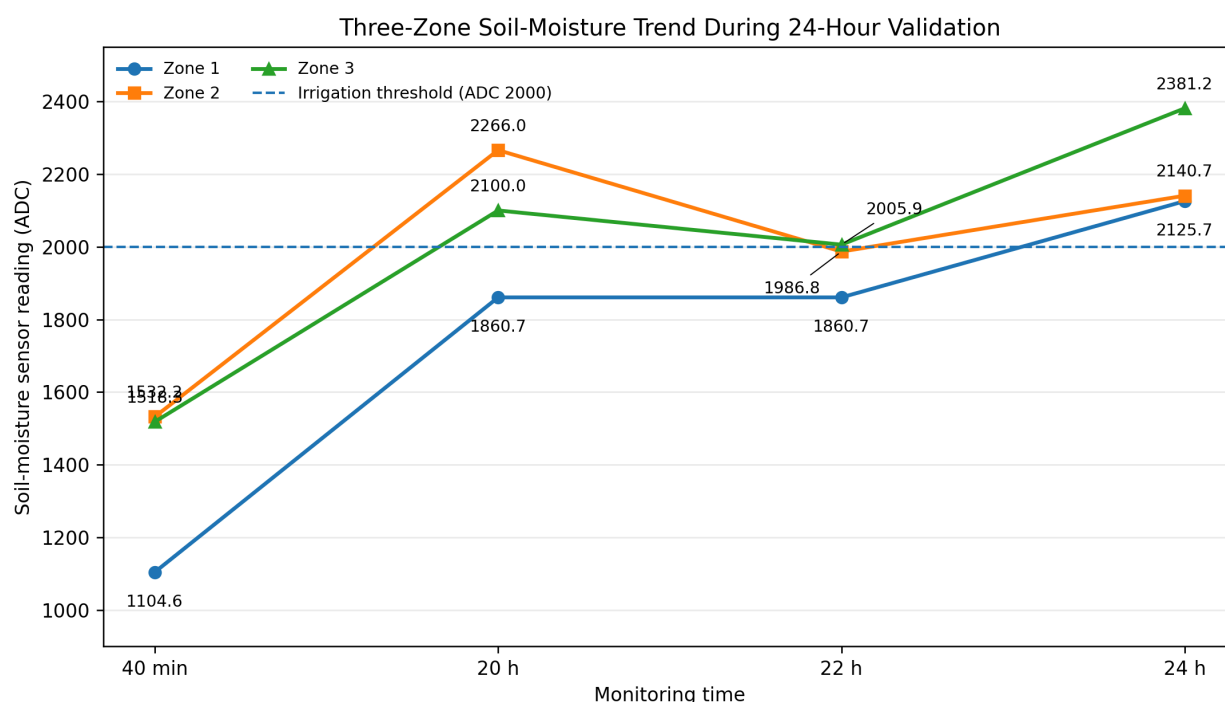


Figure 6.3. Three zone soil moisture trend across the 40 min, 20 h, 22 h, and 24 h monitoring points. Every measured ADC value is labelled directly on the graph, and the dashed line represents the ADC 2000 irrigation threshold. The graph shows the measured condition at each monitoring point; pulse counts describe the subsequent irrigation response. Lower ADC values indicate wetter soil.

Before the initial irrigation sequence, Zone 1 measured 2570.7 ADC, Zone 2 measured 3521.5 ADC, and Zone 3 measured 2984.2 ADC. All three zones were classified as dry. Zone 1 required 1 one second pulse, Zone 2 required 4 pulses, and Zone 3 required 3 pulses.

Forty minutes after the initial irrigation, the readings had fallen to 1104.6 ADC for Zone 1, 1532.2 ADC for Zone 2, and 1518.3 ADC for Zone 3. All three zones were below the threshold, so no additional irrigation was required at this monitoring point.

At 20 h, Zone 1 measured 1860.7 ADC and remained below the threshold, requiring no irrigation. Zone 2 measured 2266.0 ADC and required 3 one second pulses. Zone 3 measured 2100.0 ADC and required 2 one second pulses.

At 22 h, Zone 1 measured 1860.7 ADC and required no irrigation. Zone 2 measured 1986.8 ADC, remaining just below the threshold, and also required no irrigation. Zone 3 measured 2005.9 ADC, slightly above the threshold, and required 1 one-second pulse.

At 24 h, Zone 1 measured 2125.7 ADC, Zone 2 measured 2140.7 ADC, and Zone 3 measured 2381.2 ADC. All three zones were above the threshold. Zone 1 required 1 one-second pulse, Zone 2 required 1 pulse, and Zone 3 required 2 pulses before its measured condition was accepted after re-evaluation.

Across the complete 24 hour record, Zone 1 received 2 pulses (1 initial + 0 at 20 h + 0 at 22 h + 1 at 24 h), Zone 2 received 8 pulses (4 + 3 + 0 + 1), and Zone 3 received 8 pulses (3 + 2 + 1 + 2). The complete adaptive sequence therefore contained **18 one second irrigation pulses**.

Using the experimentally measured multi outlet flow rate of 17.50 mL/s, each 1 second pulse delivered approximately 17.5 mL. The recorded irrigation corresponds to approximately 35.0 mL for Zone 1, 140.0 mL for Zone 2, and 140.0 mL for Zone 3, giving a total adaptive water use of approximately 315.0 mL during the 24 hour validation

The results demonstrate that irrigation demand was both plant-specific and time dependent. Zone 1 required only 2 pulses over the complete record, whereas Zones 2 and 3 each required 8. The 22 hour measurement provides a clear example of selective control: Zone 2 measured 1986.8 ADC and received no water, while Zone 3 measured 2005.9 ADC and received one pulse. The controller therefore responded to the measured condition of each zone instead of applying the same irrigation event to all plants.

For the defined equal dose benchmark used in this project, all three zones would receive the same 10 one-second pulses over the corresponding validation cycle, producing 30 pulses in total. At 17.50 mL/s, this represents approximately 525.0 mL. The adaptive system used 18 pulses and approximately 315.0 mL, avoiding 12 unnecessary one second pump activations and approximately 210.0 mL of water. Relative to this defined benchmark, the experiment specific **water use reduction was 40.0%**.

The final validation therefore confirms the intended closed-loop behaviour of the prototype: each plant zone was measured independently, the servo controlled manifold routed the shared water source only to the selected outlet, and irrigation was delivered in short 1 second increments according to the measured soil condition. The measured 2–8 pulse distribution and the **40.0%** benchmark reduction demonstrate the practical value of combining plant specific sensing, selective water routing, and feedback based dosing in one three zone irrigation system.

6.4 Engineering Interpretation and Water Saving Assessment

The functional results confirm that the prototype achieved closed loop, zone specific irrigation rather than fixed equal watering. Each control decision used the mean of 50 sensor readings and compared the result with the experimental ADC 2000 threshold. A zone at or above 2000 ADC received a 1 second pump pulse, after which its soil condition was re-evaluated. A zone below the threshold received no water. This feedback sequence allowed the controller to stop irrigating a sufficiently wet plant while continuing to respond to a drier zone.

The recorded 24 hour demand was clearly different between the three plants. Zone 1 received 2 one second pulses in total, Zone 2 received 8, and Zone 3 received 8. At the measured multi outlet flow rate of 17.50 mL/s, one pulse corresponds to approximately 17.5 mL. The adaptive water allocation was therefore approximately 35.0 mL for Zone 1, 140.0 mL for Zone 2, and 140.0 mL for Zone 3. The complete 18 pulse sequence used approximately 315.0 mL.

The 22 hour measurement provides a direct example of the engineering value of independent control. Zone 2 measured 1986.8 ADC, which was below the threshold, so it received no irrigation. Zone 3 measured 2005.9 ADC, slightly above the threshold, and therefore received one 1 second pulse. Although the two readings were close, the controller treated the zones independently and supplied water only where the measured condition required it.

For the defined equal dose benchmark used in this report, each of the three zones would receive 10 one second pulses over the corresponding validation cycle. The benchmark therefore contains 30 pulses and, at 17.50 mL per pulse, would use approximately 525.0 mL. The adaptive prototype used 18 pulses and approximately 315.0 mL. It consequently avoided 12 unnecessary pump activations and approximately 210.0 mL of water. The experiment-specific reduction is $(525.0 - 315.0) / 525.0 \times 100 = 40.0\%$.

The same comparison illustrates the effect on reservoir use. A 2.5 L reservoir corresponds theoretically to approximately 7.9 adaptive 24 hour cycles at 315.0 mL per cycle, compared with approximately 4.8 benchmark cycles at 525.0 mL per cycle. These values are theoretical ratios based on the recorded test consumption and do not include a practical reserve volume or other hydraulic losses.

The engineering significance of the result is therefore not that one plant species will always require a fixed amount of water. Instead, the prototype demonstrated that demand changes by zone and over time, and that the controller can respond without applying the highest required dose to every plant. This selective approach can reduce unnecessary saturation, drainage, and repeated overwatering. Long term effects on plant growth, root health, nutrient retention, and yield were not measured in this short validation and are therefore not claimed as experimental outcomes.

6.5 Challenges and Engineering Decisions

A major mechanical challenge was maintaining a sealed internal flow path while allowing the rotor to move freely. O-ring interfaces, the manifold body cavity, the top cover fasteners, and the rotor clearances had to work together: excessive clearance could create leakage between outlets, while excessive compression could restrict servo movement. The final screw fastened cover and sealed rotor arrangement produced no visible external leakage or simultaneous discharge from non selected outlets during the functional test.

A second challenge was achieving reliable alignment between the MG996R servo and the three hydraulic outlets. The final calibrated positions were 0° for Zone 1, 90° for Zone 3, and 180° for Zone 2. A settling interval was retained after each movement, and the controller stored the last servo position so that unnecessary return movements were avoided. Sequential routing was selected because one pump and one rotary manifold could serve all three zones without requiring three separate pumps or solenoid valves.

Moisture sensing introduced variation caused by soil contact, local compaction, sensor differences, and electrical noise. Each decision was therefore based on the average of 50 readings rather than on a single ADC sample. Individual dry and wet calibration values were used to report approximate wetness percentages, while ADC 2000 was retained as a simple common trigger for the final functional validation. A future field version should replace the common raw ADC threshold with independently calibrated, plant specific wetness thresholds.

The multi outlet emitter was retained because earlier equal volume testing showed a more homogeneous wetting pattern than the single outlet. To control the ponding and drainage observed during longer applications, the final algorithm used short 1 second pulses followed by measurement and waiting periods. This converted a hydraulic limitation into a feedback control decision: water was added incrementally and stopped as soon as the zone passed the acceptance threshold.

Electrical reliability also required deliberate design decisions. The pump was switched through a MOSFET with flyback protection, the servo and pump were powered from the 6 V supply rather than from the ESP32 regulator, and a common ground was maintained for control references. WAGO connectors were used to distribute positive and ground conductors more safely and clearly than long chained jumper wire connections.

6.6 Cost and Sustainability

The prototype uses widely available, relatively low cost components: an ESP32, one R385 pump, one MG996R servo, three capacitive moisture sensors, a MOSFET switching stage, WAGO connectors, tubing, and custom 3D printed mechanical parts. Because itemised purchase prices were not recorded as part of the experimental dataset and market prices vary, the cost assessment is based on system architecture rather than on an unsupported fixed total.

The principal cost advantage comes from sharing active hardware. One pump and one servo actuated rotary manifold serve three independently controlled zones, reducing the need for a separate pump or powered valve for each plant. The manifold body, rotor, cover, emitters, and hose interfaces are modular and replaceable, so individual parts can be repaired, reprinted, or redesigned without discarding the complete system.

The final 24 hour validation also provides a measured sustainability result. The adaptive controller used 18 one second pump activations and approximately 315.0 mL of water. The defined equal dose benchmark used 30 activations and approximately 525.0 mL. The prototype therefore avoided 12 seconds of pump operation and approximately 210.0 mL of water, corresponding to a 40.0% experiment specific reduction. With a 2.5 L reservoir, the same measured consumption would correspond to approximately 7.9 adaptive 24 hour cycles, compared with approximately 4.8 benchmark cycles, before accounting for practical refill margins.

The sustainability benefit is not limited to the percentage reduction. Independent sensing prevents a sufficiently wet plant from receiving water simply because another zone is dry, while the 1 second pulse and recheck strategy limits each irrigation event to a small incremental dose. Direct root zone delivery through the selected emitter further concentrates the required water near the plant rather than broadly wetting unrelated soil.

Broader environmental claims require longer testing. Electrical energy consumption of the ESP32, servo, and pump was not separately logged, and seasonal evaporation, drainage, plant growth, and maintenance impacts were outside the scope of the final 24 hour validation. Future versions should combine continuous water flow logging with energy measurements and longer plant trials. Nevertheless, the present prototype demonstrates a resource conscious architecture based on three principles: measure each plant independently, irrigate only when its threshold is crossed, and deliver a short targeted dose before measuring again.

6.7 Scope and Limitations

The final validation demonstrates closed loop three zone irrigation under the specific conditions of this prototype. The reported 40.0% water use reduction is tied to the measured 17.50 mL/s multi outlet flow rate, the 1 second pulse duration, the ADC 2000 experimental threshold, the recorded 24 hour demand pattern, and the defined 30 pulse equal dose benchmark. It should therefore be interpreted as an experiment specific comparison rather than as a universal daily, seasonal, or agricultural water saving rate.

The validation record covered approximately 24 hours and included initial irrigation followed by measurements at 40 minutes, 20 hours, 22 hours, and 24 hours. The measured ADC values at these monitoring points and the resulting pulse counts were recorded, but variables such as evaporation, plant uptake, drainage volume, pump start up transients, long term sensor drift, and environmental variation were not independently quantified. Repeated multi day and seasonal trials would be required before the result could be generalized to other plants, soils, climates, or irrigation systems.

The moisture sensors were used as relative control instruments rather than laboratory grade volumetric water content sensors. Although 50 sample averaging reduced short term noise, the readings can still be influenced by sensor to sensor variation, insertion depth, soil contact, compaction, and local wetting patterns. The common ADC 2000 threshold was suitable for the final prototype demonstration, but future versions should use individually calibrated plant specific moisture thresholds.

6.8 Practical and Societal Significance

The practical significance of the system is its ability to allocate one shared water source according to local plant demand. During the 24 hour validation, Zone 1 required only 2 pulses, whereas Zones 2 and 3 each required 8. This difference shows why equal scheduled irrigation can be inefficient in a multi plant system: a zone that remains sufficiently wet does not necessarily require the same dose as a drier zone.

The defined benchmark provides a quantitative example. The adaptive controller used 18 one-second pulses and approximately 315.0 mL, whereas the equal dose benchmark used 30 pulses and approximately 525.0 mL. The adaptive strategy therefore avoided 12 unnecessary pump activations and approximately 210.0 mL of water, producing a 40.0% reduction for this experiment. The saving was achieved by withholding water from zones that were already below the ADC 2000 threshold and by adding water in small 1 second increments instead of committing to a large fixed dose.

The system also improves accessibility of independent irrigation by avoiding a separate pump or powered valve for every plant. One pump is shared, and the servo controlled manifold mechanically selects the required outlet. Combined with modular 3D printed components, this architecture offers a compact and repairable basis for home gardens, educational prototypes, balcony growing systems, and other small multi zone applications where hardware simplicity and water awareness are important.

The project also demonstrates the value of iterative engineering. Mechanical leakage, sealing, servo alignment, pump reliability, power distribution, sensor variability, and emitter wetting behaviour were investigated through repeated testing. The final design therefore reflects measured observations and engineering corrections rather than assumptions alone.

This project demonstrates how low-cost, IoT-enabled precision irrigation can contribute to more sustainable water use at both household and community levels. By delivering water only when each plant actually needs it, the system reduces unnecessary water consumption while maintaining healthy plant conditions. The approach is scalable and can be applied to home gardens, urban farming, greenhouses, and educational settings, supporting broader awareness and adoption of smart, resource-efficient agriculture.

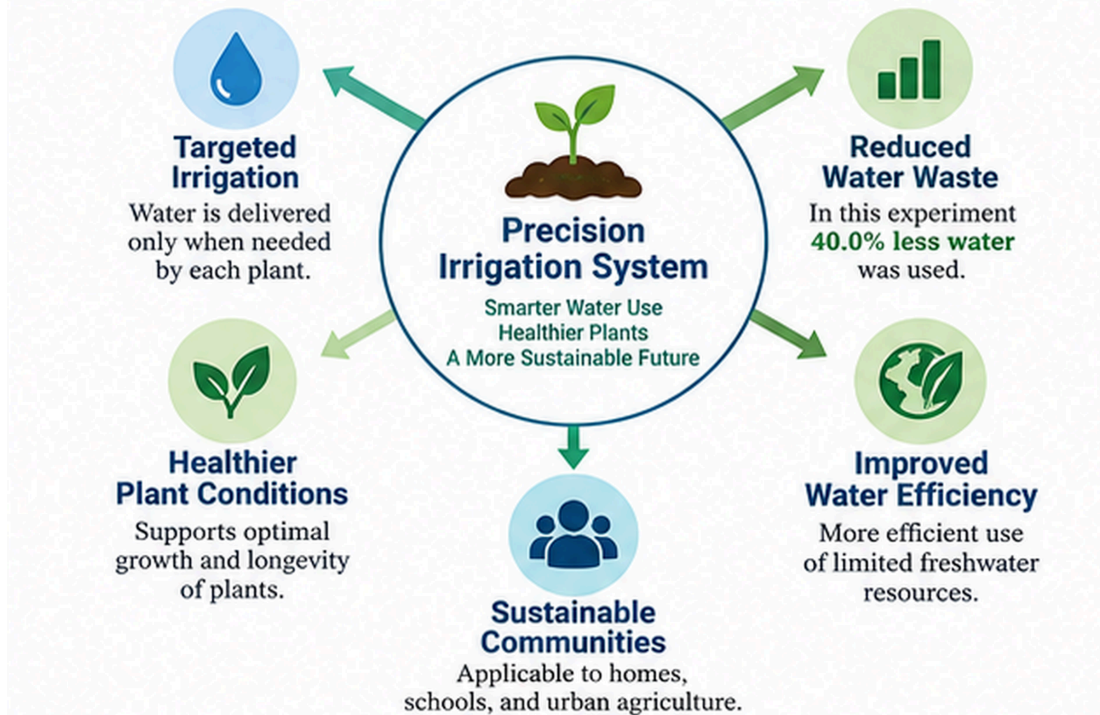


Figure 6.4. Project impact diagram summarizing how plant specific sensing and targeted irrigation can reduce unnecessary water application, improve water use efficiency, and support more resource conscious small-scale irrigation.

6.9 30 Day Operational Evaluation

Following the controlled 24 hour validation, the prototype remained in use with the three real plants for approximately one month. Because a separately metered 30 day irrigation dataset was not collected for every individual event, the 30 day quantities below are projections based on the measured 24 hour pulse distribution and should be interpreted as operating estimates rather than as independently measured monthly totals.

Using the validated daily reference of 18 one second pulses, the adaptive system corresponds to approximately 540 pulses over 30 days. At 17.50 mL per pulse, this is approximately 9.45 L of projected water use. Applying the same 30 pulse equal dose benchmark each day gives approximately 900 pulses and 15.75 L over 30 days. The projected difference is therefore 360 avoided one second pump activations and approximately 6.30 L of water, preserving the same 40.0% experiment specific reduction as the underlying daily benchmark.

The projected plant specific distribution further illustrates the importance of independent control. Zone 1 would correspond to approximately 60 pulses over 30 days, while Zone 2 and Zone 3 would each correspond to approximately 240 pulses. At 17.50 mL per pulse, these values represent approximately 1.05 L for Zone 1 and 4.20 L each for Zones 2 and 3. The fourfold difference between 2 and 8 pulses in the

measured 24 hour record shows why forcing all three plants into the same irrigation duration can apply unnecessary water to lower demand zones.

Water efficiency in the prototype is produced by two complementary mechanisms. The control algorithm avoids irrigation when a zone is already sufficiently wet, while the selected multi outlet emitter delivers each required pulse close to the plant root zone area. The monthly projection therefore illustrates the potential cumulative effect of the measured daily behaviour, but long term water savings should ultimately be verified with continuous flow logging, environmental measurements, and a matched conventional irrigation control group.

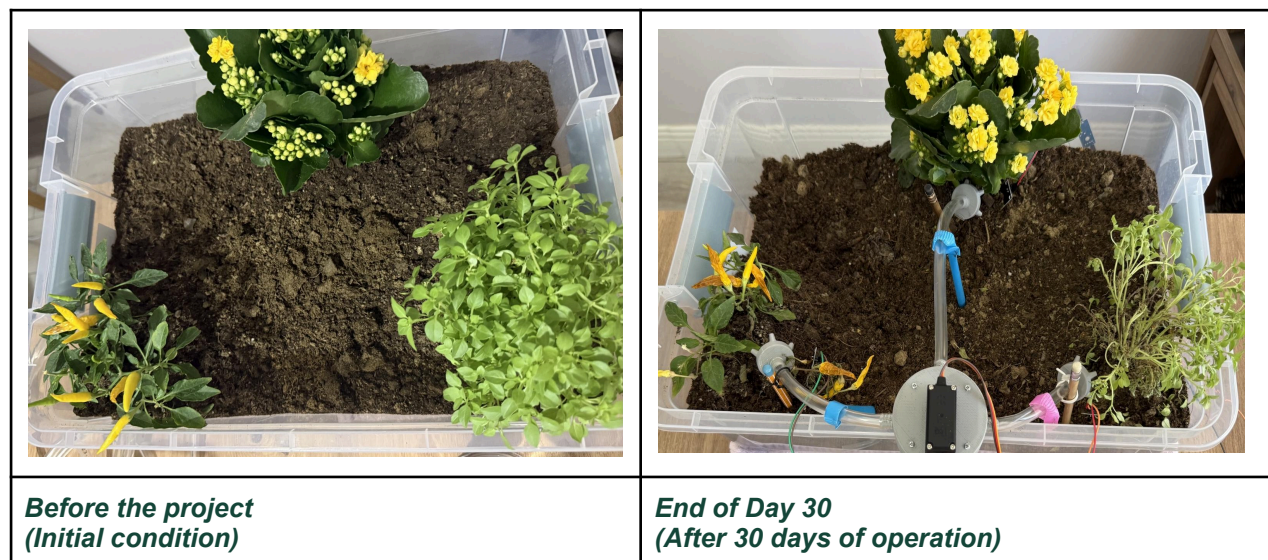


Figure 6.5. Comparison of the planter before the irrigation project and at the end of the approximately 30 day operational period. The images document the transition from the initial planting arrangement to the completed three zone prototype operating with the servo controlled manifold, independent irrigation lines, multi outlet emitters, and soil moisture sensing hardware. The comparison is used as qualitative visual documentation of the completed system and its month long real plant operation; plant growth or health changes are not attributed solely to the irrigation system because a controlled biological comparison was not performed.

6.10 Chapter Summary

The final prototype successfully integrated the mechanical manifold, ESP32 controller, three soil moisture sensing channels, servo positioning, and pump actuation into one closed loop three zone irrigation system. During the recorded 24 hour validation, Zone 1 required 2 one second pulses, Zone 2 required 8 pulses, and Zone 3 required 8 pulses. At the measured multi outlet flow rate of 17.50 mL/s, these 18 pulses correspond to approximately 35.0 mL, 140.0 mL, and 140.0 mL respectively, for a total adaptive water use of approximately 315.0 mL.

The experiment also demonstrated how feedback control can prevent unnecessary irrigation. Each zone was measured independently using a 50 reading ADC average, compared with the experimental ADC 2000 threshold, routed through its calibrated manifold position, and irrigated in 1 second increments only when required. For the defined equal dose benchmark, 30 one second pulses would have delivered approximately 525.0 mL. The adaptive system therefore avoided 12 pump activations and approximately 210.0 mL of water, corresponding to an experiment specific reduction of 40.0%.

The chapter confirms the main functional objective of the prototype: one shared pump and one servo controlled manifold can provide selective, sensor guided irrigation to three different plant zones. The result is not evidence of a universal seasonal saving rate, but it provides a measured demonstration that independent sensing, targeted routing, and short feedback based dosing can reduce unnecessary water application compared with the defined equal dose strategy.

CHAPTER 7 – FUTURE DEVELOPMENT AND FINAL REMARKS

This chapter outlines the next engineering steps required to develop the validated prototype into a more robust, connected, and scalable precision irrigation platform. The proposed architecture builds directly on the system validated in Chapter 6: soil moisture measurements remain the primary input, the ESP32 remains responsible for the irrigation decision, and the servo controlled manifold and pump remain the local actuation layer. Future sensors for temperature, humidity, light, and rain can provide additional environmental context, while Wi-Fi connectivity can transfer timestamped measurements and irrigation events to Supabase for historical analysis and a mobile/web dashboard.

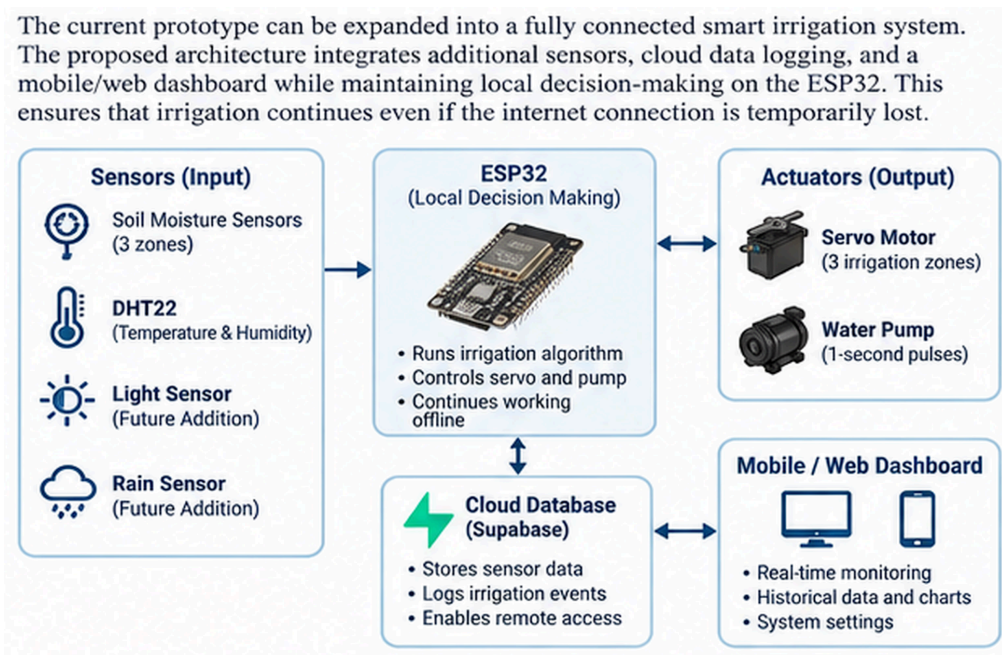


Figure 7.1. Proposed future system architecture extending the validated local controller with environmental sensing, Wi-Fi data transfer, Supabase logging, and mobile/web monitoring while preserving autonomous ESP32 based irrigation control.

The architecture shown in **Figure 7.1** deliberately keeps the irrigation loop local. Cloud connectivity is intended to extend visibility and data collection, not to replace the controller. If Wi-Fi or the remote database becomes unavailable, the ESP32 should still be able to read each plant zone, compare its measured condition with the relevant threshold, select the correct manifold outlet, deliver a short irrigation pulse, and remeasure the soil. This separation between autonomous control and connected monitoring improves reliability while creating a clear path from the current three zone prototype toward a data driven precision irrigation platform.

7.1 Plant Specific Moisture Control

The first priority is to replace the common ADC 2000 irrigation threshold with independently calibrated control limits for each plant and soil condition. The approximately one month operating period showed why this is important: the three zones did not exhibit equal irrigation demand. A future controller should therefore store separate dry and wet calibration references for yellow pepper, basil, Kalanchoe, and any additional plant species rather than assuming that one raw ADC value represents the same moisture condition in every zone.

Plant specific thresholds could be expressed as calibrated moisture percentages rather than raw ADC counts. This would make the control logic easier to interpret and would allow thresholds to be adjusted as plants grow, root systems expand, or soil composition changes. The existing pulse and recheck strategy should be retained so that even a plant specific target is approached incrementally rather than through one large predetermined dose.

7.2 Connected Monitoring and Data Logging

The ESP32's integrated Wi-Fi capability provides a direct path toward remote monitoring and historical data collection. A future version can connect to Wi-Fi and send timestamped operating data to Supabase, including Zone 1, Zone 2, and Zone 3 moisture readings, active zone, servo position, pump state, irrigation duration, and later environmental measurements.

Cloud connectivity should remain a logging and dashboard layer rather than a requirement for irrigation. The ESP32 should continue to read sensors, make threshold decisions, select the manifold outlet, and operate the pump locally even if Wi-Fi or the cloud database is unavailable. A phone accessible dashboard could then display historical moisture trends and irrigation events without reducing the reliability of the local controller.

7.3 Environmental Sensing and Predictive Irrigation

Additional sensors can extend the controller beyond soil moisture alone. Temperature and humidity sensing, ambient light measurement, and rain detection could provide environmental context for interpreting plant water demand. These variables should initially be logged alongside the irrigation record so that their relationship with soil drying can be evaluated experimentally.

With a sufficiently long dataset, the system could later use recent drying rate and environmental conditions to anticipate when a zone is likely to require irrigation. Any predictive decision should still be verified against the local soil moisture condition before water is delivered. This would preserve the safety and simplicity of feedback control while allowing the system to anticipate demand more intelligently.

7.4 Manifold Reliability and Hydraulic Development

The rotary manifold should be subjected to longer duration mechanical and hydraulic reliability testing. Future experiments should quantify leakage rather than relying only on visual inspection, record outlet to outlet flow variation, and evaluate O-ring wear, rotor friction, dimensional change, and sealing performance after hundreds or thousands of selection cycles. These tests would establish maintenance intervals and identify whether the current **PETG** geometry is suitable for prolonged service.

Further manifold development should focus on reducing pressure losses and improving repeatability between outlets. The rotor passage, outlet geometry, O-ring compression, hose interfaces, and internal clearances can be parametrically optimized in **Fusion 360**. Alternative sealing materials and replaceable sealing cartridges could also be evaluated. Because the present design is modular and 3D printable, these changes can be implemented without redesigning the electronic controller.

The multi outlet emitter should likewise be refined through outlet by outlet flow measurement. The experimental work demonstrated strong spatial uniformity, but future versions should investigate smaller outlet diameters, alternative outlet orientations, pressure regulation, and blockage resistance. The aim should be to retain the broad and uniform wetting pattern while reducing the possibility of ponding during high flow operation.

7.5 Electrical and Hardware Reliability

A practical long term version should move beyond temporary breadboard wiring. The ESP32, MOSFET driver, power distribution, protection components, and connectors should be installed in a water resistant enclosure with strain relief for cables and hoses. A dedicated printed circuit board or secure terminal based wiring system would reduce loose connections and simplify maintenance. Appropriate fusing, decoupling capacitors, reverse polarity protection, and clearly separated pump and servo power paths should be retained as standard design requirements.

Reservoir level sensing should be added so that the pump cannot run dry. Flow sensing could provide an additional safety layer by detecting a disconnected hose, blocked emitter, empty reservoir, or failed pump when commanded irrigation does not produce the expected water movement. Servo position verification or

a mechanical reference sensor could similarly detect misalignment before the pump is activated. These additions would convert several currently assumed operating conditions into measurable fault states.

7.6 Scalability and Wider Application

The three zone prototype establishes a modular basis that can be expanded. A future manifold can include additional indexed outlets while retaining one common pump and one rotary selector. The software architecture can also be extended by storing a sensor channel, calibrated threshold, servo position, and irrigation history for each added zone. Scaling should be performed progressively because increasing the number of outlets will affect rotor geometry, angular spacing, sealing area, servo positioning tolerance, pressure losses, and total system response time.

The concept is most directly applicable to home gardens, balcony and urban growing systems, educational laboratories, and small greenhouse installations where several plants require independent irrigation but a separate powered valve or pump for every zone would add unnecessary hardware. Larger scale use would require higher capacity hydraulic components and formal reliability testing, but the underlying principle remains transferable: one shared water source can be allocated selectively according to measured local demand.

7.7 Long Term Experimental Validation

Future testing should extend beyond the current validation period and cover complete seasonal growing cycles. Water delivered to every zone should be automatically accumulated from measured flow and pump duration rather than estimated manually. Environmental conditions, reservoir refill volume, drainage, sensor drift, plant growth, and visible plant health indicators should be recorded alongside irrigation events. A conventional fixed schedule control group should be operated under comparable conditions so that long-term water savings can be quantified experimentally rather than extrapolated from a shorter reference period.

This longer dataset would also allow the system to distinguish temporary soil response from persistent plant specific demand. It could determine whether the observed differences between the yellow pepper, basil, and Kalanchoe remain stable as the plants grow, roots expand, weather changes, and seasonal water demand increases. The resulting evidence would provide a stronger basis for evaluating water conservation, plant performance, system reliability, and maintenance requirements.

7.8 Final Project Perspective

The completed project demonstrates a full engineering progression from problem definition to a working physical prototype. Mechanical components were designed and repeatedly revised in Fusion 360, manufactured by 3D printing, assembled into a sealed rotary distribution mechanism, integrated with electronic sensing and actuation, controlled through progressively developed ESP32 firmware, and evaluated through hydraulic, soil wetting, and real plant experiments. The final system therefore represents the integration of mechanical design, electronics, embedded software, experimentation, and sustainability oriented decision making.

The central contribution is the combination of a servo controlled rotary manifold with closed loop, plant specific irrigation. One pump can serve multiple zones without forcing every plant to receive the same amount of water. The sensors determine whether irrigation is required, the manifold determines where the water is delivered, and the pulse and recheck algorithm determines whether another dose is necessary. Direct root zone delivery further limits irrigation to the area where the plant can use it.

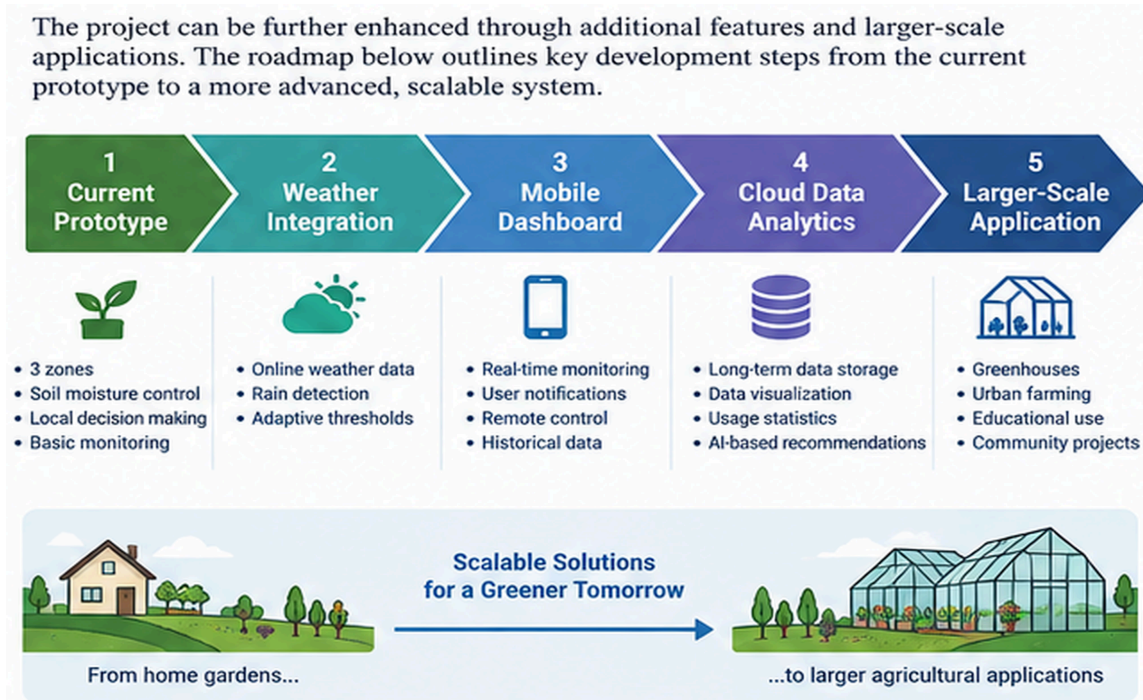


Figure 7.2. Future development roadmap from the validated three zone prototype toward environmental sensing, connected monitoring, long term data analysis, and progressively larger multi zone irrigation applications.

Future development should preserve this principle while improving calibration, reliability, connectivity, environmental awareness, and scale. The long term objective is not simply to automate watering, but to make every irrigation decision measurable, selective, and resource conscious.

Ultimately, precision irrigation means delivering the right amount of water to the right plant, at the right place, and at the right time.

This concludes the design, development, experimental evaluation, and future development roadmap of the Modular Smart Irrigation System.

CLOSING REMARKS

The Modular Smart Irrigation System began with one central engineering challenge: how can plants with different water requirements be irrigated independently without assigning a separate pump or powered valve to every zone? Through CAD design, 3D printing, mechanical redesign, sealing trials, servo calibration, electrical troubleshooting, sensor calibration, firmware development, emitter testing, and real-plant operation, the project produced a complete working prototype. A single pump, one servo controlled rotary manifold, three independent soil moisture sensing zones, multi outlet emitters, and a closed loop 1 second pulse and recheck algorithm were successfully integrated into one three zone precision irrigation system.

The experimental work showed that both emitter geometry and control strategy affected irrigation performance. The selected multi-outlet emitter delivered an average flow rate of 17.50 mL/s compared with 12.83 mL/s for the single outlet design. More importantly, after 15 minutes its calibrated moisture readings remained within 63.7–67.4%, with a Christiansen uniformity coefficient of 98.0%, whereas the single outlet emitter produced a much wider 45.0–77.0% range. These results justified selecting the multi outlet geometry and controlling its higher flow through short feedback-based pulses rather than long continuous watering.

The final 24 hour closed loop validation demonstrated the central value of plant specific irrigation. Zone 1, containing the yellow pepper, required 2 one second pulses in total. Zone 2, containing basil, required 8 pulses, and Zone 3, containing Kalanchoe, also required 8 pulses. The complete adaptive sequence therefore contained 18 one second pump activations. At the measured multi outlet flow rate of 17.50 mL/s, this corresponds to approximately 35.0 mL for Zone 1, 140.0 mL for Zone 2, and 140.0 mL for Zone 3, giving a total adaptive water use of approximately 315.0 mL.

For the defined equal dose benchmark used in this project, all three zones would receive the same 10 one second pulses over the corresponding validation cycle. This produces 30 pulses and approximately 525.0 mL of water. Compared with this benchmark, the adaptive controller avoided 12 unnecessary pump activations and approximately 210.0 mL of water. The experiment specific reduction in water use was therefore 40.0%. This percentage is a result of the defined 24 hour prototype comparison and is not presented as a universal seasonal saving rate.

The result gives the project value beyond simple automation. The system makes three separate decisions that a fixed timer based irrigation routine does not: the sensors determine whether irrigation is required, the rotary manifold determines where the water is delivered, and the pulse and recheck feedback determines how much water is supplied. At the 22 hour measurement, for example, Zone 2 measured 1986.8 ADC and received no irrigation, while Zone 3 measured 2005.9 ADC and received one pulse. The controller therefore acted on the measured condition of each individual zone rather than forcing all plants to follow the same watering event.

The rotary manifold is central to this contribution. By allowing one shared pump and one servo to serve three independently controlled outlets, the design reduces duplicated actuators and provides a compact, modular, 3D printable, repairable, and expandable architecture for small multi zone irrigation. Individual mechanical components can be modified or replaced without rebuilding the complete system, while the ESP32 control architecture can be extended to additional sensing and data logging functions.

The completed prototype also represents an iterative engineering process. Leakage, rotor sealing, servo alignment, unreliable low PWM pump behaviour, power distribution problems, sensor variability, and emitter wetting behaviour were identified during development and converted into design or control changes. The final system was therefore produced through a repeated design build test measure improve process rather than through a single successful trial.

The prototype is not presented as a finished commercial product. It is a validated engineering platform with a clear path toward plant specific calibration, longer seasonal trials, Wi-Fi and Supabase data logging, mobile monitoring, environmental sensing, improved hydraulic reliability, and larger multi zone configurations. Future connectivity should extend the system without changing its core autonomous principle: irrigation decisions should continue locally on the ESP32 so that basic watering does not depend on network or cloud availability.

In conclusion, the project achieved its central objective: a low cost three zone irrigation system was designed, manufactured, integrated, and experimentally evaluated, and one shared water source was successfully allocated according to independent plant zone demand. The final validation demonstrated selective routing, feedback based 1 second dosing, differentiated 2-8-8 pulse demand, approximately 315.0 mL of adaptive water use, and a 40.0% reduction relative to the defined 525.0 mL equal dose benchmark.

The final principle of the project is simple: measure each plant independently, route water only to the zone that requires it, deliver the smallest practical dose, and measure again before supplying more.

REFERENCES

[1] **Espressif Systems**, “ESP32 Series Datasheet,” technical documentation for ESP32 microcontrollers.

[2] **TowerPro**, “MG996R High Torque Digital Servo,” manufacturer technical specifications.

[3] **Autodesk**, “Fusion 360 Documentation,” computer aided design and parametric modelling documentation.

[4] **Arduino**, “Arduino Language Reference,” documentation used for embedded control program development.

[5] **Supabase**, “Supabase Documentation,” database and connected data platform documentation referenced for the proposed future monitoring architecture.

[6] Project experimental records, CAD models, firmware iterations, calibration notes, photographs, flow rate measurements, soil wetting measurements, and final prototype validation data generated during development of the Modular Smart Irrigation System, 2026.

THANK YOU

Modular Smart Irrigation System

Design, Development & Experimental Validation

Developed by: Melike Musdal

Project Field: Mechanical Engineering · Product Design · Embedded Systems · Precision Irrigation

Project Year: 2026

Location: Istanbul, Türkiye

PROJECT PRESENTATION VIDEO

Watch the Project Presentation: melikemusdal.com/projects/modular-irrigation/video

Thank you for taking the time to explore my project and the engineering process behind it. This project represents several weeks of designing, building, testing, measuring, troubleshooting, and improving a complete physical system from an initial engineering idea to a validated working prototype.

I look forward to continuing to develop this work and applying the same design, build, test approach to future engineering challenges.