A Solar-Powered Cyber-Physical System for Optimization of Aquaponics Cycles in Metropolitan Environments

BY

JACQUELINE KAVULA EBOSO KAMADI

166570

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Information Technology (MSc.IT) at Strathmore University

Strathmore University,

Nairobi. Kenya.

June, 2025.

Declaration and Approval

I declare that this work has not been previously submitted and approved for the award of a degree by this or any other University. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Student’s Name: JACQUELINE KAVULA EBOSO KAMADI

Signature Ekamadi Date: 21st May, 2025.

Approval

The thesis of JACQUELINE KAVULA EBOSO KAMADI was reviewed and approved for examination by the following:

DR. ALLAN OMONDI

Lecturer, School of Computing and Engineering Sciences.

Strathmore University.

DR. JULIUS BUTIME,

Dean, School of Computing & Engineering Sciences,

Strathmore University.

PROF. BERNARD SHIBWABO,

Director of Graduate Studies,

Strathmore University.

Abstract

Urbanization has intensified food security challenges, especially in densely populated and resource-constrained metropolitan areas where limited space and environmental degradation hinder traditional agriculture. Current urban farming approaches, including community gardens and small-scale farms, face several shortcomings, such as dependence on chemical fertilizers, use of polluted water sources, and high maintenance requirements. Moreover, existing aquaponics systems often lack automation and real-time monitoring capabilities, making them unsuitable for individuals with busy, non-agricultural lifestyles. To address this problem, this research proposes a solar-powered Cyber-Physical System (CPS) that integrates Internet of Things (IoT) technologies to optimize aquaponics cycles for urban food production. The methodology involves deploying a network of sensors to measure critical water quality parameters, including Total Dissolved Solids (TDS), pH, temperature, and water level float sensor. The system utilizes real-time automation to control water pump operations, ensuring optimal growing conditions for both aquatic life and plants. Furthermore, a K-Nearest Neighbors (KNN) algorithm is implemented for predictive analytics to forecast system health and support timely decision-making. Results from experimental testing demonstrate that the system effectively regulates water quality, automates key operations, and sustains power through solar energy, although efficiency may vary under cloudy conditions. The integration of KNN enabled accurate prediction of potential system failures, thereby improving proactive management and operational stability. In conclusion, the proposed CPS enhances the efficiency, sustainability, and reliability of urban aquaponics systems. It reduces reliance on non-renewable energy and harmful agricultural inputs, making it more accessible to urban residents with limited time and space. The implications of this research are significant: it contributes to the advancement of smart agriculture by demonstrating how CPS, powered by renewable energy and driven by intelligent automation, can offer a scalable and sustainable solution for improving food security, particularly in urban and resource-constrained environments.

Keywords: Urbanization, food security, aquaponics, cyber-physical system, solar energy, sustainable agriculture, monitoring sensors, automation, ecosystem health and scalable solutions.

Table of Contents

List of Figures

List of Equations

List of Tables

Abbreviations /Acronyms

ANN	Artificial Neural Networks
CPS	Cyber-Physical System
DFD	Data Flow Diagram
DWC	Deep-Water Culture
GST	General System Theory
HTTP/HTTPS	HyperText Transfer Protocol/Secure
IoT	Internet of Things
KNN	K-Nearest Neighbors
LQR	Linear Quadratic Regulator
MPC	Model Predictive Control
MQTT	Message Queuing Telemetry Transport
OCT	Optimal Control Theory
pH	Potential of Hydrogen
RL	Reinforcement Learning
SVM	Support Vector Machines
TDS	Total Dissolved Solids

Definition of Terms

Aquaponics	A sustainable farming method that integrates fish farming with plant cultivation in a closed-loop system where fish waste fertilizes plants, and plants clean the water for fish (Channa et al., 2024).
Automated Control	Technology that manages system parameters automatically to ensure efficiency without manual input (Kok et al., 2024).
Cyber-Physical System	A network where computers and physical devices interact in real-time, monitoring, controlling, and optimizing processes by using sensors to collect data and actuators to implement changes in the physical world (Januario et al., 2019).
Food Security	The condition where all individuals have consistent access to sufficient, safe, and nutritious food necessary for health and well-being (Djan, 2023).
IoT (Internet of Things)	A network of physical devices embedded with sensors, software, and other technologies that connect and exchange data over the internet, allowing real-time monitoring and control (Mouha, 2021).
LoRaWAN	A low-power, wide-area networking protocol designed for connecting IoT devices in a cost-effective manner, enabling long-range communication with minimal energy consumption, ideal for urban environments (Jabbar et al., 2024).
Nutrition	The process of consuming food to meet the body's dietary needs for maintaining health (*The State of Food Security and Nutrition in the World 2024*, 2024).
Optimization	The process of finding the best possible solution or outcome from a set of feasible options while satisfying given constraints (Bradley & Atkins, 2014).
Real-Time Monitoring	Continuous observation and analysis of system data to make immediate adjustments and maintain optimal conditions(Real Time Monitoring, 2024).
Solar-Powered System	A system that uses solar energy to power devices, making it an eco-friendly option for operating IoT components in the aquaponics system (Mosbah, 2024).
Sustainability	The practice of maintaining resources and minimizing environmental impact while producing food (Noor, 2024).
Urban Balcony Gardens	Small-scale gardens on urban balconies designed to grow food in limited space (Solanki & Pal, 2020).

Urbanization	The increasing shift of populations from rural to urban areas, leading to crowded cities with limited gardening space (Djan, 2023).

Acknowledgments

I would like to start by expressing my deepest gratitude to God, whose Grace has been sufficient throughout my academic journey. I extend my heartfelt appreciation to my supervisor, Dr Allan Omondi, his patience, guidance and unwavering support were instrumental in enabling me to conduct this research. I am also grateful to my immediate boss, Mr. Lewis Mocha, whose support, encouragement and flexibility in scheduling facilitated the successful completion of this course.

Additionally, I would like to acknowledge Strathmore University, the support and resources provided fostered an environment conducive to learning and research. Lastly, my sincere appreciation to my family for their endless love, understanding, and encouragement throughout this journey.

Dedication

I dedicate this work to my beloved mother, Judith Angeshi Kihugwa, whose love and sacrifices have been my unwavering support. To my late father, Edward Kamadi, who valued education, your legacy continues to inspire me every day. To my sister, Lilian Richa Kamadi, whose wisdom and encouragement have illuminated my path, and to my nephew Archie Kipruto Ayabei, your infectious, toothless smile keeps motivating me each day.

Chapter 1: Introduction

1.1 Background of the Study

Urbanization has introduced numerous challenges to food security and nutrition, significantly impacting the well-being of urban residents (Koscica, 2014). As of 2024, over 55% of the global population resides in urban areas, a figure expected to rise to 68% by 2050 (UN, 2018). This rapid urbanization has led to significant constraints on natural resources, particularly arable land, making it increasingly difficult for urban dwellers to access fresh, safe, and nutritious food. A key concern is the limited space available for traditional gardening, especially in densely populated areas where only about 2% of urban land is suitable for farming (Abu Hatab et al., 2019; Du Toit et al., 2022). This scarcity, coupled with the high costs of fresh produce, estimated to be 30% higher in urban areas compared to rural areas, and pollution affecting food quality, exacerbates the challenge. The absence of community garden plots and local farming infrastructure further limits opportunities for urban residents to grow their own food and improve their health (PlantedPerfection, 2023).

The fast-paced urban lifestyle also contributes to these difficulties. Over 60% of urban residents report having less than an hour per day for leisure activities, including gardening. This time constraint, combined with the prevalence of food deserts—areas where more than 20% of the population lives below the poverty line and has limited access to affordable and nutritious food—forces many to rely on commercially available produce, which may not meet desired quality and safety standards (Jayne et al., 2014). Fast food, a tempting alternative due to its convenience and affordability, accounts for up to 35% of meals consumed in urban households (Janssen et al., 2018). However, this comes at a significant cost, with fast food contributing to an increase in obesity rates over the past decade (Janssen et al., 2018).

Traditional farming methods, which require extensive land and resources, are not feasible in urban environments where space is limited, and contamination risks are high (Dijkgraaf, Goddek, & Keesman, 2019). The potential for contamination from unsafe agricultural practices, such as using sewage water, complicates urban food production (The Sewage Headache That Won’t Go Away, 2023). These issues underscore the urgent need for alternative, sustainable food production methods that are suited to the constraints of urban settings. While rural areas house 70% of the world's arable land, urban areas are rapidly expanding, consuming this valuable resource at an alarming rate. If current trends continue, urban sprawl could reduce global arable land by up to 1.8% by 2050, enough to feed 300 million people annually.

Satellite imagery as shown in *Figure 1.1* below, reveals cities gradual expansion into neighboring counties over the past decades, leading to a significant reduction in grassland and forested areas. This urban growth is driven by increasing demand for housing and amenities as the population rises.

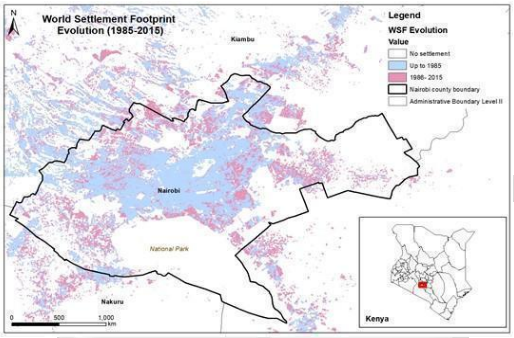


Figure 1.1: Effects of Urbanization on natural resources.

(Mbuthia et al., 2022)

Aquaponics offers a promising solution by integrating aquaculture (raising fish) with hydroponics (growing plants in water) in a closed-loop system (Pohshna et al., 2024). In an aquaponics system, fish waste provides essential nutrients for plant growth, while the plants help filter and clean the water, which is recirculated back to the fish. This symbiotic relationship creates an efficient food production system that requires 90% less water than traditional farming methods and uses 50% less space, making it particularly well-suited for urban environments where resources are scarce (Santosh & Shukla, 2024). However, setting up and maintaining an aquaponics system presents several challenges. For instance, finding the optimal balance between fish density and plant growth can increase yield by up to 40%, but requires precise monitoring and control. Factors such as the timing of water pumping, which can reduce water usage by 15%, and managing ammonia levels, which must remain below 2 mg/L to prevent fish toxicity, highlight the need for a sophisticated, optimized system that can automate and streamline these processes.

The potential of aquaponics systems can be further enhanced through the integration of advanced technologies such as the Internet of Things (IoT). IoT technology enables real-time monitoring and automated control of critical parameters such as pH, ammonia levels, and water temperature, ensuring that the system remains in optimal condition for both fish and plants (Channa et al., 2024). This technology could reduce labor costs by 25% and make aquaponics systems more accessible and manageable for urban residents with busy lifestyles, providing a practical solution for growing fresh, nutritious food at home (Dawa et al., 2022; Ibrahim et al., 2023).

This research seeks to explore how aquaponics can be effectively utilized in urban spaces to address the unique challenges of limited space and resource constraints. The integration of solar power, which could reduce operational costs by 20%, ensures that the system is sustainable and eco-friendly, aligning with broader environmental sustainability goals. By leveraging advanced technologies and sustainable practices, this research contributes to the development of innovative solutions for urban food production, ultimately aiming to improve food security and nutrition in metropolitan areas (New Paper, 2024).

1.2 Problem Statement

Urban areas struggle to access fresh, nutritious, and safe food due to limited gardening space and the demands of non-agricultural jobs, leading to poor nutrition and reliance on processed foods (Djan, 2023). High costs for quality produce, often sourced externally, further exacerbate food insecurity (Abdi et al., 2024). In rapidly urbanizing cities like Nairobi, space scarcity and lack of training in alternative food production worsen the situation (PBS Terra, 2023; Omondi et al., 2017). While initiatives such as community gardens and small-scale urban farms aim to improve food security, they face challenges, including reliance on harmful soil fertilizers and contaminated water sources (Diaz et al., 2018).

A comprehensive and scalable solution is essential, as existing systems face significant challenges, including the lack of automated controls, inefficient use of space, and high maintenance requirements. Simplified urban food production solutions are critical for key stakeholders, including urban residents, innovative farmers, NGOs, and local governments (Diaz et al., 2018). Aquaponics, which combines aquaculture and hydroponics in a closed-loop system, presents a viable alternative. This method eliminates the need for soil and reduces dependency on harmful fertilizers. In aquaponics systems, fish waste supplies essential nutrients for plant growth, while plants filter and clean the water for recirculation back to the fish. This symbiotic relationship offers an efficient food production model well-suited for space-constrained urban environments (Pohshna et al., 2024; Santosh & Shukla, 2024).

Addressing urban food security requires sustainable solutions that are easy to monitor and manage, catering to individuals with busy lifestyles and non-agricultural occupations.

1.3 Aim / Purpose

The aim of this research is to enhance sustainable urban food security by implementing a solar-powered cyber-physical aquaponics system that leverages automation, real-time monitoring, and renewable energy in order to optimize food production in resource-constrained urban environments.

1.4 Research Objectives

i. To review relevant technologies for designing a sustainable cyber-physical aquaponics system.
ii. To identify the system requirements for a cyber-physical aquaponics system in resource-constrained urban environments.
iii. To develop a cyber-physical aquaponics system optimized for sustainability in metropolitan areas.
iv. To test the cyber-physical aquaponics system.

1.5 Research Questions

i. What are the relevant technologies that can be utilized in designing a sustainable cyber-physical aquaponics system?
ii. How can a cyber-physical aquaponics system be tailored to meet the requirements of resource-constrained urban environments?
iii. How can a cyber-physical aquaponics system be developed to optimize sustainability in metropolitan areas?
iv. How can the effectiveness of the cyber-physical aquaponics system be tested and validated?

1.6 Justification

Undertaking this project is essential for addressing urban food security and sustainability challenges, with potential significant benefits for urban dwellers, property managers, and local governments (Obirikorang et al., 2021). For urban dwellers, the cyber-physical system offers a practical solution to the constraints of limited space and engagement in contemporary non-agricultural occupations, enabling the cultivation of fresh, nutritious food in small urban areas like balconies (Yuan et al., 2022). This ease of use is particularly valuable for individuals with demanding schedules, improving diet quality and reducing dependence on costly, potentially unsafe store-bought produce. Property managers can benefit from enhanced property value and appeal by integrating such modern, eco-friendly technologies, attracting environmentally conscious tenants and adding unique selling points to their properties. For local governments and NGOs, the project aligns with urban planning and sustainability goals, contributing to improved food security, reduced environmental impact, and enhanced community well-being (Ibrahim et al., 2023). The system's scalability and adaptability make it a valuable tool for advancing food security and sustainability initiatives, offering a model for future urban agriculture projects.

1.7 Scope

This project will focus on developing a solar-powered cyber-physical system (CPS) specifically designed to monitor and control key parameters of an aquaponics system, including pH levels, water temperature, and TDS levels. The system will be tailored for resource-constrained urban environments, such as balcony gardens in apartments, where space and natural resources are limited. By integrating real-time monitoring with automated control mechanisms, the solution will enhance the efficiency and sustainability of urban food production, providing a scalable and practical approach to address food security challenges in metropolitan areas.

i. System Design and Development
    a. Design and build a CPS for aquaponics.
    b. Integrate solar-powered sensors and actuators for real-time monitoring and control.
ii. Sensor Integration and Automation
    a. Develop an automated control system responsive to sensor readings.
    b. Ensure regulation of water quality parameters to maintain a balanced and sustainable ecosystem.
iii. Software Development
    a. Create a user-friendly interface for real-time data visualization, system alerts, and remote management.
    b. Enable users to monitor and adjust the system remotely via mobile or web-based platforms.

iv. Testing and Validation
    a. Evaluate the system’s functionality, focusing on the accuracy and reliability of sensor readings and automated responses.
    b. Test the efficiency of solar power integration and the system’s ability to maintain optimal water quality conditions.
    c. Validate the user interface for ease of use and effectiveness in providing actionable insights.

The research will not address long-term maintenance or sustainability beyond the initial setup and testing phases. It will also exclude considerations for scalability or adaptation to large-scale agricultural contexts. Advanced technological integrations and extensive user training are not within the scope. Additionally, the project will not focus on continuous adaptation to evolving technologies and urban gardening practices.

1.8 Limitations

The project may encounter certain challenges that could impact its outcomes. Space constraints could limit the applicability of the aquaponics system designed for balcony gardens to larger-scale or different urban agricultural contexts. This limitation could be addressed by optimizing the system design for small-scale setups while exploring adaptable solutions that might be modified for various environments. Resource constraints, including budget limitations and time restrictions, may affect the depth of prototype development and testing. This challenge could be managed through careful planning and resource management, with a focus on prioritizing essential features and conducting phased development to manage both costs and time effectively. Sensor data accuracy presents another potential limitation, as inaccurate data from faulty sensors could affect system performance. This issue could be mitigated by selecting high-quality sensors and implementing rigorous calibration and testing procedures to ensure accurate data collection and reliable system performance. By addressing these potential limitations, the research aims to develop a robust and adaptable solution for urban food production.

Chapter 2: Literature Review

2.1 Introduction

The growing global population, urbanization, and environmental challenges have amplified the need for sustainable food production solutions, particularly in urban areas. Urban environments often face significant barriers, such as limited space, inflated costs, and inadequate infrastructure, which make access to fresh, nutritious food difficult. As a result, urban food security has become a pressing issue. In response, sustainable solutions like aquaponics, combined with cyber-physical systems (CPS), offer a promising approach to addressing food insecurity in cities (Ibrahim et al., 2023). Aquaponics, which integrate aquaculture and hydroponics in a closed-loop system, presents an efficient and sustainable method of food production, especially in resource-constrained urban settings. However, optimizing these systems for maximum sustainability, efficiency, and scalability requires advanced technologies to monitor and manage the complex processes involved.

Cyber-physical systems (CPS) provide a key technological solution by enabling real-time data collection, automation, and system optimization through sensors, actuators, and computational algorithms ("Cyber Physical Systems," 2022). In the context of aquaponics, CPS can facilitate the monitoring and management of critical variables, such as pH, ammonia levels, temperature, and nutrient balance, improving system performance and food production. Moreover, integrating renewable energy sources like solar power into these systems enhances their sustainability, making them more suitable for urban applications. This literature review explores the current state of research on urban food security, aquaponics, and CPS, examining existing solutions, challenges, and areas for innovation, and aims to lay the groundwork for developing a solar-powered CPS that can contribute to more resilient and secure food systems in urban environments.

2.2 Theoretical Framework

The theoretical framework provides the foundational principles for understanding complex systems, such as aquaponics systems. This section explores key theories relevant to the research, including General Systems Theory (GST) with its subtopics of Systems Thinking, Holism and Reductionism, Interdependence, Open versus Closed Systems, Hierarchy, Feedback Loops, and Equifinality. Additionally, it covers Cyber-Physical Systems (CPS), addressing CPS architecture (physical, network, application layers), core concepts like real-time feedback loops and network performance modeling, and advanced techniques such as Linear Quadratic Regulators (LQR), Model Predictive Control (MPC), and Reinforcement Learning. These theories and CPS subtopics provide critical insights for the integration and optimization of complex systems.

2.2.1 General Systems Theory (GST)

GST, developed by Ludwig von Bertalanffy, is a broad framework for understanding complex systems across various domains. GST provides a lens for analyzing how different parts of a system interact and influence one another (Bashan & Kordova, 2021). By focusing on the relationships and interdependencies within a system, GST enables a comprehensive understanding of how systems function and adapt.

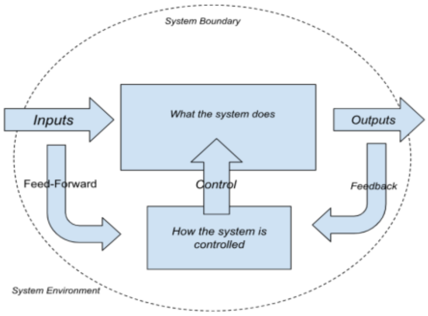


Figure 2.1: General Systems Theory Overview

(ScienceDirect Topics,2024).

The key concepts of General Systems Theory (GST) provide a foundational understanding of how complex systems operate. First, the holistic perspective emphasizes viewing systems as integrated wholes rather than isolated parts. In the context of an aquaponics system, this perspective focuses on the interactions between fish, plants, and water, rather than examining each component independently. Second, the concept of interdependence highlights how components within a system rely on each other for functionality. For instance, in aquaponics, fish waste serves as a vital nutrient source for plants, while the plants help maintain water quality for the fish, illustrating the critical relationships that contribute to the system’s overall health and efficiency. Lastly, the distinction between open and closed systems is essential; open systems exchange matter and energy with their environment, while closed systems operate in a self-contained manner. Aquaponics systems exemplify closed systems, where water and nutrients are recycled internally, minimizing waste and reliance on external inputs.

Together, these concepts illustrate the interconnectedness and complexity of systems, offering valuable insights for optimizing aquaponics practices.

2.2.1.1 Systems Thinking

Systems Thinking is an approach that focuses on understanding the relationships and interactions between system components. It builds on GST by emphasizing the interconnected nature of systems (Zhang, et al. 2020). One key concept within Systems Thinking is the distinction between holism and reductionism, it advocates for a holistic perspective that acknowledges the importance of analyzing the system as a whole rather than isolating individual components, as this can overlook emergent properties. For instance, in aquaponics, the benefits of nutrient cycling and waste reduction are fully realized only when the system is considered collectively. Additionally, Systems Thinking focuses on dynamic interactions, illustrating how changes in one part of the system can impact others. In an aquaponics system, altering fish feeding rates can significantly affect plant growth and water quality, exemplifying these interdependencies. Furthermore, Systems Thinking differentiates between open and closed systems as shown in *Figure 2.2*. Open systems interact with their environment by exchanging matter and energy, while closed systems, like aquaponics, operate within a self-contained environment that recycles resources internally.

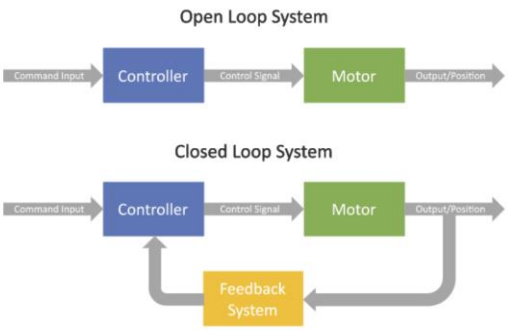


Figure 2.2: Open vs. Closed Systems

(Open vs. Closed Loop Picomotor Control, 2024)

2.2.1.2 Hierarchy

Hierarchy refers to the structured arrangement of system components in levels or tiers, with higher levels controlling and regulating lower levels.

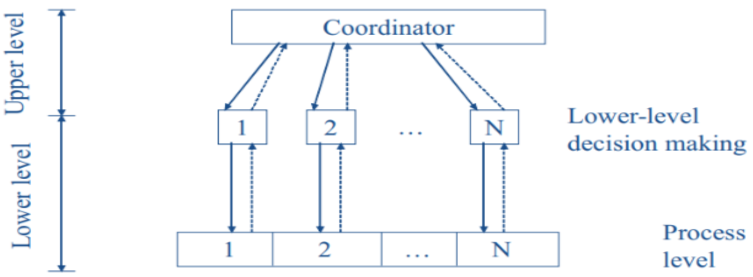


Figure 2.3: A 2 Level Hierarchy System Overview

(Hätönen, 2004)

In the context of aquaponics, this concept is exemplified by the organization of critical components, including fish tanks, grow beds, and filtration systems. Higher-level management as shown in *Figure 2.3* is responsible for coordinating these elements to achieve the overall objectives of the system. Recognizing the importance of hierarchy is essential for designing effective systems that manage resources efficiently and maintain balance. For instance, the filtration system in an aquaponics setup plays a crucial role in regulating water quality, which significantly impacts the health of both fish and plants. This understanding of hierarchy will inform the design and optimization strategies employed in this research.

2.2.1.3 Feedback Loops

Feedback Loops are mechanisms that allow systems to adjust and regulate based on their outputs. They can be either positive (amplifying changes) as shown in *Figure 2.5* or negative (counteracting changes) as shown in *Figure 2.4*. Positive feedback loops can lead to system instability if not carefully managed. For instance, an increase in plant growth may initially enhance nutrient uptake, however, if left unchecked, this growth could deplete nutrients faster than they can be replenished. Conversely, negative feedback loops play a crucial role in stabilizing the system by counteracting fluctuations. In the context of aquaponics, these loops help maintain water quality by adjusting nutrient levels and fish feeding rates in response to variations in plant growth. Understanding the dynamics of feedback loops is vital for optimizing the performance and sustainability of aquaponics systems.

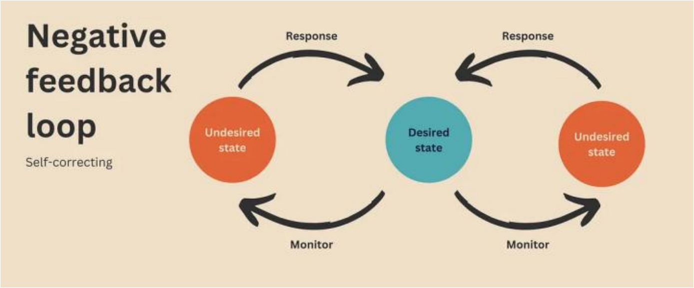


Figure 2.4: Negative Feedback Loop

(Brunckhorst, 2023)

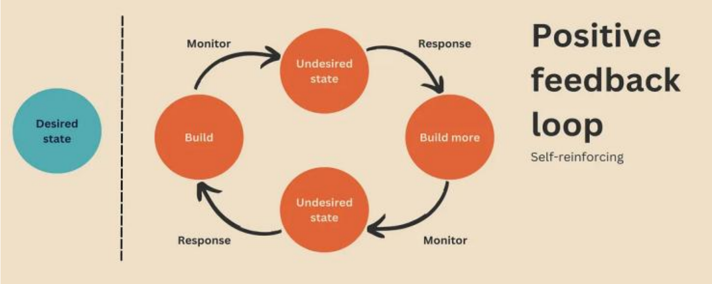


Figure 2.5: Positive Feedback Loop

(Brunckhorst, 2023)

2.2.1.4 Equifinality

Equifinality, as shown in *Figure 2.6*, suggests that different methods or pathways can achieve the same outcome. This principle allows for flexibility in system design and management. One significant aspect of equifinality is the notion of multiple pathways. In aquaponics, various configurations and practices can achieve successful results, demonstrating that different combinations of fish species and plant types can still yield effective outcomes regarding resource efficiency and overall productivity. Additionally, design flexibility is a crucial component of equifinality, allowing researchers and practitioners to explore diverse approaches and solutions tailored to specific needs and environmental conditions while still reaching similar objectives. This adaptability is essential for optimizing aquaponics systems in urban settings, particularly within resource-constrained environments.

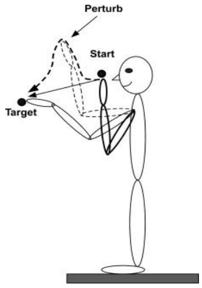


Figure 2.6: Equifinality Loop

(Latash, 2012)

2.2.1.5 System Dynamics

System Dynamics is a methodology for understanding and modeling complex systems through feedback loops, delays, and non-linear interactions. It helps analyze how changes in one part of a system can affect the whole system over time. A fundamental aspect of System Dynamics is the examination of feedback loops and delays as indicated in *Figure 2.7*. In aquaponics, for example, delays in nutrient replenishment can significantly impact both plant growth and overall system stability. Understanding these dynamics is crucial for effective system management. Another key component is modeling and simulation, which involves creating models to simulate system behavior and predict outcomes. By modeling aquaponics systems, researchers can evaluate how changes in fish feeding rates or water quality affect plant growth. These simulations enable the optimization of system parameters, ensuring the sustainability and efficiency of aquaponics operations.

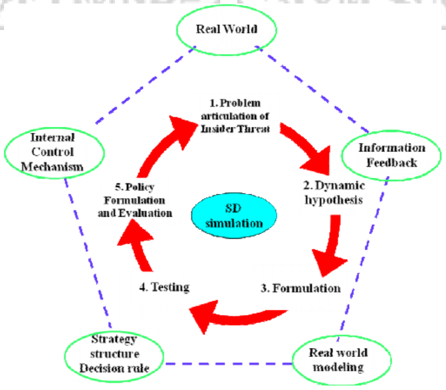


Figure 2.7: System Dynamics

(Yang & Wang, 2011)

2.2.1.6 Homeostasis

Homeostasis as illustrated in *Figure 2.8*, refers to the ability of a system to maintain stability and balance despite changes in the environment. It involves processes that regulate internal conditions to ensure optimal functioning. Key to achieving homeostasis are regulation mechanisms that maintain stable water quality, nutrient levels, and fish health within aquaponics systems. For instance, adjusting feeding rates and filtration processes can help stabilize these parameters, contributing to overall system health. Additionally, the system's adaptive responses play a crucial role; its ability to adjust to fluctuations in nutrient levels or temperature is essential for sustaining homeostasis. This adaptability ensures that the aquaponics system remains resilient, promoting long-term productivity and sustainability.

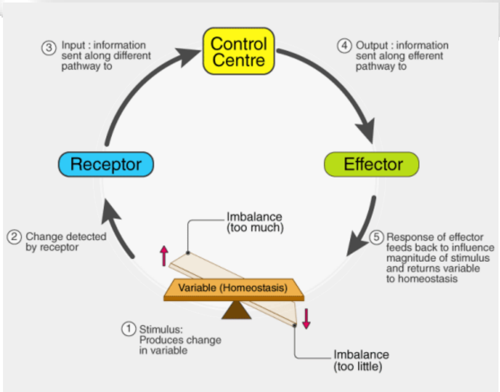


Figure 2.8: Homeostasis Mechanism Overview

(Choudhary, 2024)

2.2.2 *Cyber-Physical Systems (CPS)*

As shown in *Figure 2.9*, Cyber-Physical Systems (CPS) represent a sophisticated integration of computational algorithms, networking, and physical processes, allowing for seamless interaction between the physical and digital realms (García-Valls et al., 2018). In the context of aquaponics, where plants and fish coexist in a closed-loop environment, CPS enhances real-time monitoring and control, ensuring optimal conditions for both organisms (Javaid et al., 2023). This integration signifies a crucial technological advancement that improves automation, precision, and efficiency across various sectors (Song et al., 2023).

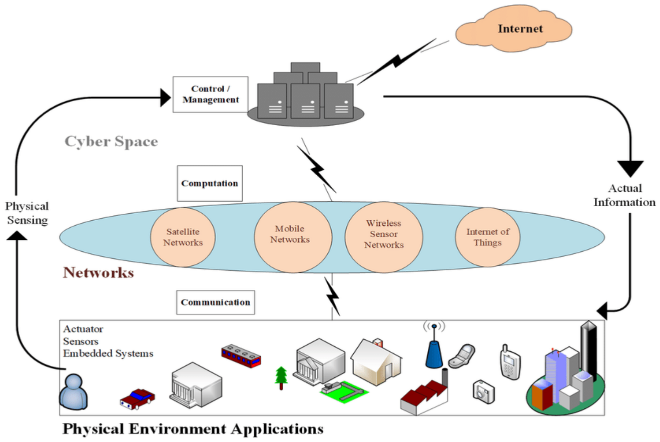


Figure 2.9: CPS Structure Overview

(Basir et al., 2019)

The evolution of CPS is driven by the convergence of embedded systems and control systems, further enhanced by networking capabilities that foster interconnected environments (Humaizi, 2024). CPS serves as a foundational component in industries such as manufacturing, healthcare, transportation, and energy, propelling innovations such as Industry 4.0, smart medical devices, autonomous vehicles, and smart grids (Abikoye et al., 2021).

2.2.2.1 Architecture of CPS

The architecture of Cyber-Physical Systems (CPS), as shown in *Figure 2.10*, generally consists of three primary layers: the physical layer, network layer, and application layer (Januario et al., 2019).

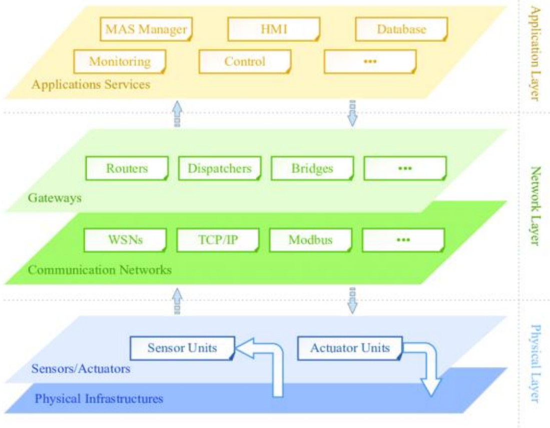


Figure 2.10: Architecture of a CPS

(Januario et al., 2019)

The Physical Layer includes the essential infrastructure, sensors, and actuators. In an aquaponics system, this layer is critical for monitoring vital parameters such as pH levels, TDS levels and water temperature. As shown in *Equation 2.1,* the rate of change in pH levels can be effectively modeled using a differential equation, allowing for real-time adjustments to maintain optimal conditions for both fish and plants.

$$\frac{d[pH]}{dt} = -k \cdot [NH_3] + inflow - outflow$$

Equation 2.1: Differential equation of a CPS physical layer

(Bai et al., 2021)

where [pH] denotes the pH level, $[NH_3]$ is the ammonia concentration, k represents the reaction rate constant, and inflow and outflow denote the rates of water entering and leaving the system (Bai et al., 2021).

The Network Layer of Cyber-Physical Systems (CPS) is essential for facilitating the transmission of data between sensors and control systems. This layer enables effective communication and coordination among various components of the system. Network performance can be modeled using queuing theory, for example in *Equation 2.2,* if sensor data packets arrive at a rate λ(lambda) and are serviced at a rate μ, the average waiting time W in the queue can be given by:

$$W = (\frac{\lambda}{\mu(\mu - \lambda)})$$

Equation 2.2: Modelling Network Performance

(Bai et al., 2021)

Equation 2.2 helps in understanding delays and optimizing data flow from sensors to the control systems.

The Application Layer of CPS aggregates distributed applications that perform functions such as monitoring, control, and user interaction. In aquaponics systems, this layer plays a crucial role by incorporating software solutions that enable real-time monitoring of critical parameters, such as water quality and nutrient levels. Additionally, it facilitates automated control processes based on sensor data, ensuring optimal conditions for both fish and plants.

By providing intuitive user interfaces, this layer enhances the usability and effectiveness of the system, allowing for timely decision-making and intervention.

2.2.2.2 Core Concepts in Cyber-Physical Systems

Embedded systems play a pivotal role in CPS by executing dedicated functions within a physical environment while maintaining real-time precision (Kang et al., 2012). These systems, as shown in *Figure 2.11*, process sensor data and execute control commands to effectively manage physical processes. The incorporation of real-time feedback loops is essential for adapting to dynamic conditions, ensuring optimal performance and responsiveness.

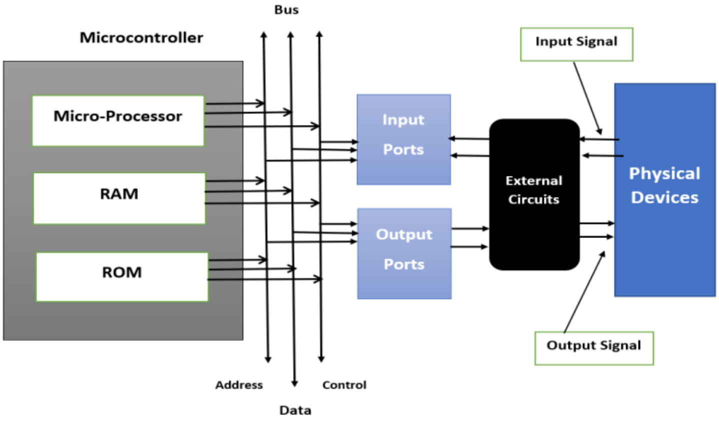


Figure 2.11: Embedded System Control Loop

(Difference between Cyber-Physical System(CPS) and Embedded System, 2023)

Equation 2.3 illustrates how the system output is adjusted based on control inputs and feedback. Networking technologies are crucial for facilitating the data exchange necessary for CPS functionality (Serôdio et al., 2024). Through real-time data processing and feedback loops, CPS can dynamically adjust to meet performance objectives (Humaizi, 2024).

$$Output = Control\ Input \cdot Gain + Feedback$$

Equation 2.3: Effect of feedback on output

(Storr, 2013)

i. *Applications and Importance of CPS*

Cyber-Physical Systems (CPS) are transformative across multiple industries. In manufacturing, they underpin Industry 4.0, enabling smart factories to automate and optimize production processes, thereby enhancing efficiency (Abikoye et al., 2021). In healthcare, CPS facilitates the creation of smart medical devices that improve patient outcomes through real-time monitoring and decision-making (Dey et al., 2018). Furthermore, autonomous vehicles rely on CPS to process sensor data and make real-time driving decisions, significantly enhancing safety and efficiency (Insights, 2023). In the energy sector, CPS supports smart grids by balancing supply and demand while integrating renewable energy sources (Insights, 2023). These diverse applications underscore CPS's vital role in enhancing efficiency, safety, and sustainability across various domains (Raisin et al., 2020).

ii. *Challenges and Future Directions in CPS*

Implementing Cyber-Physical Systems (CPS) presents several challenges, including the complexity of designing systems that operate reliably in real-time, which demands careful attention (Raisin et al., 2020). Security and privacy are also critical issues, as CPS often interact with networks vulnerable to cyber threats, necessitating robust protection (Raisin et al., 2020). Looking to the future, advancements are likely to integrate artificial intelligence and machine learning, enhancing adaptability and decision-making capabilities (Radanliev et al., 2021). Additionally, the growth of CPS in conjunction with the Internet of Things (IoT) will result in more interconnected systems, while innovations in sensor technology will further refine CPS capabilities (Abikoye et al., 2021).

2.2.3 *Integration of Optimal Control Theory (OCT) with CPS*

Optimal Control Theory (OCT) offers a systematic approach to optimizing control strategies within dynamic systems, enhancing system performance through advanced mathematical models and optimization techniques (Bradley & Atkins, 2014). The fundamental steps in OCT begin with Mathematical Modeling, where state-space representation is employed to model system dynamics (Wilson & Jardon, 2024.). This representation, as mathematically expressed in *Equation 2.4*, captures the relationships between system inputs, states, and outputs, facilitating the development of control strategies that ensure optimal performance across various conditions.

$$x^{\cdot}(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t)$$

Equation 2.4: State-Space Representation

(Miquel, 2022)

where:

x(t) represents the state vector, capturing the system's internal states.

u(t) is the control input, which influences the system's behavior.

y(t) denotes the system's output, reflecting the system's response.

A, B, C, and D are matrices that describe the system dynamics and control relationships.

Next, OCT focuses on Identifying Control Variables and Constraints, defining these elements to ensure efficient system operation within practical limits. Constraints may encompass physical limitations, such as the maximum or minimum allowable control inputs, as well as operational restrictions, including safety or regulatory compliance (Gamkrelidze, 2013). The process of optimization problem formulation involves creating objective functions to guide optimization. These functions such as the cost function in *Equation 2.5,* aim to balance multiple factors, such as performance and resource usage, to achieve the desired system behavior (Gamkrelidze, 2013).

$$J = \int_0^T \quad (x^T Q^x + u^T Ru)dt$$

Equation 2.5: Cost Function

(Gamkrelidze, 2013)

where: J represents the cost function, which quantifies the performance of the control strategy. Q and R are weighting matrices that determine the relative importance of state regulation and control effort. T is the time horizon over which the optimization is evaluated.

This cost function is instrumental in achieving an optimal balance between system efficiency and resource expenditure.

Finally, OCT integrates various advanced control strategies to further optimize system performance, including:

1. Linear Quadratic Regulator (LQR) / Linear Quadratic Gaussian (LQG) control
2. Model Predictive Control
3. Reinforcement Learning
4. Extremum Seeking Control
5. H-Infinity synthesis

These strategies contribute to enhanced adaptability and effectiveness in the management of Cyber-Physical Systems, ensuring robust and responsive control under diverse operational conditions.

2.2.3.1 Linear Quadratic Regulators (LQR)

LQR is a feedback control law designed to minimize a quadratic cost function, balancing system state regulation and control effort (Hespanha, 2005). LQR is a key method within OCT that determines the optimal state for a system through a feedback control law. This method is widely used because it provides a systematic way to design controllers that minimize a defined cost function (Hespanha, 2005).

$$u(t) = -Kx(t)$$

Equation 2.6: LQR Control Strategy

(Rodrigues Da Silva et al., 2017)

where: K is the gain matrix determined from the Riccati equation.

In *Equation 2.6,* the LQR controller adjusts the control input $u(t)$ based on the state vector $x(t)$ to minimize the cost function (*Equation 2.5*). This function evaluates the trade-off between system state regulation and control effort.

A Linear Quadratic Gaussian (LQG) controller extends LQR by incorporating a Kalman filter to estimate system states when direct measurements are unavailable. The LQG controller integrates state estimation with the LQR control law, improving its applicability in scenarios where some system states are not directly measurable (*Linear-Quadratic-Gaussian (LQG) Design - MATLAB & Simulink*, 2024). The weighting factors Q, R, and N shown in *Figure*

2.13, are set based on performance specifications to balance between effective state regulation and control costs

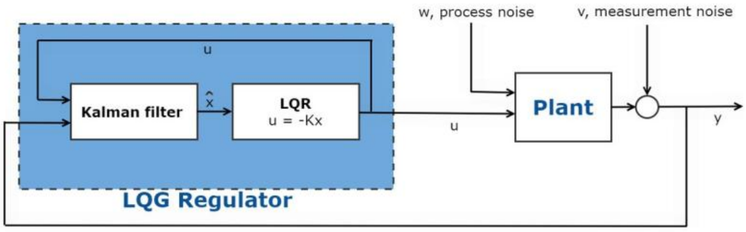


Figure 2.12: LQG Regulator Overview

(Rodrigues Da Silva et al., 2017)

2.2.3.2 Model Predictive Control (MPC)

MPC Controller, as shown in *Figure 2.13*, minimizes a cost function (*Equation 2.5*) in multi-input multi-output systems by predicting future outputs and solving an optimization problem to adjust control variables (Sotelo et al., 2020).

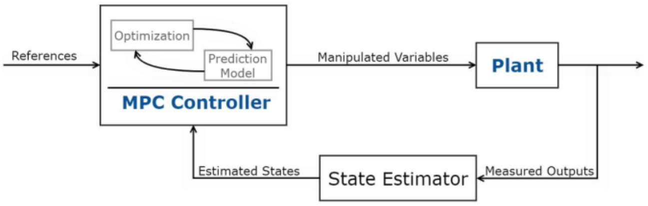


Figure 2.13: Model Predictive Control Overview

(FİGES, n.d.)

2.2.3.3 Reinforcement Learning

This is a machine learning approach where an agent learns optimal actions through trial and error, aiming to maximize cumulative rewards (*Reinforcement Learning*, 2024). This approach enables adaptive control strategies by allowing the system to continuously improve its decision-making process based on real-time feedback from its environment. The agent explores various actions and learns from the consequences, adjusting its strategy to enhance overall system performance and efficiency. This method is especially valuable in complex and dynamic systems where traditional control methods may not be feasible or effective. *Figure 2.14* illustrates reinforcement learning in action.

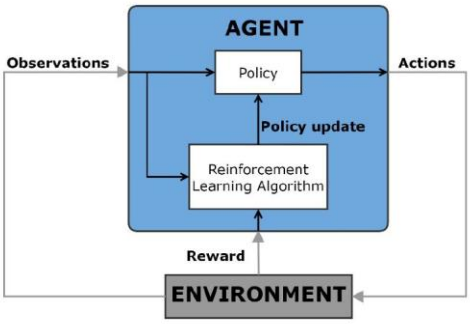


Figure 2.14: Reinforcement Learning

(Amolong, 2024)

2.2.3.4 Extremum Seeking Control

Extremum Seeking Control, illustrated in *Figure 2.15*, is a model-free technique that adapts control parameters in real-time to maximize an objective function, illustrates suitable for systems with slowly changing parameters (*Extremum Seeking Control - MATLAB & Simulink*, n.d.). the technique.

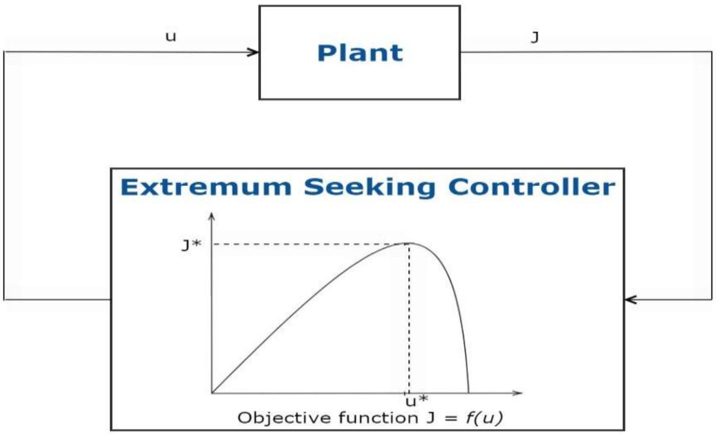


Figure 2.15: Extremum Seeking Control Overview

(FİGES, n.d.)

2.2.3.5 H-Infinity Synthesis

This is a robust control technique designed to optimize performance by minimizing the closed-loop gain, useful in multivariable control systems requiring robust stability and performance *(What Is Optimal Control?, n.d)*.

Table 2.1 below compares the optimal control methods described above.

Table 2.1: Comparison between the optimal control methods

Optimal control method	Is optimization carried out at runtime? (Yes/No)	How does the optimization process work for this optimal control process?	Can it handle hard constraints?* (Yes/No)	Does it use Model-based technique? (Yes/No)	What is the throughput? (High/Low)
LQR/LQG	No	Uses closed-form solution that works with known linear time-invariant systems	No	Yes	High
MPC	Implicit MPC (Yes)	Using a prediction model, solves an online optimization problem to compute the optimal control actions	Yes	Yes	Low (nonlinear MPC), High (linear MPC)
	Explicit MPC (No)	Solution to the optimization problem for computing optimal control actions is calculated offline	Yes	Yes	High
Reinforcement Learning	Yes**	Learns optimal behavior for a task to maximize a reward metric	No***	Depends on training algorithm	Low (with training), Medium-High (during inference)
Extremum Seeking Control	Yes	Perturbs and adapts control parameters to maximize an objective function	No	No	High
H-infinity synthesis	No	Automatically computes a controller that minimizes normalized closed-loop gain	No	Yes	High

The asterisk (*) on the column indicates flexibility in handling constraints. Reinforcement Learning (RL) has asterisks because it involves real-time optimization during operation, adjusting strategies continuously based on ongoing feedback. The extra asterisk (*) highlights that RL’s ability to handle constraints depends on its training algorithm and may vary during inference, unlike methods with fixed, precomputed solutions.

2.2.4 Graphical Summary of the Theoretical Framework

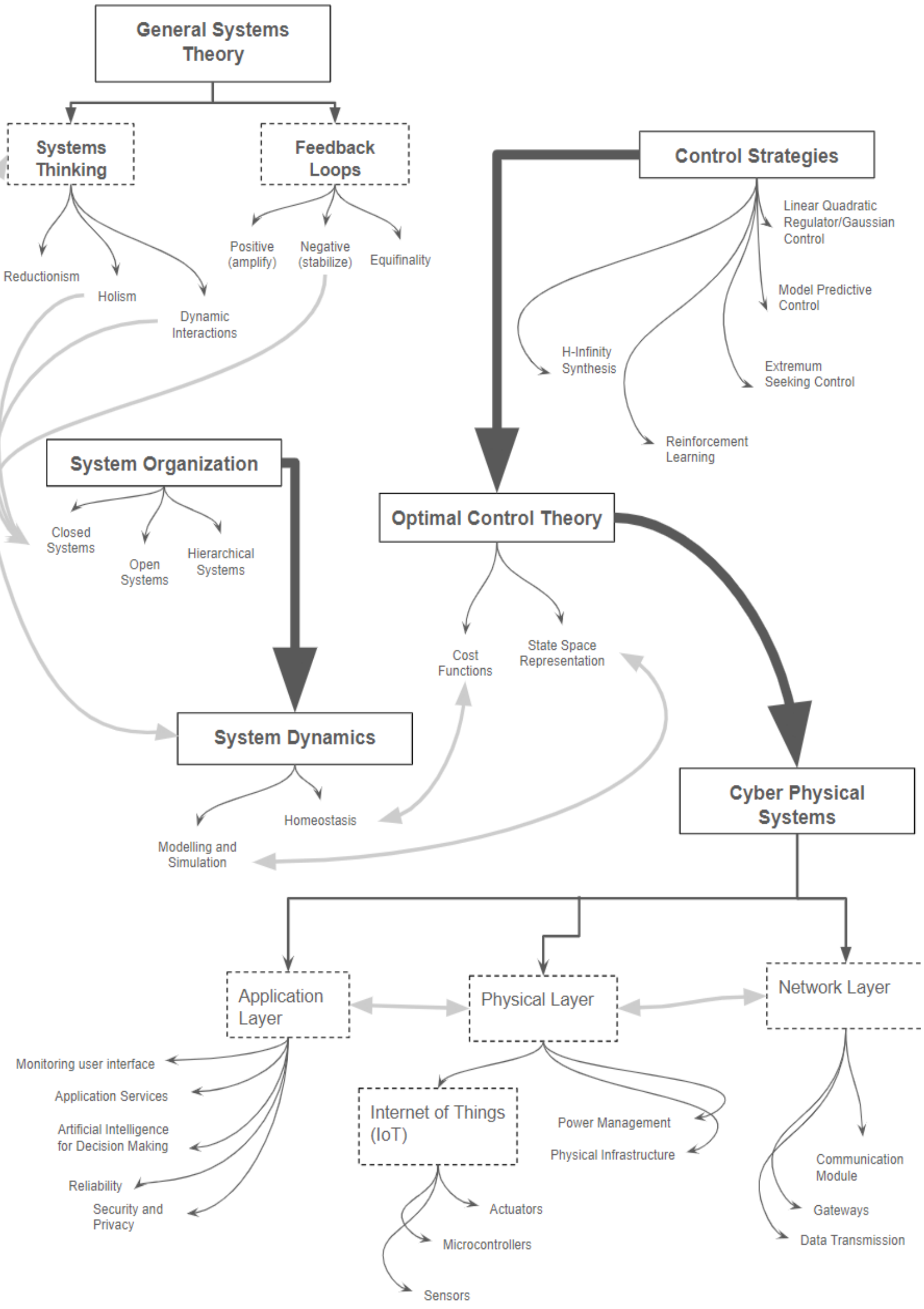


Figure 2.16: Graphical Summary of the Theoretical Framework

In the theoretical framework for this research, the integration of Cyber-Physical Systems (CPS) and General Systems Theory (GST) forms the foundation for optimizing aquaponics in urban environments as shown in *Figure 2.16*. CPS components include IoT devices such as sensors, actuators, microcontrollers, and communication modules, which enable real-time monitoring and control of the aquaponics system. Key elements such as power management through solar energy and safety mechanisms ensure efficient and secure system operation. GST provides a holistic view by emphasizing the interrelationships and hierarchy within the system, where subsystems like aquaculture and hydroponics interact with each other and the broader urban food production network. The framework considers the system's open and closed nature, focusing on energy and nutrient exchanges, while also addressing feedback loops and interdependencies between components. Optimization techniques such as Linear Quadratic Regulator (LQR), Model Predictive Control (MPC), and Reinforcement Learning (RL) are employed to enhance performance, efficiency, and sustainability, aligning with the principles of equifinality and adaptability to urban constraints. This approach underscores the dynamic interplay between physical and cyber components, aiming for an optimized, self-sustaining aquaponics system that contributes to environmental sustainability and efficient resource management.

2.3 Empirical Framework

2.3.1 Major Breakthroughs

i) Automation in Aquaponics Systems

Recent advancements in automated control systems leverage real-time sensor data to manage nutrient and water levels in aquaponics, significantly reducing manual intervention and optimizing resource use (Reidel, 2023). For instance, AI-driven algorithms can autonomously adjust water flow and aeration based on real-time environmental conditions, promoting optimal growth for both fish and plants. Channa et al., (2024) expounded on how AI algorithms can improve resource efficiency, showcasing the potential of automation in reducing labor costs and improving aquaponics systems performance. Paul et al. (2024) found that integrating automated controls resulted in an increase in crop yield compared to traditional methods, emphasizing the advantages of real-time adjustments. Murdan & Joyram, (2021) presented a hybrid system combining automation and user feedback, which allowed for greater flexibility in operational strategies, highlighting the evolving nature of automated aquaponics.

ii) Solar Energy Integration

The integration of solar power into aquaponics systems has become a pivotal innovation, especially in resource-constrained environments. Recent breakthroughs in energy storage technologies and enhancements in solar panel efficiency enable reliable and sustainable operation. Systems designed to harness solar energy effectively reduce operational costs and reliance on non-renewable energy sources, making aquaponics more accessible and environmentally friendly. *Getricity* (2024) reported that systems utilizing advanced solar panels achieved lower operational costs, demonstrating significant economic benefits. Parajuli et al. (2023) highlighted a case study where solar-powered aquaponics-maintained system functionality during power outages, illustrating resilience in energy management. The Solar Learning Center (2024) explored the environmental impacts, showing that solar integration reduced carbon footprints, underscoring the sustainability benefits of solar energy.

iii) IoT Technologies for Monitoring and Control

The application of Internet of Things (IoT) technologies has revolutionized the monitoring and control of aquaponics systems. Cloud-based platforms enable continuous data analysis and real-time monitoring, allowing for remote adjustments based on ongoing environmental assessments. This integration supports improved decision-making and enhances the sustainability of urban aquaponics systems, where space and resources may be limited. Dutta et al. (2018) showcased an IoT-enabled system that reduced water usage by 90% through precise monitoring and automated adjustments, emphasizing the efficiency gains from IoT integration. Channa et al. (2024) compared various IoT platforms, finding that those with comprehensive data analytics capabilities improved system performance. Reidel (2023) conducted a study that demonstrated the long-term benefits of IoT systems in urban aquaponics, leading to enhanced crop health and yield consistency.

2.3.2 Key Algorithms and Technologies Used

The algorithms and technologies employed in smart aquaponics systems are designed to monitor and control various parameters, ensuring optimal growth conditions for both fish and plants.

i) Monitoring Algorithms

IoT technology is central to modern aquaponics systems, enabling remote monitoring of environmental conditions through sensors that track pH levels, temperature, nutrient concentrations, and water quality. Alselek et al. (2022) emphasised the effectiveness of pH and temperature sensors, reporting improved maintenance of optimal conditions for both fish and plants. Alkhayyal & Mostafa, (2024) highlighted that advanced IoT technologies, such as LoRaWAN, enhance data transmission efficiency in urban environments, critical for real-time monitoring.

ii) Control Algorithms

Automated control algorithms are vital for managing pumps, aerators, and lighting systems, responding dynamically to real-time sensor data. Maulini et al. (2022) demonstrated an Arduino-based system that adjusts water flow and aeration in response to changing water quality parameters, significantly reducing manual intervention and improving operational efficiency. In contrast, Ibrahim et al. (2023) noted that while automation enhances efficiency, the initial setup complexity and need for skilled personnel for calibration can be barriers to widespread adoption.

iii) Energy Management

Algorithms are utilized to maximize the efficiency of solar energy capture and distribution in aquaponics systems. Al-Ali et al. (2019) described how systems can optimize power distribution from solar panels, ensuring continuous operation during daylight. This integration is especially beneficial in resource-constrained environments. However, Karimanzira & Rauschenbach (2018) cautioned that reliance on solar energy can lead to challenges during periods of low sunlight, suggesting that hybrid energy solutions may be necessary for consistent functionality.

iv) Data Analysis and Feedback Loops

Feedback control systems analyze sensor data to enable real-time adjustments, maintaining balance in nutrient levels and water quality. Yau et al. (2024) showed that implementing feedback control systems significantly enhances system responsiveness, enabling maintenance of nutrient levels within optimal thresholds through automated adjustments. Conversely, Kok et al., (2024) pointed out that effective feedback loops require sophisticated algorithms capable of processing data accurately and quickly, emphasizing the importance of high-quality sensors.

Table 2.2: Key Algorithms and Technologies

Aspect	Author	Description of the Study	Merit	Demerit
Monitoring Algorithms	Alselek et al. (2022)	Studied IoT integration with pH and temperature sensors to improve environmental monitoring in aquaponics.	Improved system monitoring for optimal plant and fish growth.	Initial setup complexity and need for skilled personnel.
Monitoring Algorithms	Alkhayyal & Mostafa (2024)	Demonstrated LoRaWAN's ability to enhance real-time data transmission for aquaponics in urban settings.	Efficient real-time monitoring in urban environments.	Limited bandwidth for more complex systems.
Control Algorithms	Maulini et al. (2022)	Implemented an Arduino-based automated system to manage water flow and aeration in aquaponics.	Reduced manual work with real-time adjustments.	Requires technical expertise for setup and calibration.
Control Algorithms	Ibrahim et al., (2023)	Explored the barriers of automation, emphasizing its complexity and the need for skilled personnel.	Automation enhances operational efficiency.	Setup complexity limits broader adoption.
Energy Management	Al-Ali et al., (2019)	Studied solar energy optimization for aquaponics, focusing on power distribution during daylight.	Efficient solar power management in resource-constrained areas.	Reliance on solar alone poses challenges during low sunlight.
Energy Management	Karimanzira & Rauschenbach (2018)	Explored hybrid energy systems to overcome solar power limitations, ensuring consistent operation.	Hybrid systems improve reliability in low-light conditions.	Hybrid systems increase complexity and cost.
Data Analysis and Feedback	Yau et al. (2024)	Demonstrated feedback control systems that use sensor data for real-time nutrient and water quality adjustments.	Real-time adjustments improve system stability and reduce manual intervention.	Requires sophisticated algorithms and high-quality sensors.
Data Analysis and Feedback	Kok et al. (2024)	Highlighted the need for advanced sensors and algorithms for effective feedback loops in aquaponics.	Maintains optimal nutrient and water conditions.	High-quality sensors and algorithms increase system costing the importance of high-quality sensors.

Table 2.2 presents a summary of key algorithms and technologies used in various studies, highlighting their respective strengths and limitations.

2.3.3 Current Trends

Recent developments in aquaponics and related systems have led to innovative solutions aimed at enhancing efficiency, sustainability, and user experience.

i) Advancements in IoT and Automation

Kombo et al. (2021) and Jabbar et al. (2024) demonstrated that IoT-enabled sensors, particularly those utilizing LoRaWAN technology, significantly improve the management of aquaponics systems. Their research showed that real-time monitoring of pH, ammonia levels, and other critical parameters facilitates more responsive and efficient system adjustments. LoRaWAN was noted for its cost-effectiveness and suitability in urban environments with limited infrastructure. In contrast, Robles-Enciso et al., (2023) contended that 5G technology could surpass LoRaWAN by providing higher bandwidth and faster data transmission. They observed that while LoRaWAN may suffice for certain settings, 5G offers a more robust solution for high-density urban areas where data volume and speed are crucial. Their findings indicate that 5G can accommodate more complex applications, though it might be excessive for simpler systems. Jacob (2023) supported Kombo et al. (2021) and Jabbar et al. (2024). conclusion by emphasizing the energy efficiency of LoRaWAN, especially in solar-powered systems.

ii) Sustainable Energy Solutions

Mosbah, (2024) explored the utilization of solar energy to power aquaponics systems, highlighting its benefits for off-grid areas and urban environments facing high energy costs. The solution illustrated that solar panels provide a sustainable power source, reducing operational expenses and dependence on non-renewable energy. Conversely, Hassan et al. (2023) raised concerns regarding solar power intermittency, suggesting that battery storage systems or hybrid solutions may be necessary for consistent operation during low sunlight periods. They proposed integrating solar power with grid electricity or other renewable sources to enhance reliability. VR (2023) agreed on the potential of solar power but stressed the need for optimal system design to maximize energy efficiency. He recommended incorporating advanced battery storage and smart grid technologies to tackle the intermittency issues noted by Hassan et al (2023). His findings suggest that a well-designed solar-powered system can be both effective and reliable when paired with appropriate energy management solutions.

Table 2.3 below provides a summary of current trends described above.

Table 2.3: Current Trends Table Summary

Aspects	Author	Description	Merit	Demerit
Advancements in IoT and Automation	Kombo et al. (2021) & Jabbar et al. (2024)	IoT-enabled sensors using LoRaWAN technology for real-time monitoring of aquaponics systems, improving management efficiency.	Cost-effective and suitable for urban areas with limited infrastructure.	May not accommodate complex, high-density urban environments.
Advancements in IoT and Automation	Robles-Enciso et al. (2023)	5G technology provides higher bandwidth and faster data transmission for aquaponics systems compared to LoRaWAN.	Robust solution for high-density urban areas with larger data volume requirements.	Excessive for simpler systems.
Advancements in IoT and Automation	Jacob (2023)	Supports the use of LoRaWAN, emphasizing its energy efficiency, especially in solar-powered systems.	Energy-efficient, particularly in conjunction with solar energy.	N/A
Sustainable Energy Solutions	Mosbah (2024)	Solar energy utilized to power aquaponics systems, reducing operational costs and reliance on non-renewable energy.	Sustainable power source, ideal for off-grid areas and reducing energy costs.	Solar power intermittency poses operational challenges.
Sustainable Energy Solutions	Hassan et al. (2023)	Raised concerns about solar power intermittency and suggested hybrid solutions or battery storage for reliable operation.	Integration of solar power with grid electricity or other renewables enhances reliability.	Intermittency issues require additional infrastructure, like battery storage or hybrid solutions.
Sustainable Energy Solutions	VR (2023)	Stressed the need for optimal system design, incorporating battery storage and smart grid technologies for solar-powered systems.	Well-designed solar systems, paired with energy management solutions, can be both effective and reliable.	Solar system design complexities need advanced technologies, adding to overall cost and infrastructure demands.

2.3.4 Related Applications and Tools

2.3.4.1 Comparative Analysis of Aquaponics Systems

In this section, we explore three prominent smart aquaponics solutions, Osiligi Farm, Onua World Smart Aquaponics Indoor Garden, and Hydroponics Africa, analyzing their merits and demerits in relation to this research. This comparison provides an empirical foundation for understanding existing solutions while identifying key areas of improvement and innovation that the thesis addresses.

i) Osiligi Farm Aquaponics System

Osiligi Farm utilises Upande sensors as shown in *Figure 2.17*, to monitor critical parameters such as water quality (pH, temperature, and electrical conductivity), and the levels of nutrients in hydroponic and aquaponic environments. Data collected by these sensors is displayed in real-time on a mobile dashboard, accessible by farm managers for informed decision-making (Netherlands Enterprise Agency, 2020).

Figure 2.17: Upande Sensors

(Netherlands Enterprise Agency, 2020).

The real-time monitoring capabilities of the Osiligi Farm aquaponics system provide significant advantages. Users can continuously track essential parameters like water and nutrient levels, pH, and environmental conditions, offering actionable insights for timely interventions. Additionally, the integration of the monitoring system with a mobile application enhances accessibility, enabling farm managers to conveniently view and manage the system's status from any location. However, despite these benefits, the system lacks automation for managing environmental factors, necessitating manual intervention from the farm manager to make adjustments. This reliance on manual adjustments can be time-consuming and limits the overall efficiency of the system.

In comparison to the existing systems, my research will incorporate aspects of real-time monitoring using environmental sensors similar to those employed by Osiligi Farm. My approach goes further by including additional features such as automation. Instead of requiring manual adjustments, my system will automatically regulate conditions based on sensor data, significantly reducing the need for human intervention. Furthermore, my system is powered by solar energy, enhancing sustainability and lowering operational costs, thus distinguishing it from existing aquaponics systems.

ii) Onua World - Smart Aquaponics Indoor Garden

The Onua World Smart Aquaponics Indoor Garden offers a mobile application for managing aquaponics gardens, providing real-time data on water levels, temperature, and pH levels (Laforest, 2023). The user-friendly interface ensures accessibility, allowing users to easily monitor their garden's health and make timely decisions (Laforest, 2023).

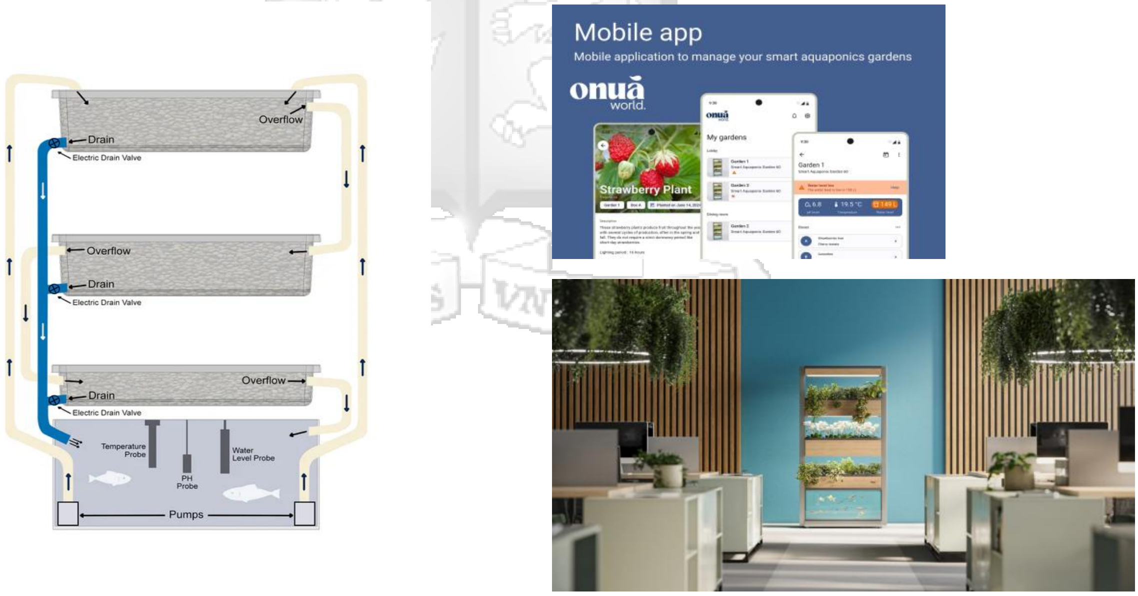


Figure 2.18: Onua's World

(Laforest, 2023).

Figure 2.18 shows the inner structure, the mobile app and the actual product of Onua's World. The system's mobile application enables real-time monitoring of essential aquaponics parameters, including water level, pH, and temperature, providing users with critical insights into their system's performance. Designed specifically for urban indoor environments, the easy-to-use interface caters to individuals with limited technical expertise, ensuring accessibility for a broader audience. Additionally, the compact setup enhances the visual appeal of the system, making it an attractive option for end users who prioritize aesthetics in their indoor spaces.

However, one limitation of the system is the absence of automation, which requires users to manually intervene based on the monitoring data, thereby increasing the burden of management. Furthermore, the system does not integrate with sustainable energy solutions, such as solar power, which could enhance its environmental and cost efficiency. This research aims to borrow the valuable concept of real-time monitoring and integrate it into the proposed system. However, it extends beyond mere monitoring by incorporating automation, allowing the system to automatically adjust components like water pumping based on sensor data. Additionally, the proposed system features a solar-powered design, enhancing sustainability and energy efficiency, which is particularly beneficial in urban environments where sustainability is a key consideration.

iii) HydroponicsAfrica

HydroponicsAfrica specializes in low-cost hydroponic and aquaponics systems that aim to address food security in urban areas (Hydroponics Africa, n.d.). Their solutions focus on creating accessible, affordable hydroponic farming setups for smallholder and urban farmers. However, the solutions prioritize manual operation over automation, relying on user input to adjust nutrient and water levels. *Figure 2.19* shows their aquaponics setup.

Figure 2.19: Hydroponics Africa Showcase

(Hydroponics Africa, n.d.).

The system’s affordability and low-cost design make it accessible to urban farmers with limited resources, addressing food security and supporting the scaling of urban agriculture. This focus aligns with broader initiatives to enhance urban farming. However, its reliance on manual interventions due to the lack of real-time monitoring and automation limits efficiency. Additionally, the absence of modern IoT-based monitoring systems hinders optimization of farming operations. In comparison, this research will adopt the low-cost approach to ensure accessibility for resource-constrained urban environments while integrating advanced IoT technologies for automated control and real-time monitoring. This proposed system is also solar-powered, enhancing sustainability and energy efficiency in urban settings.

Table 2.4: Summary of Empirical Framework

System	Merits	Demerits	Aspects to Borrow	Additional Aspects in Thesis
Osiligi Farm Aquaponics System	- Real-time monitoring of water quality, nutrient levels, pH, and temperature. - Integration with an app for accessibility.	- Lacks automation; requires manual intervention for managing environmental conditions.	- Real-time monitoring with environmental sensors.	- Incorporates automation where conditions are adjusted automatically based on sensor data. - Solar-powered system enhances sustainability and reduces operational costs.
Onua World Smart Aquaponics Indoor Garden	- Mobile app for real-time monitoring of water levels, temperature, and pH. - User-friendly interface. - Compact and aesthetically appealing design.	- No automation; users must intervene manually based on monitoring data. - Lacks integration with sustainable energy like solar power.	- Real-time monitoring concept.	- Incorporates automation to adjust the system based on sensor data. - Solar-powered design for energy efficiency in urban environments.
Hydroponics Africa	- Low-cost and affordable solution. - Focuses on addressing food security for urban farmers.	- Relies on manual operations for adjusting nutrient and water levels. - Lacks IoT-based monitoring systems.	- Low-cost focus for accessibility in resource-constrained urban environments.	- Integrates IoT technologies for automated control and real-time monitoring. - Solar-powered system addresses sustainability and operational efficiency

As shown in *Table 2.4*, the empirical comparison of existing solutions like Osiligi Farm, Onua World, and HydroponicsAfrica reveals significant opportunities for improvement, especially regarding automation and sustainability. While each system offers valuable input, whether in real-time monitoring, mobile accessibility, or affordability, my thesis introduces innovations such as automation, solar power, and IoT-driven management. These features ensure a more efficient, scalable, and environmentally conscious solution for aquaponics systems in urban environments. My setup will integrate key monitoring and control features from these systems while maintaining a balance between simplicity and efficiency, ensuring it remains practical for urban environments.

2.4 Existing Technologies and Algorithms

2.4.1 Sensor Technologies

Sensor technologies are fundamental for effective monitoring and control in aquaponics systems(Yanes et al., 2020). They provide critical data on various parameters, enabling the system to maintain optimal conditions for both plant and fish health. Accurate and reliable sensors ensure that water quality, environmental conditions, and system performance are continually assessed (Yanes et al., 2020).

i) Analog pH Sensor

Figure 2.20: Analog pH Sensor

(Analog pH Sensor / Meter Kit, 2021)

The Analog pH Sensor, as shown in *Figure 2.20*, plays a crucial role in measuring the pH level of solutions within an aquaponics system, ensuring the right balance of acidity and alkalinity (Aquaponics, 2024). This sensor outputs a voltage that corresponds to the pH level, allowing it to be read by an analog input on a microcontroller. For effective integration, the sensor connects to an analog input pin on the microcontroller and requires calibration to ensure accurate readings. The pH value is then derived from the voltage output, enabling precise monitoring and management of the system's pH levels, which is essential for optimal aquaponics performance.

ii) DFRobot Gravity Analog TDS Sensor Module

Figure 2.21: TDS Sensor

(DFRobot Gravity Analog TDS Sensor Module, 2021)

TDS sensor, as shown in *Figure 2.21,* is a crucial component for measuring the concentration of dissolved solids in water, providing insights into its purity and quality. This measurement is particularly valuable for monitoring nutrient levels in aquaponics systems (Conductivity TDS Meter & Sensor - Apure, 2021). The TDS sensor interfaces with the microcontroller through an analog input pin, delivering a voltage output that directly correlates with the TDS level in the water. By integrating this sensor into the proposed system, the research aims to enhance the monitoring of water quality, ensuring optimal conditions for plant and fish growth in urban aquaponics environments.

iii) Water Level Sensor Float Switch

Figure 2.22: Water Level Sensor

(Water Level Sensor Float Switch, 2021)

The Water Level Sensor Float Switch, as shown in *Figure 2.22,* is a straightforward device designed to detect the presence of water at a specific level, playing a critical role in preventing overflows and maintaining water levels within desired parameters in aquaponics systems (Mahfuz & Al-Mayeed, 2020). This sensor connects to a digital input pin on the microcontroller and functions as a switch, providing either a high or low signal based on the water level detected. By incorporating the Water Level Sensor Float Switch into the proposed system, this research aims to enhance the automation and reliability of water management in urban aquaponics environments, ensuring optimal conditions for plant and fish growth.

iv) Micro Water Submersible Pump

Figure 2.23: Micro Water Submersive Pump

(Micro Water Submersive Pump, 2021)

The Micro Water Submersible Pump, as shown in *Figure 2.23*, plays a crucial role in circulating water within the aquaponics system, ensuring even distribution of nutrients and maintaining oxygenation levels for both plants and fish (A Guide to Ideal Water Pump Placement in Aquaponics - Go Green Aquaponics, 2024). This pump is typically controlled by the microcontroller via a relay or transistor circuit, enabling the microcontroller to turn the pump on or off as necessary.

v) Temperature Sensor

Figure 2.24: Temperature Sensor

(DS18B20 Digital Temperature Sensor, 2021)

The temperature sensor, as shown in *Figure 2.24*, is essential for monitoring water temperature in an aquaponics system, as it significantly impacts the health of both plants and fish. Maintaining an optimal temperature range is crucial for system stability (Mahmoud et al., 2023). The DS18B20, a digital temperature sensor, can be interfaced with the microcontroller using a single digital input. By incorporating a temperature sensor into the proposed aquaponics system, this research aims to enhance overall system stability and support optimal growth conditions for both plants and aquatic life.

2.4.2 Machine Learning and Predictive Analytics

Machine learning and predictive analytics utilize historical and real-time data to enhance the performance of aquaponics systems (Channa et al., 2024). By analyzing data patterns and trends, these techniques can predict future conditions, optimize system operations, and improve overall efficiency.

i) Random Forest

This is an ensemble learning method that constructs multiple decision trees and combines their outputs to enhance prediction accuracy (Random Forest, 2024). This technique can be employed to predict water quality parameters and identify system anomalies by analyzing complex data patterns. Its application includes improving predictions of nutrient levels and enabling the early detection of potential issues, helping to mitigate any adverse effects on system performance.

ii) Support Vector Machines (SVM)

This is a classification technique that identifies the optimal hyperplane to separate different classes within a dataset. This method can classify system states based on sensor data, effectively identifying and addressing anomalies or deviations (Support Vector Machine (SVM) Algorithm | by Sumbatilinda | Medium, 2024). Its application includes detecting unusual patterns in water quality data and classifying system conditions, which can trigger necessary adjustments to maintain optimal operational performance (Channa et al., 2024).

iii) Artificial Neural Networks (ANN)

ANNs mimic the neural networks of the human brain to model complex relationships between inputs and outputs. These networks are utilized to predict optimal conditions for plant growth by analyzing various environmental factors (Podder & Majumder, 2016). Their application includes predicting plant growth rates and adjusting environmental parameters to optimize yields, thereby enhancing overall system performance (Channa et al., 2024).

iv) K-Nearest Neighbors (KNN)

This is a classification technique that predicts the class of a data point based on the majority class of its nearest neighbors (What Is the K-Nearest Neighbors Algorithm? 2021). In the context of aquaponics systems, KNN is used to compare current sensor data with historical data to determine system states. Its application includes identifying current system conditions by making real-time adjustments based on comparisons with historical data, ensuring optimal performance and stability.

v) Time Series Analysis (ARIMA)

A forecasting technique that uses historical data to predict future values by analyzing trends and seasonal patterns. ARIMA is applied to forecast future environmental conditions and nutrient levels (Hayes, 2024). Its application involves predicting future water quality parameters, allowing for proactive adjustments to system operations, which enhances overall efficiency and stability.

vi) Linear Regression

This is a statistical method that models the relationship between dependent and independent variables using a linear equation (Kiernan, 2014). In the context of aquaponics systems, linear regression is utilized to understand how various environmental factors, such as temperature and nutrient levels, affect plant growth. This application enables researchers to analyze the impact of these variables on plant development, facilitating informed decisions to optimize growth conditions and improve overall system performance.

2.4.3 Solar-Powered Systems

Solar-powered systems offer a sustainable and eco-friendly energy source for aquaponics, reducing dependency on grid power, lowering operational costs, and promoting environmental sustainability (Solar Power Irrigation System, 2023). The foundation of these systems includes several key components.

i) Solar Cell

Converts sunlight into electricity using semiconductor cells. The system operates off-grid, powered by an 18V solar cell (Paul et al., 2022). *Figure 2.25* shows an 18V solar panel that can be used to power the CPS.

Figure 2.25: Solar Cell 18V 5W 380mAh

(Solar Cell 18V 5W 380mAh - Miniature Polycrystalline Solar, 2021)

ii) Charge Controller

A solar charge controller regulates the current from the solar cell to the battery, preventing overcharging and enhancing battery longevity (Paul et al., 2022). *Figure 2.26* shows the charge controller that will to regulated the current from the solar cell, *Figure 2.25*, to the battery.

Figure 2.26: Charge Control Module

(XH-M604 DC 6-60v Battery Charger Controller, 2021)

iii) **Battery**

Utilizes a sealed lead-acid battery (12V 7Ah), which is well-suited for repeated discharges and meets the system's voltage requirements (Paul et al., 2022). *Figure 2.27* shows the sealed lead acid battery used for storing power generated by the solar panel.

Figure 2.27: Sealed lead acid battery

(Sealed lead acid battery 12V 7Ah, 2021)

iv) Buck Converter

The system incorporates a buck converter, *Figure 2.28,* to step down the voltage from the sealed lead acid battery to the optimal level required for the ESP32 microcontroller. This converter ensures efficient power delivery while minimizing energy loss, which is essential for maintaining the performance of the aquaponics system. By regulating the voltage output, the buck converter enhances the overall energy efficiency of the solar-powered Cyber-Physical System (CPS), allowing the ESP32 to operate effectively even under varying power demands (Paul et al., 2022).

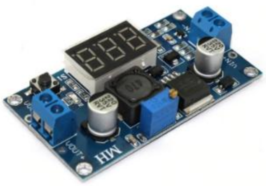


Figure 2.28: Buck Converter

(LM2596 DC-DC Buck/Step-down Converter, 2021)

2.4.4 *Internet of Things (IoT) Integration*

The integration of the Internet of Things (IoT) facilitates the remote monitoring and management of aquaponics systems by connecting various sensors, devices, and controllers to the internet. This connectivity provides real-time data access, enables system automation, and enhances control, ultimately improving overall efficiency and user convenience (Taha et al., 2022). The key components involved in this integration include:

i) Microcontrollers with IoT Capabilities

The ESP32S DevKIT Wi-Fi + BLE Module, as shown in *Figure 2.29*, is a cost-effective microcontroller with built-in Wi-Fi and Bluetooth Low Energy (BLE) capabilities, making it ideal for IoT applications that require seamless network connectivity.

Figure 2.29: SP32S DevKIT WIFI + BLE Module - Microcontroller

(ESP32S DevKIT WIFI + BLE Module - Microcontroller, 2023

ii) IoT Communication Protocols

IoT communication protocols play a crucial role in enabling data exchange between devices and platforms. MQTT (Message Queuing Telemetry Transport) is a lightweight messaging protocol that facilitates efficient communication between IoT devices and cloud services, ensuring reliable data transmission (Inc, 2024). HTTP/HTTPS (HyperText Transfer Protocol/Secure) are standard web protocols used for transferring data, enabling secure communication between IoT devices and web-based platforms (Inc, 2024).

iii. Cloud Platforms for Data Management

Cloud platforms play a vital role in managing and processing data in IoT-based aquaponics systems. AWS (Amazon Web Services) offers secure and scalable data management, integrating seamlessly with other AWS services to provide comprehensive IoT solutions (Chakraborty & Aithal, 2023). Similarly, Google Cloud provides real-time data processing and management capabilities, enabling efficient operations and advanced analytics to optimize system performance (Maruti & Chow, 2024).

iv. Data Visualization and Analysis Tools

Data visualization and analysis tools are essential for extracting actionable insights from IoT sensor data in aquaponics systems. Laravel, a robust PHP framework, excels in web development and data analytics, enabling custom data processing and seamless integration with various databases, making it ideal for analyzing IoT sensor data (Silveira et al., 2019). Grafana, an open-source platform, allows the creation of interactive dashboards for real-time monitoring and analysis of sensor data, enhancing system oversight (Grafana: Real-Time Data Visualization and Monitoring, 2024). Tableau offers advanced data visualization capabilities, transforming complex sensor data into interactive reports to support data-driven decision-making and system optimization (Mella, 2024).

v) Mobile and Web Applications

Mobile and web applications play a crucial role in managing and monitoring IoT-enabled aquaponics systems. Blynk, an IoT platform, allows for the creation of custom mobile apps that enable users to remotely control and monitor their systems through user-friendly interfaces (Blynk, 2024). Home Assistant, an open-source automation platform, provides a web interface for managing and automating IoT devices, offering extensive integration options for seamless system management (Integrating with Home Assistant via MQTT and Setting Up Automations, 2024). Additionally, Laravel, when used alongside JavaScript, supports the development of applications with robust data analytics and seamless user experiences. Node.js enhances backend capabilities, ensuring efficient real-time data handling and scalable application development (Laravel vs Node.Js, 2024).

2.5 Research Gap

This research addresses some of the essential gaps in urban aquaponics with a proposed solution that bridges these challenges and enhances existing systems. Presently, most studies are inadequate in their focus on integrating solar-powered technology within aquaponics systems that are specifically tailored for resource-constrained urban environments like Nairobi, Kenya. This research will explore how solar energy works to further enhance the sustainability of aquaponics systems in reducing reliance on conventional energy sources. Besides, CPS applications in urban agriculture are not fully explored, especially in real-time monitoring and automated control aspects (Chinnasamy et al., 2023). This research will design an optimized CPS for urban balcony gardens that could manage resources precisely and enhance system performance. Unlike most of the existing solutions that offer limited automation (Laforest, 2023), the proposed system will be integrated with advanced monitoring and automation technologies to maintain consistent conditions for both fish and plants.

Moreover, most of the literature lacks consideration of the specific needs and views of heterogeneous user groups in urban aquaponics, especially in developing countries. This research will bridge this gap by integrating novice farmers, active practitioners, and community organizations to make sure that a user-centered design approach has been considered. By assessing the usability and performance of the CPS, the research will deliver an efficient solution, accessible and practical to users at different levels of experience (Taha et al., 2022). This will advance sustainable urban food production by integrating renewable energy, automation, and user-focused design to provide a scalable model for resource-constrained metropolitan environments.

2.6 Conceptual Framework

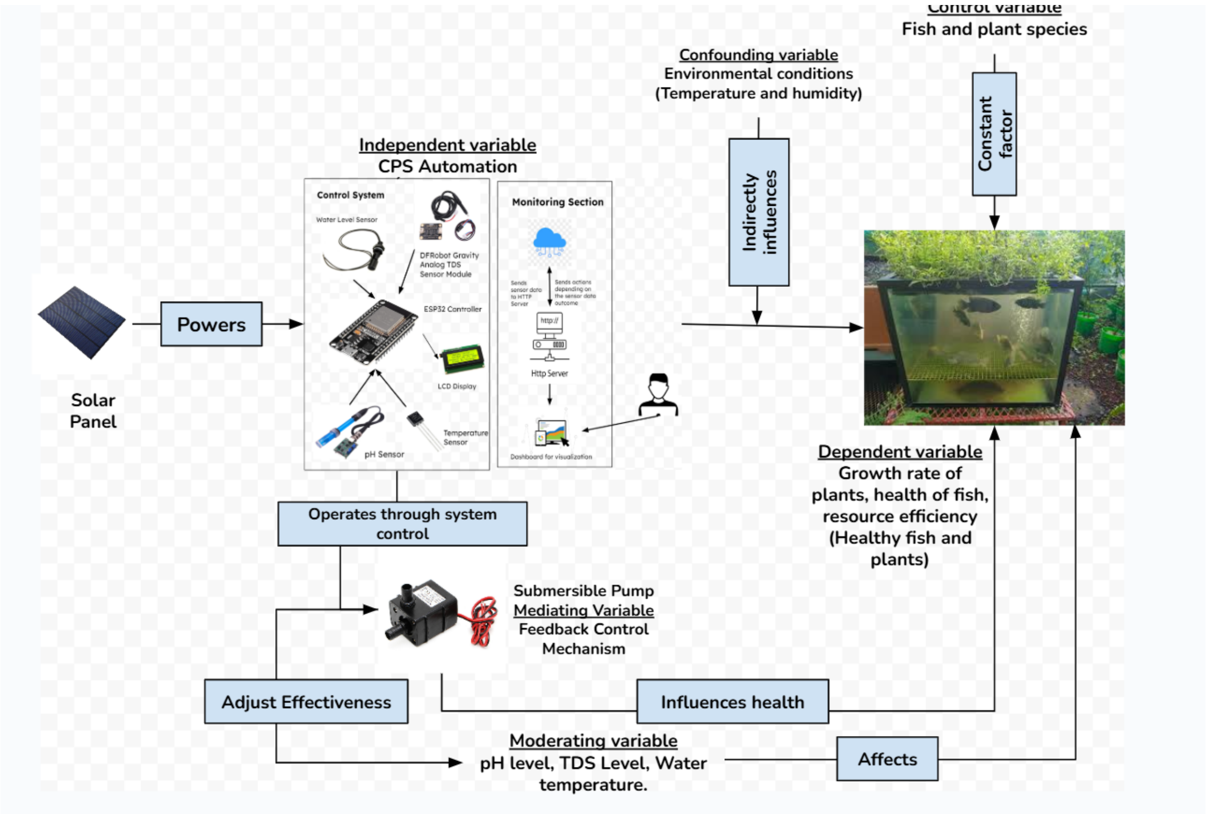


Figure 2.30: Conceptual Framework

The conceptual framework for optimizing aquaponics system performance identifies several key variables, as shown in *Figure 2.30*. The independent variable, CPS Automation, powered by solar energy, integrates smart technologies like IoT systems and automated controls to enhance system efficiency and responsiveness. Feedback Control Systems, a mediating variable, analyze sensor data to maintain optimal conditions such as pH, water temperature, and water levels, ensuring the health of plants and fish, thus improving overall system performance. System Performance, the dependent variable, is measured by outcomes like plant growth, fish health, and resource efficiency, all of which depend on the effectiveness of CPS automation and feedback control systems in maintaining homeostasis.

Moderating variables—pH Level, TDS Level, and Water Temperature—affect the relationship between CPS automation, feedback control systems, and overall system performance, with their influence potentially enhancing or diminishing the effectiveness of the independent variable. Control variables, such as Fish and Plant Species, are essential for ensuring the reliability and consistency of the research results, acting as constant factors that help isolate the effects of other variables. Lastly, confounding variables, including environmental conditions like temperature and humidity, can influence the relationships within the framework and obscure true causal effects, complicating result interpretation. This detailed exploration of variable interactions forms the basis for optimizing aquaponics system performance.

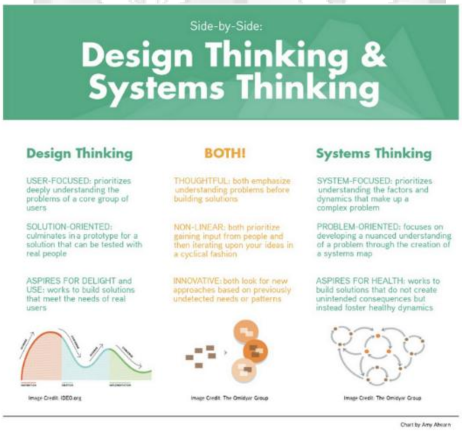
Chapter 3: Research Methodology

3.1 Introduction

The research methodology outlines the structured approach adopted to achieve the objectives of this research. This research focuses on the design and development of a solar-powered cyber-physical system (CPS) for optimizing aquaponics in urban environments. The system automates the monitoring and management of key parameters, creating a sustainable and efficient aquaponics cycle. This section details the research design, data collection methods, statistical analysis techniques, system architecture, and the tools utilized throughout the development and testing processes. By employing both qualitative and quantitative methods, the research provides a comprehensive framework for evaluating the proposed system and its potential applications areas.

3.2 Methodology

The research adopted a Systems Design Thinking methodology, well-suited for developing innovative solutions that address complex, real-world challenges through a user-centered approach.



Side-by-Side:

Design Thinking & Systems Thinking

Design Thinking	BOTH!	Systems Thinking
USER-FOCUSED: prioritizes deeply understanding the problems of a core group of users	THOUGHTFUL: both emphasize understanding problems before building solutions	SYSTEM-FOCUSED: prioritizes understanding the factors and dynamics that make up a complex problem
SOLUTION-ORIENTED: culminates in a prototype for a solution that can be tested with real people	NON-LINEAR: both prioritize gaining input from people and then iterating upon your ideas in a cyclical fashion	PROBLEM-ORIENTED: focuses on developing a nuanced understanding of a problem through the creation of a systems map
ASPIRES FOR DELIGHT and USE: works to build solutions that meet the needs of real users	INNOVATIVE: both look for new approaches based on previously undetected needs or patterns	ASPIRES FOR HEALTH: works to build solutions that do not create unintended consequences but instead foster healthy dynamics
Image Credit: IDEO.org	Image Credit: The Omidyar Group	Image Credit: The Omidyar Group

Chart by Amy Ahearn

Figure 3.1: System Design Thinking Framework

(Ospina, 2019)

The selection of Systems Design Thinking, as illustrated in *Figure 3.1*, was based on several key factors. First, this methodology emphasizes understanding user needs and experiences, aligning with the objective of designing a CPS that enhances urban aquaponics through automation and real-time monitoring. Second, iterative prototyping and testing played a crucial role in refining the system based on continuous user feedback and real-time data analysis. Finally, this approach encouraged collaboration among stakeholders, ensuring that diverse perspectives were incorporated into the design process. The adoption of Systems Design Thinking was grounded in established literature, reinforcing the importance of a holistic and adaptive framework for creating effective and sustainable solutions.

3.3 Research Design

The research design systematically followed the Systems Design Thinking approach in iterative stages to develop, prototype, and evaluate the CPS. The process began with a thorough understanding and observation phase, engaging urban aquaponics practitioners to identify their needs and challenges. Insights gathered informed the definition of system requirements, focusing on real-time monitoring of key aquaponics parameters, including pH, TDS, and water temperature, while incorporating remote monitoring capabilities via an IoT-enabled platform. In the ideation phase, the system was conceptualized, integrating hardware components such as sensors, solar panels, and water pumps with a software platform for real-time monitoring and automation. A prototype of the monitoring system was developed and tested to validate its functionality and ensure alignment with technical requirements. The iterative approach facilitated continuous refinement of the design, ensuring the system effectively met functional and operational objectives.

3.4 Data Collection Methods

Data collection for this project involved both primary and secondary data.

3.4.1 Primary Data

Primary data was obtained from two main sources:

a. Sensor Data: Collected from pH, TDS, and temperature sensors integrated with the ESP32 microcontroller. These sensors provided continuous, real-time monitoring of environmental conditions critical for optimal system performance.
b. User Interviews: Interviews were conducted with urban aquaponics practitioners to understand their challenges, experiences, and expectations regarding aquaponics system management.

The research gathered user feedback through case studies involving

a. An aquaponics expert who started with a balcony aquaponics setup, such as Robert Mwakio (Reporter, 2018).

b. A large-scale aquaponics farm, such as Grandeur Africa Limited in Kitengela.
c. A farm that offers aquaponics setup services, such as Hydroponics Africa (Aquaponic Systems, 2024).

While the interviews provided insights into user needs and expectations, feedback on the developed system will be collected in future iterations.

3.4.2 Secondary Data

Secondary data was gathered through an extensive review of academic and industry literature on aquaponics, CPS, and smart irrigation systems. This provided valuable insights into best practices, technological advancements, and existing gaps, helping to refine the system's design and implementation.

3.5 Statistical Analysis

The data collected for this study underwent comprehensive analysis using both quantitative and qualitative techniques.

3.5.1 Quantitative Analysis

Quantitative analysis included descriptive statistics to summarize sensor data by calculating key metrics such as mean, median, standard deviation, and range for parameters like pH, TDS, and temperature. These calculations helped establish normal operating ranges and detect anomalies in system performance. Additionally, inferential statistical methods such as correlation and regression analysis were used to explore relationships between environmental factors (e.g., temperature and pH) and overall system performance. Time-series analysis was applied to identify trends and patterns in sensor readings over time, facilitating predictive adjustments for system optimization.

3.5.2 Qualitative Analysis

Qualitative data, gathered through interviews and case studies, was analyzed using thematic analysis. This involved coding the qualitative data to identify recurring themes, such as common challenges, user expectations, and desired features in aquaponics systems. These insights informed refinements in system design and functionality to better align with user needs.

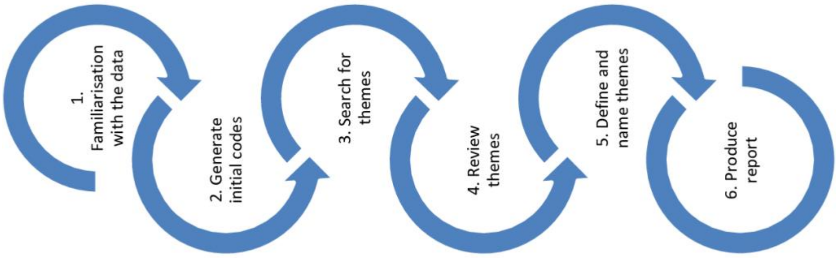


Figure 3.2: Thematics Analysis Structure

(*How to Do Thematic Analysis | A Complete Step-by-Step Guide*, 2021)

To support the analysis, quantitative computations were conducted using R and Python, utilizing libraries such as Pandas, SciPy, and StatsModels for statistical analysis. Chart.js was employed as the primary visualization tool to present findings in an interactive and visually intuitive format. For qualitative data, Excel was used for thematic coding and interpretation. By integrating quantitative insights from sensor data with qualitative themes derived from user feedback, the analysis provided a comprehensive understanding of system performance and user requirements, facilitating continuous improvement in the aquaponics system.

3.6 Tools and Techniques

A combination of hardware and software tools was utilized to implement the CPS. The hardware included the ESP32 microcontroller, which managed inputs from the pH, TDS, and temperature sensors and controlled the water pump based on predefined thresholds. These sensors continuously monitored crucial environmental conditions, while the solar power system provided sustainable energy to power the CPS components. On the software side, a web-based dashboard was developed using Laravel and jQuery, enabling users to monitor the system in real-time through a user-friendly interface. Sensor data was transmitted to a cloud-based server for storage and analysis, ensuring remote access and control of the system.

3.7 System Architecture

The architecture of the CPS was built around the ESP32 microcontroller, serving as the system’s central control unit. The microcontroller collected data from pH, TDS, and temperature sensors and automated the operation of the water pump based on predefined conditions. Solar panels provided renewable energy, ensuring autonomous operation and environmental sustainability. Sensor data was transmitted via a Wi-Fi connection to a cloud-based server, enabling real-time synchronization. Users could remotely access system metrics through a web-based dashboard, facilitating seamless monitoring and control.

3.8 Prototype Development and Implementation

The prototype development integrated hardware components, including the ESP32 microcontroller and sensors, to form a cohesive system capable of real-time water quality monitoring and automated pump control. The microcontroller was programmed to interface with the sensors and actuate the water pump as needed. Solar panels were installed to enable independent operation from the grid, utilizing renewable energy. The software development focused on creating a web-based dashboard using Laravel and jQuery, providing intuitive data visualization and remote control of the system. Sensor data was transmitted to a cloud server in real-time, ensuring users had continuous access to up-to-date system performance metrics.

3.9 Machine Learning Algorithms to Support CPS

To enhance the efficiency and adaptability of the CPS, machine learning algorithms were leveraged to analyze sensor-generated data for predictive tasks. The K-Nearest Neighbors (KNN) algorithm was employed for regression and prediction, estimating future pH levels based on historical sensor data. KNN predicts outcomes by analyzing the "k" nearest data points in the dataset, determining the value of a given point based on its proximity to others (Sen et al., 2023). KNN was chosen for its simplicity, ease of implementation, and ability to adapt to changing data trends without requiring extensive recalibration. Additionally, as a non-parametric algorithm, it effectively accommodated real-world aquaponics data, which may not conform to standard statistical distributions. However, the algorithm has certain limitations: its performance diminishes when handling large datasets due to the increasing computational demands of nearest-neighbor searches. Furthermore, KNN is sensitive to noise and outliers, which can compromise prediction accuracy. To enhance model reliability, data preprocessing steps were implemented. Key numeric features, including pH, temperature, and TDS, were normalized to ensure uniformity in distance-based calculations and missing values were handled through forward-filling to maintain continuity in time-series data. By integrating KNN into the CPS, the system gained predictive capabilities, enabling it to anticipate pH fluctuations and adjust operations in real time. This predictive functionality enhanced resource efficiency and supported sustainable food production in space-constrained urban environments.

3.10 Testing and Validation

The testing phase involved a comprehensive evaluation of the CPS to verify its functionality, reliability, and performance. Functional testing confirmed that the system accurately monitored water quality and controlled the water pump in response to real-time sensor data. Performance testing assessed the system’s efficiency under various conditions, with a particular focus on the solar power system’s ability to maintain uninterrupted operation. Reliability testing subjected the system to extended operational periods to evaluate its capability to sustain optimal water conditions over time with minimal manual intervention. These tests ensured that the CPS met the essential requirements for real-time monitoring, automation, and sustainability in urban aquaponics environments.

3.11 System Architecture Design

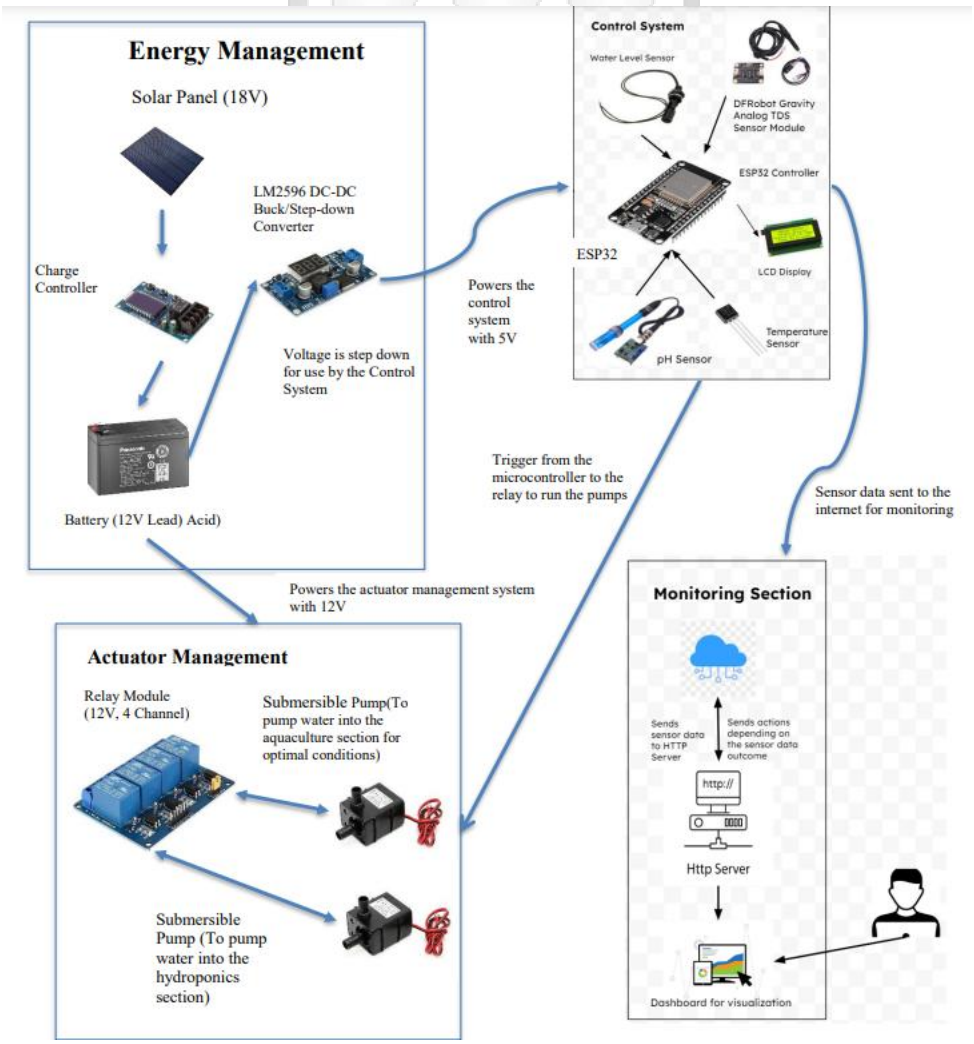


Figure 3.3: Systems Architecture

Figure 3.3 shows the system architecture, outlining how the various components interacted to enable real-time monitoring and automation of the urban aquaponics system. The system was powered by a solar panel, which generated electricity to charge a battery. A charge controller regulated the charging process, ensuring efficient power management and preventing overcharging or deep discharge. This configuration ensured continuous operation, making the system sustainable and independent of the electrical grid. At the core of the system was the ESP32 microcontroller, which functioned as the central processing unit. It collected real-time data from three key sensors: a pH sensor, which measured the acidity or alkalinity of the water to maintain optimal conditions for plant and fish health; a TDS sensor, which monitored the concentration of dissolved solids in the water to ensure proper nutrient balance; and a temperature sensor, which tracked water temperature to maintain stable environmental conditions for aquatic life. Based on predefined thresholds, the ESP32 microcontroller automatically controlled the water pump, regulating water circulation and maintaining optimal water quality. The collected sensor data was transmitted via Wi-Fi to a cloud-based server, where it was stored and processed in real-time. The cloud infrastructure enabled data accessibility and facilitated historical data tracking for predictive analytics. A web-based dashboard, developed using Laravel and jQuery, provided users with an intuitive interface for monitoring system performance. Through this platform, users were able to view real-time sensor readings, receive system alerts when critical thresholds were exceeded, and remotely monitor and manage system operations. This architecture ensured seamless integration between hardware and software components, enabling efficient monitoring and control of the aquaponics system while utilizing solar energy for sustainability.

3.12 Dissemination and Utilization of Results

The development of a solar-powered cyber-physical system for optimizing aquaponics in urban environments aimed to provide an efficient and sustainable solution to enhance urban food production. The outcome of this project is a functional prototype capable of monitoring water parameters and automating control processes to improve aquaponics cycles in resource-constrained metropolitan settings. The data collected and the source code developed contribute to both academic research and practical applications in smart agriculture and urban farming. Open-access dissemination channels were used where possible to ensure that researchers, developers, and practitioners could access and build upon the project outputs.

a. Academic Dissemination

The findings will be published in peer-reviewed journals focusing on smart agriculture, cyber-physical systems, and sustainable urban development. In addition, relevant academic conferences and symposia will be targeted for the presentation of key outcomes, enabling further academic engagement and knowledge sharing.

b. Digital Access and Open-Source Contribution

The project’s source code, including modules for the IoT devices, monitoring systems, and related artifacts, has been made openly available through the GitHub repository https://github.com/Jacqueline777/166570-MASTERS-IT.

This open-access repository ensures that researchers and developers can access, reproduce, and extend the work, encouraging collaboration and innovation.

c. Sensor Data Access and Responsible Use

All collected sensor data were transmitted and securely stored on a cloud-based platform, enabling real-time access, data backup, and future scalability. The system logged data at regular intervals using standardized formats to ensure ease of analysis and integration. Interested parties may request access to the dataset by contacting the researcher at jacquelinekavula.kamadi@strathmore.edu, and will be provided with guidelines to ensure ethical and responsible use of the data.

d. Utilization of Results

The results of this study offer practical value across several domains. Urban farmers and hobbyists can adopt the prototype system to improve the efficiency and productivity of small-scale aquaponics setups in city environments. For the academic community, the research serves as a foundational reference for further research in the fields of smart agriculture and cyber-physical systems. Developers and innovators can use the model as a replicable framework for designing solar-powered, sensor-driven aquaponics systems tailored for resource-constrained settings. Furthermore, the project supports broader urban food security efforts by demonstrating a low-cost, easily adoptable solution for sustainable farming. Through open access and active dissemination, the study aims to inspire and enable scalable implementations that contribute to resilient and self-sufficient urban food systems.

3.13 Ethical Consideration

The ethical considerations of this research centered on ensuring data privacy, obtaining stakeholder consent, and minimizing environmental impact. Data collected through the cyber-physical system (CPS) was securely stored and processed in compliance with data protection regulations, with personal information anonymized to prevent misuse. Stakeholders, including participants in questionnaires, were fully informed about the purpose of the research, and their voluntary participation was secured through a clear consent process. To minimize environmental impact, the research utilized solar-powered technology, aligning with sustainability objectives. Transparency and ethical responsibility were upheld throughout the research process, ensuring integrity and adherence to ethical standards.

Chapter 4: System analysis and design

4.1 Introduction

The proposed system is a solar-powered cyber-physical system designed to optimize urban aquaponics. It integrates real-time sensors, automation, and a closed-loop control system to stabilize key conditions such as pH, TDS levels, and water temperature, improving plant and fish growth while reducing manual intervention and resource consumption. The system benefits urban farmers, researchers, and hobbyists by providing an easily manageable and sustainable aquaponics solution. Additionally, it is designed to be modular and customizable for different aquaponics setups.

4.2 Thematic Analysis of Interview Findings

The interviews conducted with aquaponics practitioners as shown in F-3: Interview Responses and Analysis, revealed several key themes related to their motivations, system design, operational challenges, technology integration, and future aspirations. These insights provide a comprehensive understanding of the practical implementation of aquaponics in various urban settings.

4.2.1 Motivation for Adopting Aquaponics

Participant, Robert Mwakio and Geoffrey Ngugi, City Shamba representative, highlighted multiple reasons for starting aquaponics, with urban sustainability and efficient space utilization being dominant factors. The ability to grow fresh produce within limited urban spaces, such as balconies and rooftops, was a major incentive. Additionally, the aesthetic appeal of aquaponics systems, combined with their functional benefits, made them attractive for home and commercial use. Some practitioners were introduced to aquaponics through academic opportunities and international exposure. For instance, Robert Mwakio developed an interest in aquaponics during a scholarship program in the United States, where they observed advanced sustainable farming techniques and also through his uncle who was practicing aquaponics. Such experiences contributed to their decision to implement aquaponics in Kenya, having been involved in the practice since 2011, before adapting their setups to the local environment in 2016.

4.2.2 System Design and Components

Aquaponics systems varied in scale, with setups ranging from small balcony units to large commercial greenhouse operations. Despite these differences, common system components remained consistent across various setups. The most commonly reared fish were tilapia and catfish, chosen for their adaptability and rapid growth. Some setups also included Azolla, a floating aquatic plant used as fish feed to enhance sustainability. Popular crops grown in aquaponics systems included spinach, kale (sukuma wiki), lettuce, tomatoes, and cucumbers due to their compatibility with hydroponic environments and fast growth rates. To maintain water quality and nutrient balance, most systems utilized biofiltration mechanisms such as pumice-based filters, which effectively removed waste and ensured water was frequently recycled between fish tanks and plant beds. This process helped sustain both plant and fish health by maintaining optimal nutrient levels.

Different irrigation techniques were used depending on the crop type and system design. Drip irrigation was preferred for crops requiring controlled water distribution, while deep-water culture (DWC) was ideal for leafy greens, allowing plant roots to absorb nutrients directly from water. Some practitioners adopted tower gardens, which utilized vertical structures to optimize space while maintaining high plant density, making them suitable for urban environments with limited space. System sizes varied significantly. Robert Mwakio, operated a balcony aquaponics setup measuring 3m x 2m, capable of holding 2000 liters of water and supporting 800–1000 fish. In contrast, larger-scale practitioners managed steel-framed greenhouses with multiple interconnected ponds, each housing thousands of fish. These variations in scale demonstrated the flexibility of aquaponics, making it adaptable to different urban and commercial agricultural needs.

4.2.3 Operational Challenges

Operating an aquaponics system, particularly in an urban environment, posed several challenges that required continuous monitoring and strategic interventions. One of the most significant issues was power fluctuations, which disrupted water circulation and aeration, potentially endangering both fish and plants. To mitigate this, some practitioners relied on manual interventions, while others explored backup power sources to ensure system stability. Leakages and structural issues were another common challenge, with some setups experiencing water leaks near pumps. These required regular maintenance and calibration adjustments to prevent overflows or shortages that could affect both plant and fish health. Maintaining water quality was equally critical, as pH fluctuations, ammonia buildup, and nutrient imbalances could compromise the system. Some practitioners manually checked for changes in water color and odor, while others utilized chemical testing kits to ensure optimal conditions.

Additionally, flooding risks posed a challenge, especially in systems containing floating plants like Azolla, which could be washed away, disrupting nutrient cycles and reducing efficiency. To address these issues, practitioners implemented various strategies, including monthly system flushing, periodic biofiltration maintenance, and careful calibration of water levels to prevent excess accumulation or depletion. These proactive measures helped sustain the functionality and productivity of their aquaponics systems in urban settings.

4.2.4 Water Quality and Nutrient Management

Ensuring optimal water quality and nutrient balance was a priority across all aquaponics setups, with practitioners employing various strategies to maintain system stability. Frequent water pumping was a common practice, as circulating water through biofilters helped break down waste and prevent ammonia accumulation, ensuring a healthy environment for both fish and plants. Some practitioners also incorporated organic additives, such as goat manure in sack filtration systems, allowing nutrients to seep gradually into the water and support plant growth. Regular physical inspections played a crucial role in water quality management. Practitioners routinely checked for color changes, odors, and algae buildup, with maintenance typically performed every three weeks to prevent imbalances. Larger systems implemented structured flushing schedules to maintain water quality without disrupting fish growth. Additionally, many emphasized the importance of not completely replacing water during cleaning, as sudden changes in water composition could stress the fish, affecting their breeding and survival. These combined efforts ensured that aquaponics systems remained productive and sustainable, even in urban environments.

4.2.5 Technology and Automation

Technology played a crucial role in improving efficiency and minimizing manual interventions in aquaponics systems. The level of automation varied, with larger systems incorporating more advanced tools, while smaller setups relied on manual monitoring. One of the key technologies used was monitoring meters as shown in *Figure 4.1*, which enabled data collection on pH levels, ammonia concentrations, and overall water conditions and transmitted this data to mobile devices, allowing users to track water quality. Additionally, solar-powered insect catchers were used in greenhouse setups to manage pests, though their effectiveness was not always selective for specific species. Smaller aquaponics systems primarily relied on basic aquaponic kits, which included manual chemical testing tools requiring users to extract water samples and observe color changes to detect imbalances. Despite these technological advancements, many practitioners expressed interest in further automating their systems by integrating Internet of Things (IoT) solutions. This would enable real-time remote control, predictive maintenance, and enhanced efficiency, reducing the need for constant manual oversight while improving system sustainability.

Figure 4.1: DR1900 Portable Spectrophotometer

4.2.6 Market and Distribution Strategies

Market engagement among aquaponics practitioners varied, with some focusing solely on self-sufficiency and training, while others supplied fresh produce to specific markets. Distribution channels were diverse, with a significant portion of the produce being donated to institutions such as Mama Lucy Hospital. Additionally, about 60-70% of the surplus stock was sold to market vendors, ensuring that excess production did not go to waste. Rather than relying on structured market forecasting, practitioners adopted a demand-driven supply approach. This meant that produce distribution was based on immediate availability, with farmers and vendors being informed whenever there was a surplus. This flexible approach allowed for efficient distribution while minimizing losses due to overproduction.

4.2.7 Future Prospects and Scalability

Looking ahead, interviewees identified several key trends and recommendations for expanding aquaponics systems. One major trend was the integration of multiple farming systems, where future setups could combine fish farming, hydroponics, and poultry farming to create a self-sustaining, closed-loop ecosystem. Additionally, while leafy greens remained the dominant crops, some practitioners saw potential in diversifying plant varieties to include fruits and medicinal plants, broadening the range of produce grown in aquaponic systems. Research-driven decision-making was also emphasized as crucial for sustainable aquaponics. Experts highlighted the importance of understanding hydroponic crop suitability and market dynamics to ensure long-term viability. For those looking to scale their operations, practitioners provided several key recommendations. They advised against monocropping, as it is less sustainable over time, and encouraged identifying niche markets to enhance profitability. Furthermore, they stressed the need for structured systems that incorporate proper maintenance schedules and expert consultations to optimize system performance and sustainability.

4.3 System Requirements

4.3.1 Functional Requirements

The system was designed to collect and display real-time sensor data, including pH, tDS level, water temperature, and water level, ensuring continuous monitoring of the aquaponics environment. To maintain optimal water quality, the system automatically regulates the water pump based on sensor readings. Sustainability is achieved through the use of solar power, reducing dependency on external power sources. A web-based dashboard provides a user-friendly interface for remote monitoring, allowing users to view system parameters and historical data visualization. Additionally, machine learning models analyze sensor data to predict system health and detect potential failures, enhancing proactive maintenance.

4.3.2 Non-Functional Requirements

The system was designed for scalability, allowing the integration of additional sensors and components without significant modifications, making it adaptable for larger aquaponics setups. Reliability is ensured through fail-safe mechanisms that maintain continuous operation with minimal downtime, guaranteeing consistent monitoring and automation. To enhance security, the system implements encryption, role-based access control, and secure API communication to protect sensor data and user access while ensuring data integrity and confidentiality during transmission and storage. Additionally, the system optimizes efficiency by minimizing power consumption through solar energy and well-optimized control logic. The web-based dashboard is designed to be responsive and accessible across various devices, including smartphones and computers, ensuring seamless user access and control.

4.3.3 System Architecture

The system followed a closed-loop cyber-physical three-tier architecture, comprising the perception layer, network layer, and application layer. As illustrated in *Figure 2.30* and *Figure 3.3*, the Conceptual Framework and System Architecture diagrams provide a visual representation of this structure. In the perception layer, sensors measure key parameters such as pH, TDS, water temperature, and water level. This data is transmitted to a microcontroller, which serves as the IoT gateway, processing sensor readings and relaying commands to the actuators. The network layer facilitates data transmission between the IoT gateway and the cloud platform, enabling real-time monitoring and control. The application layer consists of actuators such as pumps, which dynamically adjust system parameters based on predefined control logic. The cloud platform plays a critical role in storing and analyzing data, generating insights that are accessible via an online dashboard. A web-based user interface allows remote monitoring, control, and predictive analytics to optimize system performance. To ensure sustainability and continuous operation, the system is powered by solar panels with battery storage, reducing dependency on external power sources and mitigating risks associated with power fluctuations.

4.3.3.1 Perception Layer (Physical Components)

This layer consists of sensors and actuators responsible for data collection and automation. The key components include pH sensor and tds level sensor for measuring water quality parameters, a temperature sensor for monitoring water temperature, and a water float switch for detecting water levels in the main tank. The ESP32 microcontroller collects sensor data and controls actuators, while a solar panel and battery provide renewable energy for continuous operation.

4.3.3.2 Network Layer (Data Transmission)

The network layer ensures reliable communication between the perception layer and the application layer. Wi-Fi communication enables real-time data transmission from the ESP32 to the web server, while the HTTP protocol facilitates lightweight and efficient data exchange between components.

4.3.3.3 Application Layer (User Interface and Analytics)

The application layer provides system monitoring, analytics, and predictive insights. A web-based dashboard displays real-time data and historical trends, while a machine learning model using the K-Nearest Neighbors (KNN) algorithm predicts system health. A cloud database stores sensor readings, ensuring data persistence and analysis. Control algorithms based on Optimal Control Theory (OCT) and closed-loop control will dynamically adjust water flow rates and response times to ensure system stability and efficiency.

4.3.4 System Workflow

The system operates through a series of interconnected processes. First, sensors measure water parameters and transmit data to the ESP32 microcontroller. The ESP32 then processes the sensor readings and sends them to the cloud database for storage. Based on predefined thresholds, the ESP32 controls the water pump and provides view in case of any anomalies. The web-based dashboard provides real-time and historical data visualization, enabling users to monitor system performance. The KNN algorithm analyzes trends, predicting system health and recommending necessary interventions to maintain optimal conditions.

4.3.5 Closed-Loop Control Mechanism

The system operates using a feedback control loop. Sensors collect real-time data from the aquaponics environment, and the microcontroller processes this data by comparing it with predefined optimal thresholds. A control algorithm, such as PID or LQR, calculates corrective actions, and actuators, including pumps adjust conditions accordingly. The feedback loop ensures continuous monitoring and optimization, while predictive analytics help forecast system health

4.3.6 Data Flow Diagram

The system's Data Flow Diagram (DFD) illustrates the interaction between sensors, the control unit, the cloud platform, and users, providing a clear overview of data movement and system operation. As shown in Figure 4.2, the process follows these key steps: (1) Data Collection – Sensors, including pH, TDS, temperature, and water level sensors, collect real-time environmental data and transmit it to the ESP32 microcontroller for processing. (2) Data Processing & Transmission – The ESP32, acting as the central control unit, analyzes sensor data, applies predefined logic, and sends relevant information to the cloud platform for storage, analytics, and optimization. (3) Server Communication – The cloud platform processes the data and, when necessary, sends control signals back to the ESP32. (4) Actuator Control – Based on received signals, the microcontroller activates actuators, water pumps to adjust system conditions accordingly. (5) User Interaction – Users access a web-based dashboard, which retrieves real-time and historical data from the cloud, enabling monitoring and decision-making. (6) Remote Control and Optimization – Through the dashboard, users can remotely monitor system performance and make necessary adjustments to enhance efficiency. This structured data flow ensures seamless integration of automation, analytics, and user control, optimizing system performance and reliability.

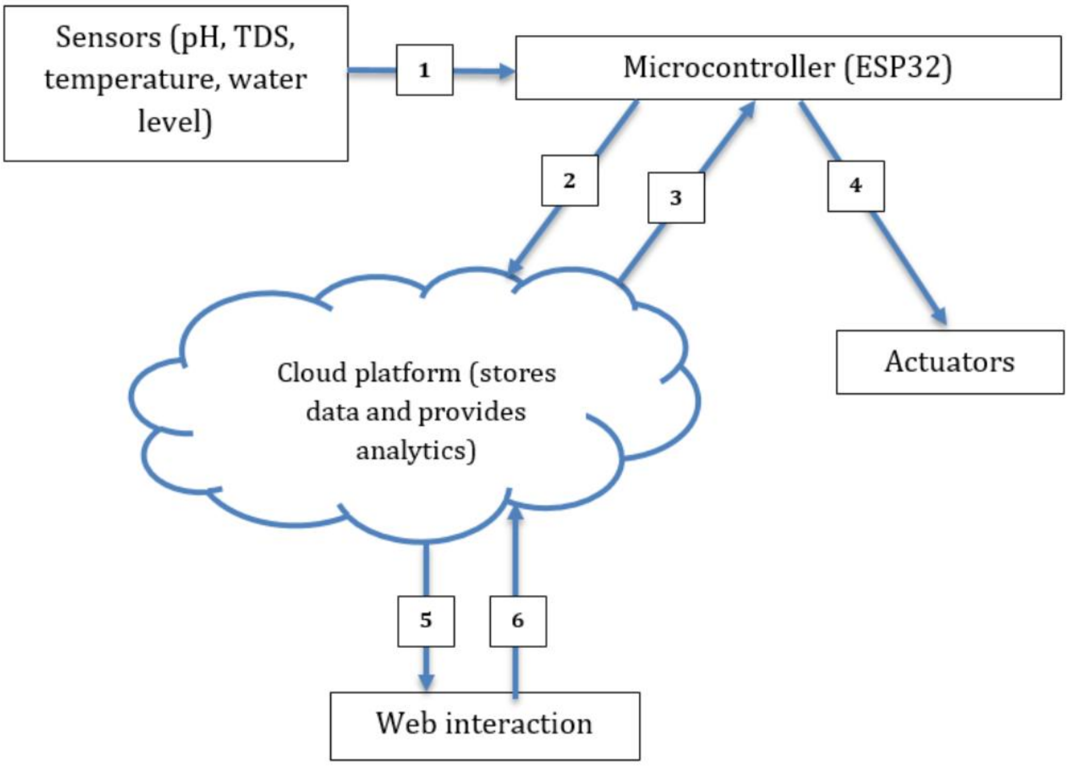


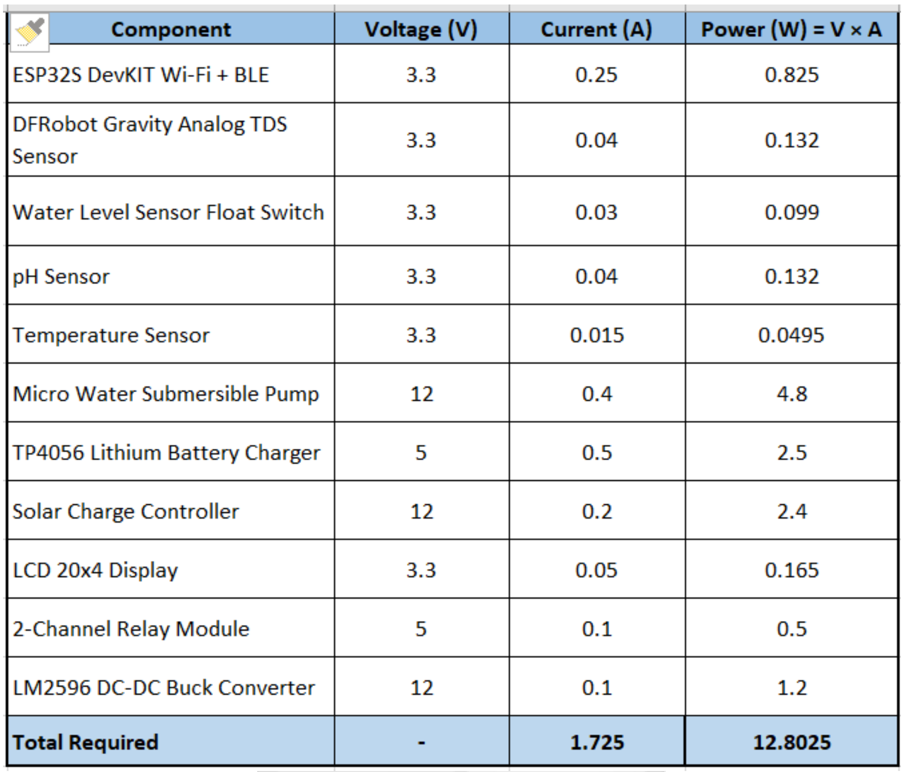
Figure 4.2: Data Flow Diagram (DFD)

4.3.7 System Design Considerations

4.3.7.1 Power Calculations

To ensure reliable and continuous operation, power requirements was carefully calculated based on system components. The total power consumption of the system is determined by summing the power requirements of all major components, including the ESP32, sensors, actuators, display modules, and communication interfaces. The total estimated power consumption as shown in *Table 4.1* is approximately 12.80W under normal operation, excluding surge currents from the water pump and relays.

Table 4.1: Power Budget



Component	Voltage (V)	Current (A)	Power (W) = V × A
ESP32S DevKIT Wi-Fi + BLE	3.3	0.25	0.825
DFRobot Gravity Analog TDS Sensor	3.3	0.04	0.132
Water Level Sensor Float Switch	3.3	0.03	0.099
pH Sensor	3.3	0.04	0.132
Temperature Sensor	3.3	0.015	0.0495
Micro Water Submersible Pump	12	0.4	4.8
TP4056 Lithium Battery Charger	5	0.5	2.5
Solar Charge Controller	12	0.2	2.4
LCD 20x4 Display	3.3	0.05	0.165
2-Channel Relay Module	5	0.1	0.5
LM2596 DC-DC Buck Converter	12	0.1	1.2
Total Required	**-**	**1.725**	**12.8025**

4.3.7.2 Battery and Solar Panel Sizing

A sealed lead-acid battery (12V, 7.2Ah) was selected to provide backup power, offering a total energy storage of 86.4Wh (12V × 7.2Ah). This capacity was sufficient to sustain system operations for approximately 12 hours under normal load. Assuming 5 peak sun hours per day, a solar panel must generate at least 7W × 24h / 5h = 33.6W per hour. Due to component availability, an 18V, 5W solar panel was used for charging. While this panel provided limited energy compared to the estimated requirements, the system was developed as a prototype for testing and validation, with future scalability in mind. The battery capacity ensured uninterrupted operation during cloudy periods.

4.3.7.3 Hardware Selection

The hardware components were selected to ensure energy efficiency, minimize power consumption, and optimize solar energy usage. The system utilizes an ESP32S DevKIT microcontroller, chosen for its low power consumption, built-in Wi-Fi and Bluetooth capabilities, and sufficient processing power for real-time data collection and automation. To ensure continuous monitoring of water quality parameters, the system integrates multiple sensors. The pH Sensor (DFRobot Analog pH Meter V2) provides accurate pH readings within a 0–14 pH range, while the TDS Sensor (DFRobot Gravity Analog TDS Sensor) measures total dissolved solids to assess dissolved solids concentration. A Water Level Sensor (Float Switch) detects water levels to prevent system dry-out, and a Temperature Sensor (DS18B20 Waterproof Digital Sensor) monitors water temperature to maintain optimal aquatic conditions.

For environmental regulation, the system incorporates several actuators. A Micro Water Submersible Pump ensures proper water circulation and water quality regulation. Additionally, a 4-Channel Relay Module is used to control various system components, including the water pump and other electrical loads as needed. To support sustainable operation, the system is powered by a solar panel and a sealed lead-acid battery, ensuring continuous functionality even during cloudy conditions. An LM2596 DC-DC Converter steps down the battery voltage to the required levels for different components. Data communication and display are facilitated through the built-in Wi-Fi module of the ESP32, enabling real-time data transmission to the cloud. Additionally, a 20x4 LCD Display provides local monitoring of system parameters, allowing users to track water quality and overall system performance.

4.3.7.4 Software Design

The software design of the system was structured into multiple layers, ensuring seamless data flow, efficient processing, and user-friendly interaction. The system was developed using Laravel, a robust PHP framework that provides a secure and scalable backend for handling sensor data, user authentication, and system automation. The ESP32 microcontroller continuously collects real-time data from sensors and transmits it to the web server using HTTP protocols. Laravel processes and stores this data in a MySQL database, allowing historical analysis and predictive insights. The backend architecture consists of Laravel controllers handling sensor data processing, user requests, and automated decision-making. The system implements a RESTful API, enabling smooth integration between the ESP32 and the web-based dashboard. Data security is ensured through role-based access control (RBAC), encryption mechanisms, and secure API communication. The frontend interface, developed using Blade templates and Bootstrap, provides a user-friendly dashboard where users can monitor real-time water parameters, system status, and historical trends.

To enhance predictive maintenance and system reliability, the K-Nearest Neighbors (KNN) algorithm is implemented for system health evaluation. This machine learning model analyzes sensor data trends, comparing current conditions to historical patterns to detect anomalies. For instance, abnormal fluctuations in pH, TDS, or temperature can indicate potential system failures, allowing proactive interventions. The KNN model is trained using labeled datasets of past system conditions, enabling it to classify the system's health status as normal, warning, or critical based on similarity to previous cases. The notification module in Laravel serves as an indicator of system health. If the system is classified as bad, it triggers the appropriate actuators to take corrective actions, ensuring continuous system stability. The entire system follows the MVC (Model-View-Controller) architecture, ensuring modularity and scalability for future enhancements. By leveraging Laravel’s capabilities alongside KNN-based predictive analytics, the system offers a data-driven, intelligent, and user-centric approach to optimizing urban aquaponics.

4.3.8 Use Case Diagram

The Use Case Diagram in Figure 4.3 illustrates the interaction between the main components of the solar-powered cyber-physical aquaponics system and its users. It captures the functional requirements and highlights the system’s key actors and their roles:

4.3.8.1 Actors

1. **User**: An urban farmer, researcher, or hobbyist who monitors and controls the aquaponics system remotely.
2. **Sensors**: Devices that collect real-time data on pH, TDS, water temperature, and water level monitor.
3. **Microcontroller (ESP32)**: Acts as the central control unit, processing sensor data, executing control logic, and managing actuators.
4. **Actuators**: Components such as water pumps that regulate the aquaponics environment based on commands from the microcontroller.
5. **Cloud Platform**: Stores sensor data, runs analytics including machine learning models, and provides a web dashboard interface for users.

4.3.8.2 Use Cases

i. **Monitor Water Quality:** Users view real-time and historical water quality parameters via the web dashboard.
ii. **Automate Water Pump Control**: The system automatically activates or deactivates pumps based on sensor inputs to maintain optimal conditions.
iii. **Manual Pump Control**: Users can manually turn the water pump on or off directly from the dashboard.
iv. **Receive Alerts**: Users receive alerts about anomalies from the dashboard.
v. **Analyze System Health:** The cloud platform applies machine learning models to predict system health in order to trigger actuatuib.
vi. **Manage Power Supply:** The solar panel system ensures sustainable power to the microcontroller and sensors.

This diagram *Figure 4.3* visually explains how the system components and users collaborate to ensure continuous and optimized operation of the aquaponics setup, reinforcing the closed-loop cyber-physical nature of the system.

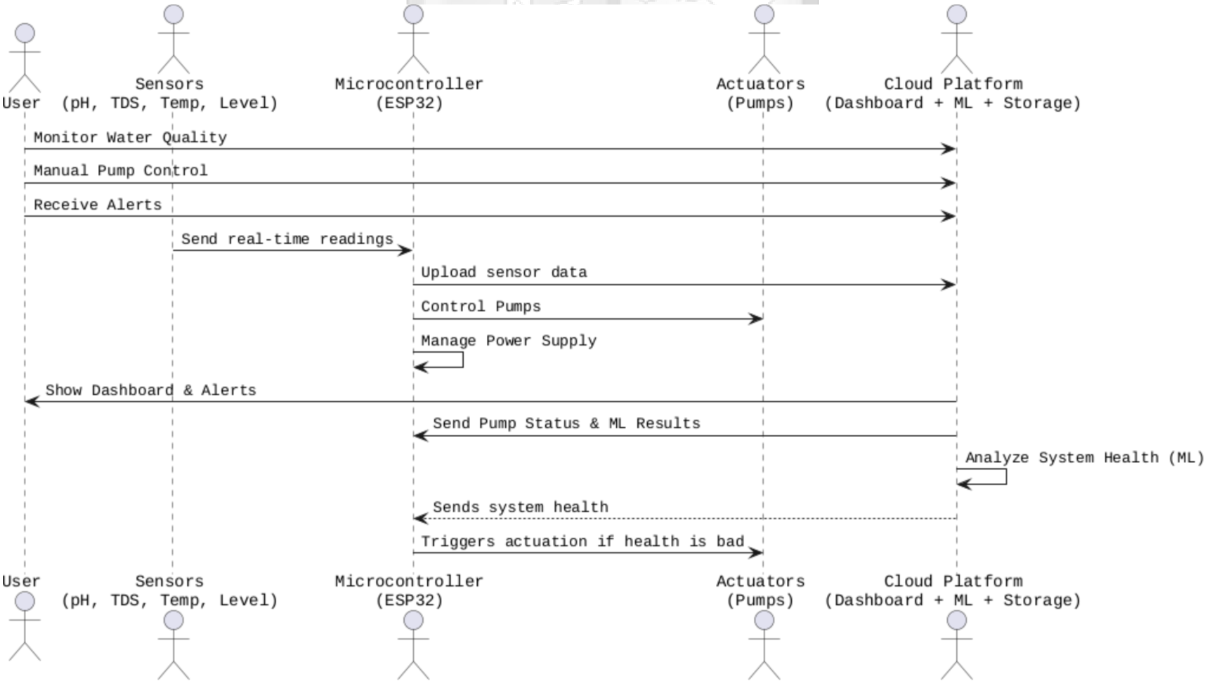


Figure 4.3: Use Case Diagram

4.3.9 Sequence Diagram

The sequence diagram illustrates the timely interaction between various components of the solar-powered cyber-physical aquaponics system. It captures the dynamic behavior of the system, showing how the user, sensors, microcontroller, cloud database, dashboard, and actuator (water pump) communicate in a time-ordered sequence. This visual representation as shown in *Figure 4.4* helps clarify how sensor readings are collected, decisions are made (automatically or by user input), and actions such as activating or deactivating the pump are executed to maintain optimal aquaponics conditions.

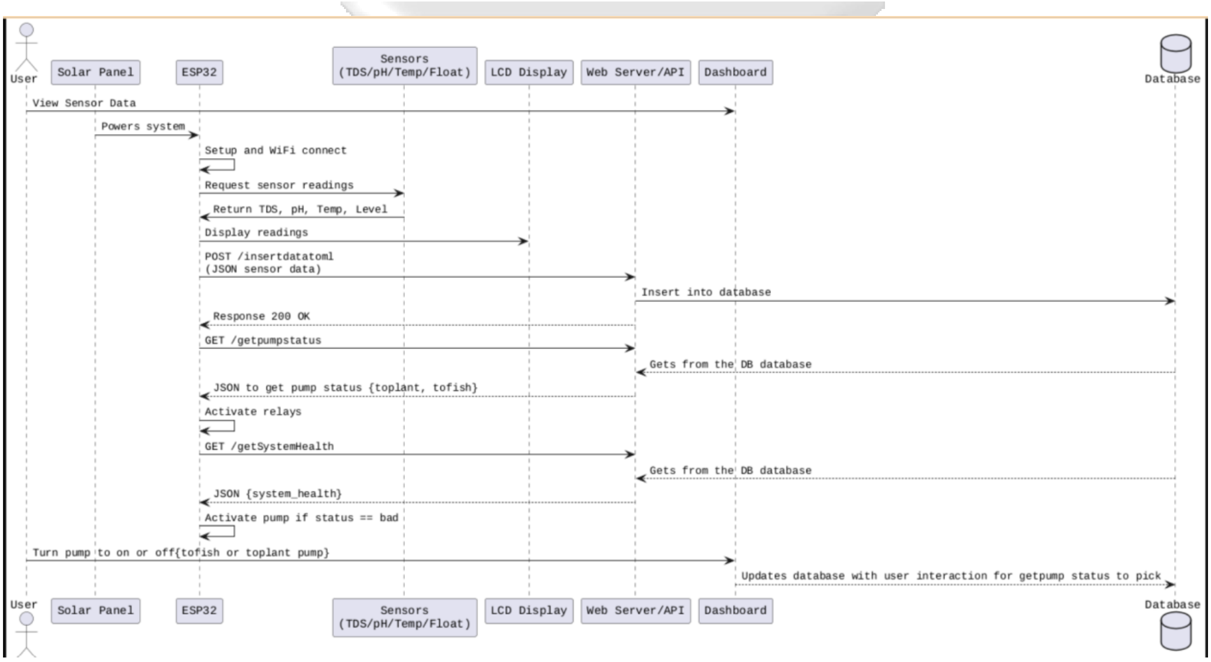


Figure 4.4: Sequence Diagram

Chapter 5: System implementation and testing

5.1 Introduction

System implementation and testing presents the findings obtained from the implementation and testing of the CPS for urban aquaponics. The results are categorized based on system functionality, sensor data analysis, system response time, solar power efficiency, reliability, and overall performance. Additionally, this chapter includes code snippets, dashboard screenshots, and images of the physical system setup to illustrate key aspects of the research.

5.2 System Implementation and Setup

The CPS as shown in Figure 5.1 was developed using an ESP32 microcontroller, integrated with pH, TDS, and water temperature sensors. The system was powered by a solar panel and battery storage unit, ensuring off-grid sustainability. Data collected from sensors were processed and transmitted to a web-based dashboard for real-time monitoring and analysis.

Figure 5.1: The CPS Monitoring System

5.2.1 *Hardware Configuration*

The hardware setup, comprising the ESP32 microcontroller, sensors, and power management system, was configured to enable seamless data acquisition, processing, and transmission. Implementation focused on integrating these components into a functional prototype while optimizing performance through calibration and automation. The ESP32, programmed using the Arduino IDE, managed sensor readings, data processing, and communication with the web server. The microcontroller collected real-time data from the sensors, applied necessary calibrations, and transmitted the readings via Wi-Fi. The water pump's activation was automated based on predefined threshold values, ensuring efficient water circulation within the aquaponics system.

5.2.2 Arduino Code Snippets and Explanation

The Arduino codes shown below demonstrate the integration of the ESP32 with the pH, TDS, and temperature sensors, along with the logic for controlling the water pump based on sensor readings.

a. Wi-Fi Configuration

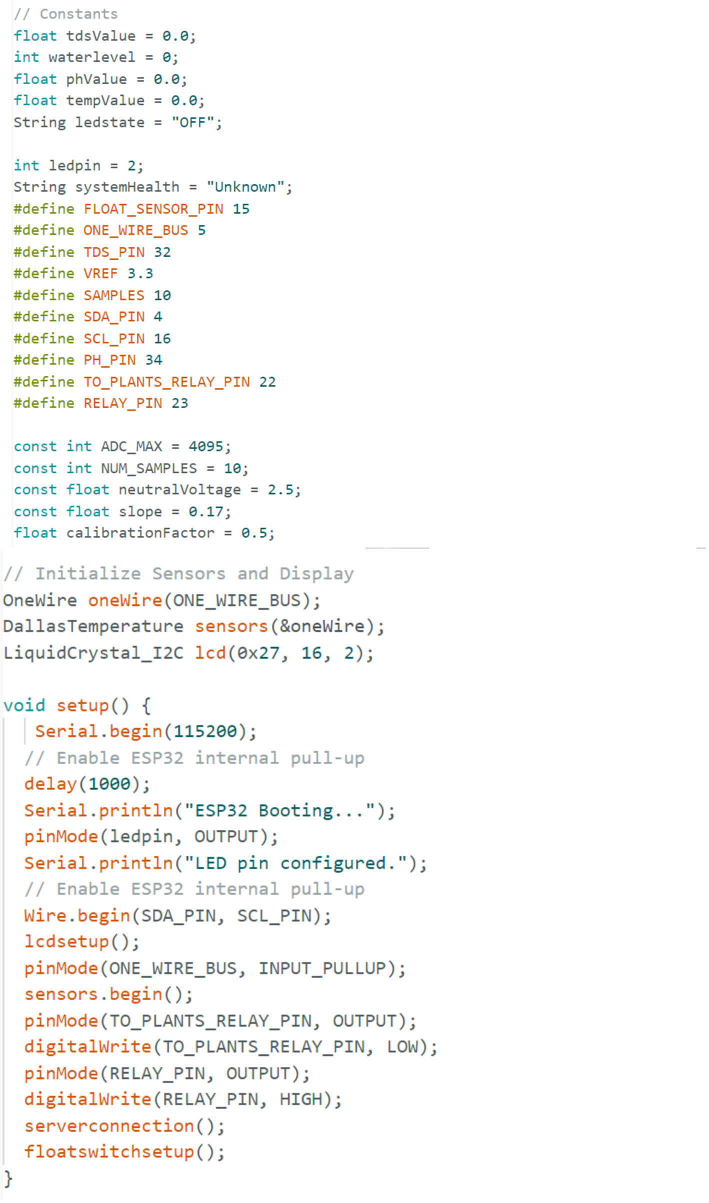
```
#include <WiFi.h>
#include <HTTPClient.h>
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <OneWire.h>
#include <DallasTemperature.h>
#include <ArduinoJson.h>

// Wi-Fi Credentials
const char *ssid = "***********";
const char *password = "*********";

// Server Setup
WiFiServer server(80);
const char *api_url = "https://*********/api/getSystemHealth";
const char *getpumpserverName = "https://*********/api/getpumpstatus";
const char *serverName = "https://*********/api/insertdatatoml";

String dbUser = "root";
String dbPassword = "";

WiFiClient client;
HTTPClient http;
```

Figure 5.2: WiFi Configuration and Loading libraries

As shown in *Figure 5.2*, implementation began by importing essential libraries to enable Wi-Fi connectivity, sensor communication, LCD display control, and JSON data formatting. The ESP32 was configured to connect to a local Wi-Fi network using predefined credentials. It used WiFiClient and HTTPClient to send and receive data from remote servers via REST APIs. URLs were defined for system health monitoring, pump status retrieval, and sensor data submission, forming the core of the system's cloud integration.

b. System Initialization and Pin Configuration

As shown in *Figure 5.3*, the ESP32 was initialized to configure sensor inputs, output pins, and display settings. Key variables were declared for storing real-time values such as pH, TDS, temperature, and water level. GPIO pins were defined for connecting sensors, relays, and the onboard LED. The OneWire protocol was set up for the DS18B20 temperature sensor, while the I2C bus was initialized for the LCD. Pull-up resistors were enabled where necessary, and relays controlling water pumps were set to their default states. The setup() function launched serial communication, started the temperature sensor, configured I/O pins, and initiated the Wi-Fi and float switch setup procedures.



```
// Constants
float tdsValue = 0.0;
int waterlevel = 0;
float phValue = 0.0;
float tempValue = 0.0;
String ledstate = "OFF";

int ledpin = 2;
String systemHealth = "Unknown";
#define FLOAT_SENSOR_PIN 15
#define ONE_WIRE_BUS 5
#define TDS_PIN 32
#define VREF 3.3
#define SAMPLES 10
#define SDA_PIN 4
#define SCL_PIN 16
#define PH_PIN 34
#define TO_PLANTS_RELAY_PIN 22
#define RELAY_PIN 23

const int ADC_MAX = 4095;
const int NUM_SAMPLES = 10;
const float neutralVoltage = 2.5;
const float slope = 0.17;
float calibrationFactor = 0.5;
```

```
// Initialize Sensors and Display
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);
LiquidCrystal_I2C lcd(0x27, 16, 2);

void setup() {
   Serial.begin(115200);
  // Enable ESP32 internal pull-up
  delay(1000);
  Serial.println("ESP32 Booting...");
  pinMode(ledpin, OUTPUT);
  Serial.println("LED pin configured.");
  // Enable ESP32 internal pull-up
  Wire.begin(SDA_PIN, SCL_PIN);
  lcdsetup();
  pinMode(ONE_WIRE_BUS, INPUT_PULLUP);
  sensors.begin();
  pinMode(TO_PLANTS_RELAY_PIN, OUTPUT);
  digitalWrite(TO_PLANTS_RELAY_PIN, LOW);
  pinMode(RELAY_PIN, OUTPUT);
  digitalWrite(RELAY_PIN, HIGH);
  serverconnection();
  floatswitchsetup();
}
```

Figure 5.3: System Initialization and Pin Configuration

c. Main Loop Execution and Data Handling

As shown in *Figure 5.4*, the loop() function served as the core of the ESP32's runtime logic, executing continuously to maintain real-time monitoring and control of the aquaponics system.

```
void loop() {
  WiFiClient client = server.available();
  clientcheck(client);
  sensors.requestTemperatures();
  // Read temperature
  float temperatureC = sensors.getTempCByIndex(0);
  if (temperatureC == DEVICE_DISCONNECTED_C) {
    Serial.println("Error: DS18B20 sensor not found.");
    temperatureC = -127.0;
  } else {
    Serial.print("Temperature: ");
    Serial.print(temperatureC);
    Serial.println(" °C");
  }

  delay(2000);  // Wait 2 seconds before next reading
  tdsValue = tdslevelcheck();
  phValue = phLevelSensor();
  waterlevel = floatsensorcheck();
  tempValue = temperatureC;
  String waterlevelstring = (waterlevel == 1) ? "HIGH" : "LOW";
  String toplantPumpStatus = (digitalRead(TO_PLANTS_RELAY_PIN) == LOW) ? "ON" : "OFF";
  String tofishPumpStatus = (digitalRead(RELAY_PIN) == HIGH) ? "ON" : "OFF";
  lcddisplay(tdsValue, phValue, tempValue, waterlevelstring);
  sendDataToDatabase(tdsValue, phValue, tempValue, waterlevelstring, toplantPumpStatus, tofishPumpStatus);
  delay(2000);
  checkpump();
  delay(3000);
  checksystemhealth();
  delay(3000);
}
```

Figure 5.4: Main Loop Execution and Data Handling

It began by checking for incoming Wi-Fi client connections to ensure responsiveness to external commands or queries. Temperature data was then requested from the DS18B20 sensor, with error handling included to account for sensor disconnection. Once validated, temperature readings were printed to the serial monitor and stored in a global variable. Following this, the system collected current values for TDS, pH, and water level using their respective functions. These values were processed and converted into user-friendly strings, "HIGH" or "LOW", for water level and used to update the I2C LCD display, providing local feedback to users. Relay states for both water circulation pumps (to fish and to plants) were also read and logged for display and cloud transmission. The gathered sensor data and system status were then packaged and sent to a remote server using a dedicated function, enabling remote monitoring and long-term data storage. Additional functions were called to evaluate pump control conditions, checkpump() as shown in *Figure 5.5* and assess system health status, checksystemhealth() as shown in Figure 5.6, both of which used cloud-based logic and predefined thresholds. Delays were inserted between key operations to prevent sensor conflicts, allow stable communication and prevent overflowing of water during pumping as discussed in Automation of Water Pump Operations section. This loop ensured continuous automation, data logging, and remote accessibility, key requirements for maintaining a cyber-physical aquaponics system.

```
void checkpump() {
  if (WiFi.status() == WL_CONNECTED) {
    HTTPClient http;
    http.begin(getpumpserverName);

    int httpResponseCode = http.GET();

    if (httpResponseCode > 0) {
      String response = http.getString();
      Serial.println(response);
      DynamicJsonDocument doc(512);
      DeserializationError error = deserializeJson(doc, response);
      if (!error) {
      String toplant = doc["toplant"];
      String tofish = doc["tofish"];
      toplant.toLowerCase();
      if (toplant == "off") {
          digitalWrite(TO_PLANTS_RELAY_PIN, HIGH);
        } else {
          digitalWrite(TO_PLANTS_RELAY_PIN, LOW);
        }
      tofish.toLowerCase();
      if (tofish == "on") {
        digitalWrite(RELAY_PIN, HIGH);
      } else {
        digitalWrite(RELAY_PIN, LOW);
      }
      } else {
        Serial.println("JSON parse error");
      }
```

```
    } else {
      Serial.println("HTTP GET failed");
    }

    http.end();
  } else {
    Serial.println("WiFi Disconnected");
  }
}
```

Figure 5.5: Arduino function to Check Pump Status

```
void checksystemhealth() {
  if (WiFi.status() == WL_CONNECTED) {
    HTTPClient http;
    http.begin(api_url);
    int httpResponseCode = http.GET();

    if (httpResponseCode > 0) {
      String payload = http.getString();
      Serial.println("Received: " + payload);
      DynamicJsonDocument doc(256);
      DeserializationError error = deserializeJson(doc, payload);
      if (!error) {
        String healthStatus = doc["system_health"];
        healthStatus.toLowerCase();
         systemHealth = healthStatus;
        if (healthStatus == "bad") {
          digitalWrite(RELAY_PIN, HIGH);
          Serial.println("Pump ON!");
          delay(3000);
          digitalWrite(RELAY_PIN, LOW);
        } else {
          digitalWrite(RELAY_PIN, LOW);
          Serial.println("Pump OFF.");
        }
      } else {
        Serial.print("Failed to parse JSON: ");
        Serial.println(error.c_str());
      }

    } else {
      Serial.print("Error fetching data. HTTP code: ");
      Serial.println(httpResponseCode);
```

```

    http.end();
  } else {
    Serial.println("WiFi not connected.");
  }
}
```

Figure 5.6: Arduino function to Check System Health

5.2.3 *Functional Testing Results*

Functional testing was conducted to verify the system’s ability to monitor water quality, automate water pump operations, and maintain adequate water levels. The following key tests were performed.

5.2.3.1 Sensor Data Collection and Processing

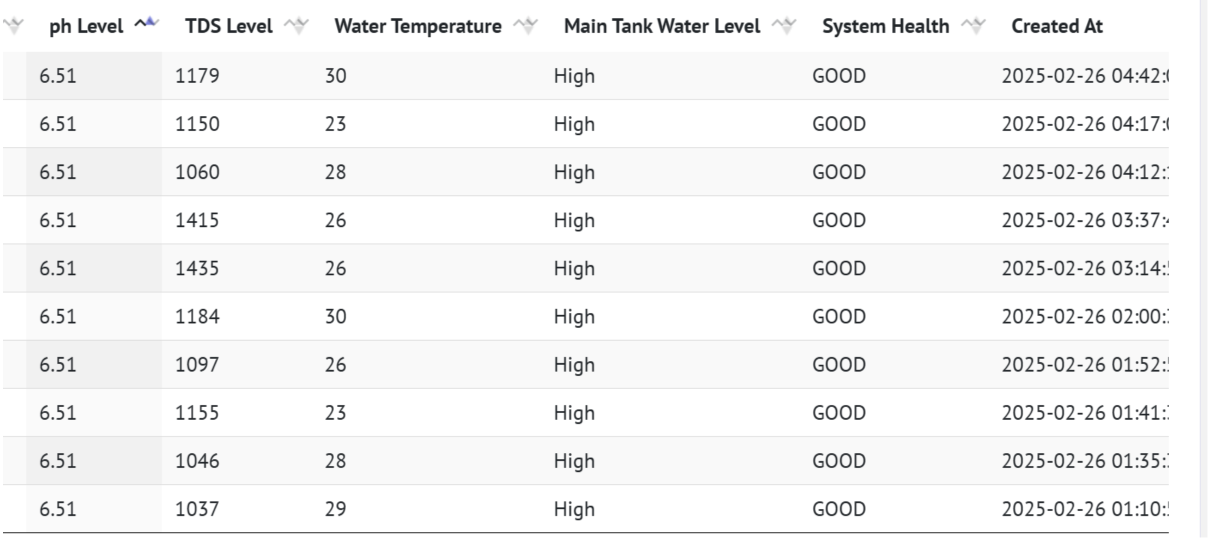
The CPS collected real-time sensor data, which was displayed on the web-based dashboard.

The *Figure 5.7* code below was used to store the sensor data into the database

```
// Create connection
$conn = new mysqli($servername, $username, $password, $dbname);

// Check connection
if ($conn->connect_error) {
    die("Connection failed: " . $conn->connect_error);
}

// Check if data is received
// if ($_SERVER["REQUEST_METHOD"] == "POST") {

$tds = isset($_POST['tds']) ? floatval($_POST['tds']) : 0;
$ph = isset($_POST['ph']) ? floatval($_POST['ph']) : 2;
$temp = isset($_POST['temp']) ? floatval($_POST['temp']) : 2;
$ledstate = isset($_POST['ledstate']) ? (string) $_POST['ledstate'] : "NOPE";

date_default_timezone_set('Africa/Nairobi');
$date_created = date('Y-m-d H:i:s');
// Validate values (optional)
// if ($tds > 0 && $ph > 0 && $temp > 0) {
    // Insert data into database
//   Auto-label system health as "Good" or "Bad"
     $system_health = (
        ($temp >= 75 && $temp <= 85) &&
        ($ph >= 7.8 && $ph <= 8.5) &&
        ($tds >= 200 && $tds <= 400)
    ) ? "Good" : "Bad";

    $sql = "INSERT INTO realtime (phlevel,tdslevel, templevel,ledstate,system_health,created_at) VALUES ('$ph','$tds',  '$temp','$ledstate','$system_health','$date_created')";

    if ($conn->query($sql) === TRUE) {
        echo "Data inserted successfully";
    } else {
        echo "Error: " . $sql . "<br>" . $conn->error;
    }
$conn->close();
?>
```

Figure 5.7: Database Code to insert data

The *Figure 5.8* below summarizes the collected data over a two-week testing period



ph Level	TDS Level	Water Temperature	Main Tank Water Level	System Health	Created At
6.51	1179	30	High	GOOD	2025-02-26 04:42:
6.51	1150	23	High	GOOD	2025-02-26 04:17:
6.51	1060	28	High	GOOD	2025-02-26 04:12:
6.51	1415	26	High	GOOD	2025-02-26 03:37:
6.51	1435	26	High	GOOD	2025-02-26 03:14:
6.51	1184	30	High	GOOD	2025-02-26 02:00:
6.51	1097	26	High	GOOD	2025-02-26 01:52:
6.51	1155	23	High	GOOD	2025-02-26 01:41:
6.51	1046	28	High	GOOD	2025-02-26 01:35:
6.51	1037	29	High	GOOD	2025-02-26 01:10:

Figure 5.8: Table snippet from web-dashboard

5.2.3.2 Water Level Monitoring and Pump Automation

Using the float switch, the system continuously monitored the main tank’s water level. When the water level dropped below the predefined threshold, the system automatically activated the water pump to restore the required level. Once the water level stabilized, the pump was turned off to prevent unnecessary circulation. Additionally, if the system health was classified as "Bad", indicating potential risks to water quality or functionality, the pump was activated as a precautionary measure to maintain optimal conditions.

5.2.3.3 Water Quality Monitoring

The system continuously monitored key water quality parameters, including pH, TDS, and temperature, using dedicated sensors. These readings were transmitted in real-time to the web-based dashboard for analysis. If any parameter deviated from the optimal range, corrective actions were triggered to maintain a stable environment.

5.2.3.4 Automation Response Time

The system's response time was measured by evaluating the time taken between a low-level alert or a "Bad" system health status and the activation of the water pump. The system consistently responded in real-time, ensuring efficient water management and timely corrective actions.

5.2.3.5 Water Level Response Time

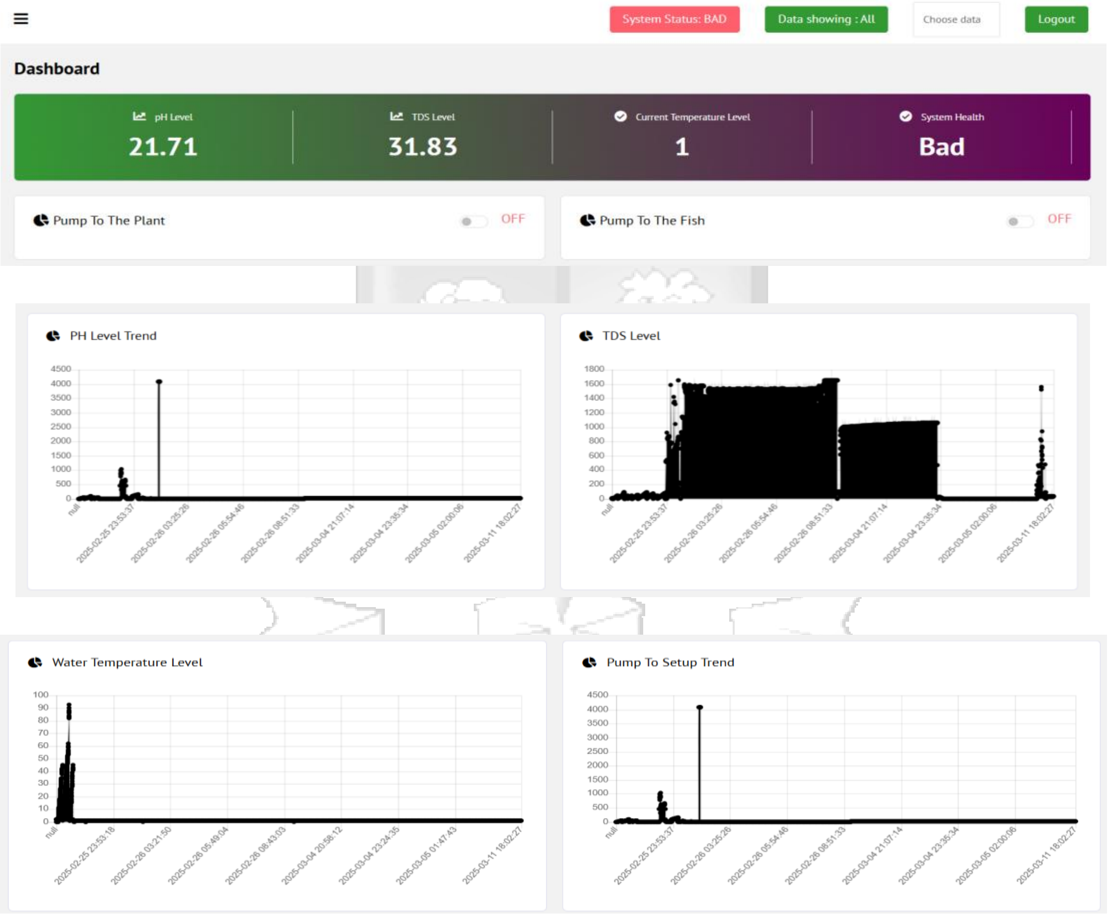
The response time of the water level monitoring system was assessed by measuring the duration between a detected low-level alert and the subsequent activation of the water pump. The system consistently responded in real-time, ensuring efficient water regulation within the aquaponics setup.

5.2.4 Web-Based Dashboard Performance

The web-based dashboard provided real-time monitoring and visualization of sensor data, including water level status.

5.2.4.1 Dashboard Features

Key features included real-time data visualization, graphical trends of pH, TDS, temperature, and water levels, as well as a remote control function for manual activation or deactivation of the water pump. The dashboard as indicated under *Figure 5.9* also included water level alerts, notifying users when intervention was required. The integration of a cloud-based database ensured data persistence, enabling users to access historical trends for informed decision-making.



pH Level 21.71

TDS Level 31.83

Current Temperature Level 1

System Health Bad

Figure 5.9: Dashboard Overview

5.2.4.2 Dashboard API Integration

Figure 5.10 below is an example of the API endpoint used to retrieve real-time water level data for the dashboard.

```
public function dashboard(){
      if (!session()->has('name')) {

              Session::flash('message',"Your session is expired");
            Session::flash('class','show alert-danger');
          return $this->login();

          }
       else{
 $labels= $this->getdata('realtime','created_at');
 $phdata = $this->getdata('realtime','phlevel');
 $tdsdata = $this->getdata('realtime','tdslevel');
 $tempdata = $this->getdata('realtime','templevel');
 $pumpdata = $this->getdata('realtime','ledstate');
 $system_health = $this->getdata('realtime','system_health');
 $system_health = $this->getdata('realtime','system_health');

   if (!empty($system_health)) {
     $latest_system_health = collect($system_health)->last();

   } else {
       $latest_system_health = "No data available"; // Or set a default value
   }
    $duration= session('month');
    return view('aquaponics.dashboard',[
     'duration'=>$duration,
     'name'=>session('name'),'phlabel'=>$labels,'pumplabel'=>$labels,'pumpdata'=>$pumpdata,'phdata'=>$phdata,
     'tdslabel'=>$labels,'tdsdata'=>$tdsdata,'templabel'=>$labels,'tempdata'=>$tempdata,'system_health'=>$system_health,'systemhealth'=>$latest_system_health]);
       }
}
```

Figure 5.10: Retrieval of data onto the dashboard

5.2.5 *Solar Power Efficiency*

The system's solar power efficiency was evaluated under varying weather conditions. An 18V, 5W solar panel was used to charge a 12V, 7.2Ah lithium battery, which has a total energy capacity of 84Wh. Although the battery, when fully charged, can sustain system operation for up to 48 hours without solar input, testing revealed that the 5W panel does not consistently generate enough energy to fully recharge the battery during typical sunlight hours. As a result, while the prototype demonstrates the viability of a hybrid power setup, it also highlights the need for additional or higher wattage solar panels to ensure reliable, continuous off-grid operation.

5.2.6 *Water Level Monitoring and Reliability*

The system was tested over a one-week period to evaluate its reliability under varying environmental conditions. During this time, sensor readings remained stable, and the automated water level monitoring functioned effectively, preventing the main tank from running dry and protecting the pump from damage. The system demonstrated consistent performance, with minimal manual intervention required. However, occasional network disruptions affected real-time data transmission, highlighting the need for improved connectivity solutions.

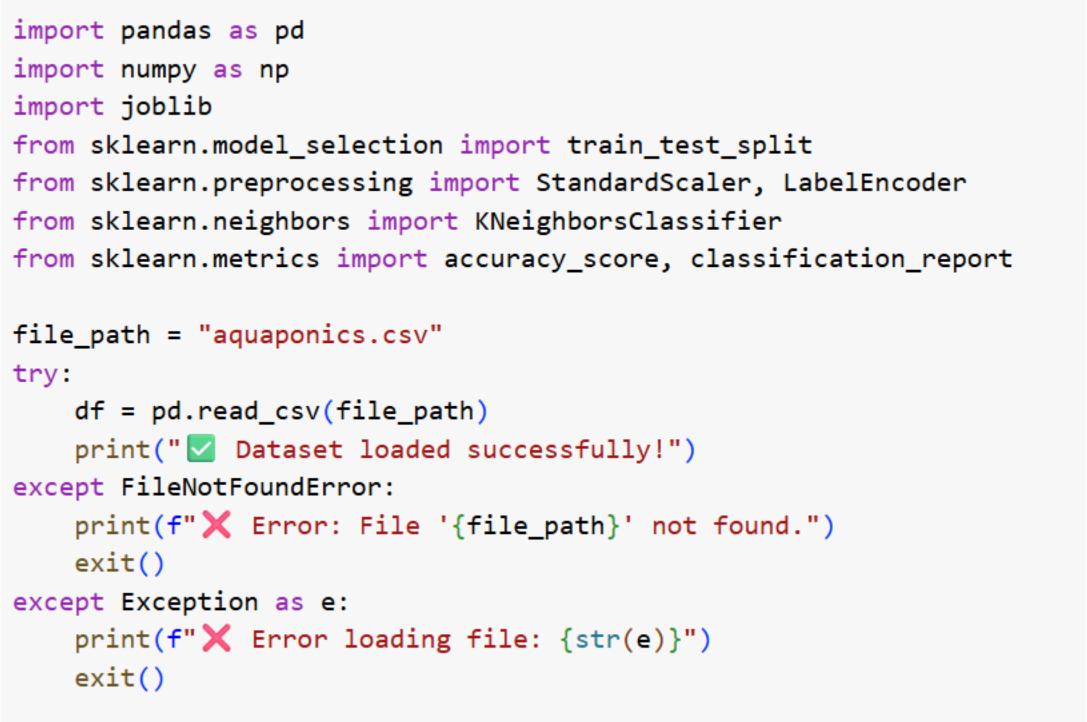
5.2.7 Machine Learning-Based Prediction of System Health

To enhance predictive maintenance, a K-Nearest Neighbors (KNN) algorithm was implemented to assess system health based on historical sensor readings. The model was trained using past pH, TDS, temperature, and water level data to predict anomalies and potential failures. The target variable, ‘System Health’, was categorized into two states: “Good” and “Bad”, ensuring a binary classification approach for simplified decision-making. During preprocessing, all feature columns were converted to numeric values to handle inconsistencies in sensor data. Any invalid or missing values were removed to maintain data integrity. The selected features were then standardized using StandardScaler() to ensure uniformity and improve model accuracy. The dataset was split into 80% training and 20% testing, with an adaptive k-value of 3, optimizing KNN’s ability to classify system health effectively. The trained model achieved an accuracy of 99%, demonstrating high reliability in detecting potential faults. The classification report showed strong performance across both classes, with precision and recall values exceeding 0.96, ensuring accurate predictions of system conditions.

After training, the model was saved as "knnmodeltwo.pkl", along with a corresponding scaler ("scalertwo.pkl") to ensure consistent normalization of future input data. A Python script (predict.py) was developed to handle real-time predictions, receiving sensor readings from the Laravel backend through command-line arguments. The script preprocessed the data, passed it through the trained KNN model, and returned a predicted “Good” or “Bad” status, which was then used to trigger appropriate system responses. This machine learning-based approach significantly enhanced the system’s ability to anticipate failures, enabling proactive interventions to maintain optimal aquaponics conditions.

5.2.8 *Code Breakdown*

a. Data Loading and Error Handling

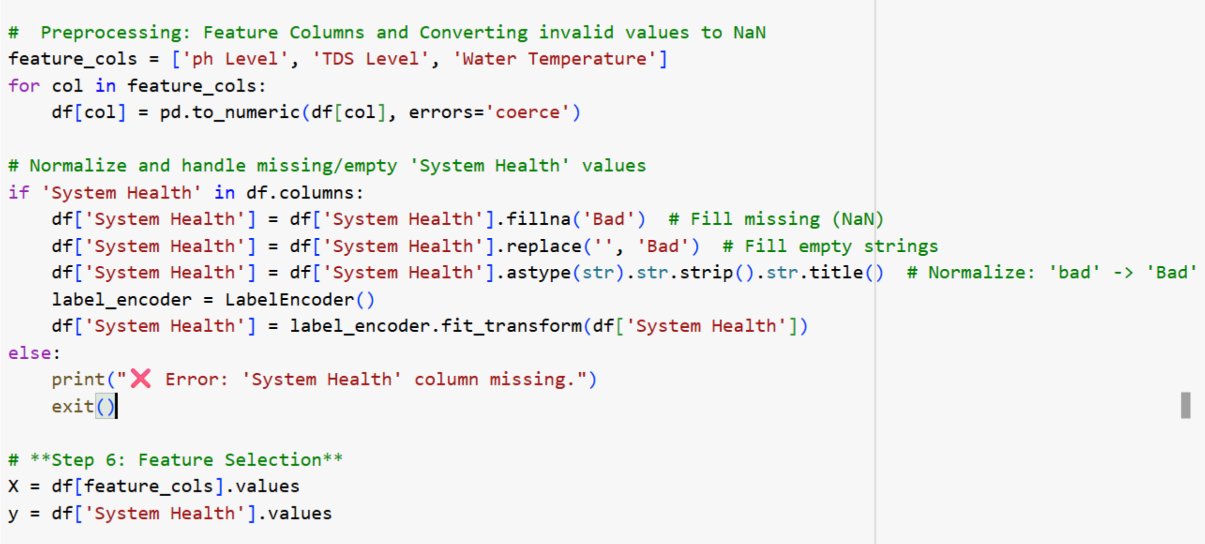


```
import pandas as pd
import numpy as np
import joblib
from sklearn.model_selection import train_test_split
from sklearn.preprocessing import StandardScaler, LabelEncoder
from sklearn.neighbors import KNeighborsClassifier
from sklearn.metrics import accuracy_score, classification_report

file_path = "aquaponics.csv"
try:
    df = pd.read_csv(file_path)
    print("✅ Dataset loaded successfully!")
except FileNotFoundError:
    print(f"❌ Error: File '{file_path}' not found.")
    exit()
except Exception as e:
    print(f"❌ Error loading file: {str(e)}")
    exit()
```

Figure 5.11: Data Loading and Error Handling

Figure 5.11 shows the essential libraries used in data processing, machine learning model creation, evaluation, and saving. These libraries facilitate tasks such as reading CSV files, pandas, numerical operations, numpy, encoding labels, scaling features, splitting datasets, and building the KNN classifier. Pandas help to load the dataset from the aquaponics.csv which contains historical aquaponics sensor readings. Error handling ensures the script fails gracefully if the file is missing or corrupt. The dataset (aquaponics.csv) was imported using the Pandas library. Proper exception handling was incorporated to manage cases where the dataset might be missing, corrupted, or inaccessible, ensuring robustness in data pipeline execution.

b. Data Preprocessing



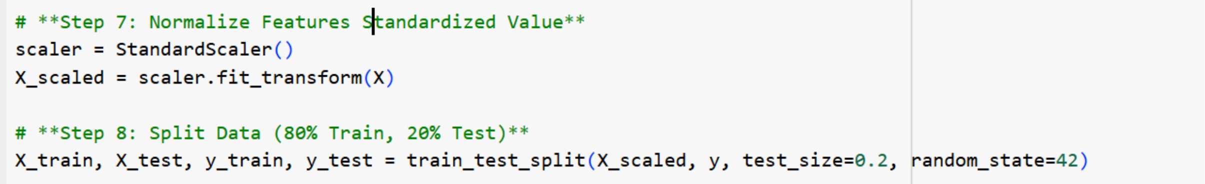
```
#  Preprocessing: Feature Columns and Converting invalid values to NaN
feature_cols = ['ph Level', 'TDS Level', 'Water Temperature']
for col in feature_cols:
    df[col] = pd.to_numeric(df[col], errors='coerce')

# Normalize and handle missing/empty 'System Health' values
if 'System Health' in df.columns:
    df['System Health'] = df['System Health'].fillna('Bad')  # Fill missing (NaN)
    df['System Health'] = df['System Health'].replace('', 'Bad')  # Fill empty strings
    df['System Health'] = df['System Health'].astype(str).str.strip().str.title()  # Normalize: 'bad' -> 'Bad'
    label_encoder = LabelEncoder()
    df['System Health'] = label_encoder.fit_transform(df['System Health'])
else:
    print("❌ Error: 'System Health' column missing.")
    exit()

# **Step 6: Feature Selection**
X = df[feature_cols].values
y = df['System Health'].values
```

Figure 5.12: Data Preprocessing

As shown in *Figure 5.12*, to ensure that the core sensor features (pH, TDS, Temperature) are numeric, any invalid values (e.g., text in numeric fields) are coerced to NaN, which prepares the data for cleaning and model training. The target column System Health, which represents the system's operational condition is cleaned and standardized by replacing missing or empty values with 'Bad', as the default, and values are encoded to integers (0 for "Bad", 1 for "Good") using LabelEncoder. This transformation is necessary for classification. Features and target variables are then defined, separating features (X) used for prediction from the target (y) that indicates system health. This step is crucial for supervised learning models like KNN.

c. Feature Scaling and Data Splitting

Distance-based models like KNN are sensitive to feature magnitude. To prevent bias towards variables with larger numeric ranges, all input features were standardized using StandardScaler() as shown in *Figure 5.13*, to ensure that all variables contributed equally to the distance-based KNN algorithm.



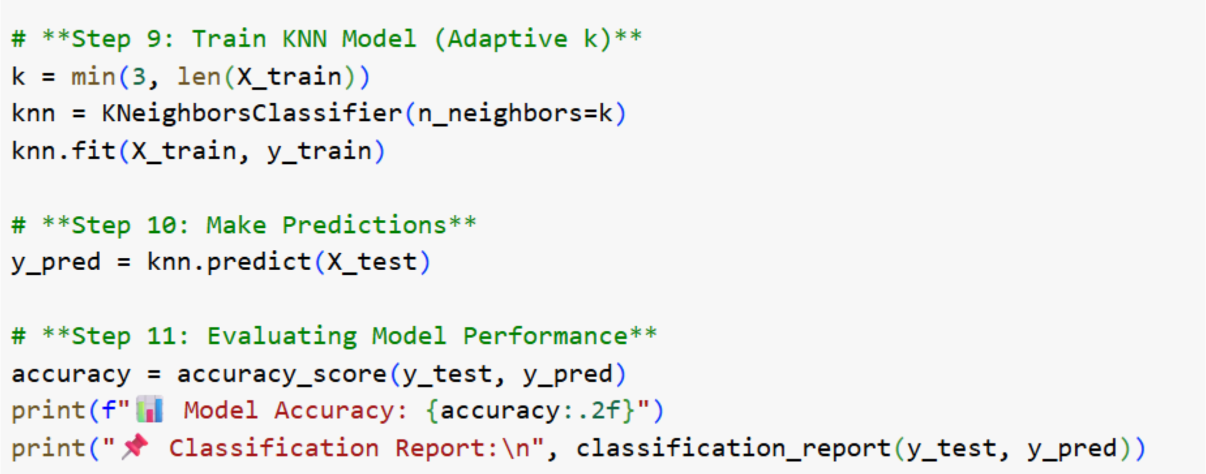
```
# **Step 7: Normalize Features Standardized Value**
scaler = StandardScaler()
X_scaled = scaler.fit_transform(X)

# **Step 8: Split Data (80% Train, 20% Test)**
X_train, X_test, y_train, y_test = train_test_split(X_scaled, y, test_size=0.2, random_state=42)
```

Figure 5.13: Feature Scaling and Data Splitting

The dataset was then divided into training and testing subsets using an 80/20 split to evaluate model generalizability. Random seed 42 ensures reproducibility of experimental results.

d. Model Training and Evaluation

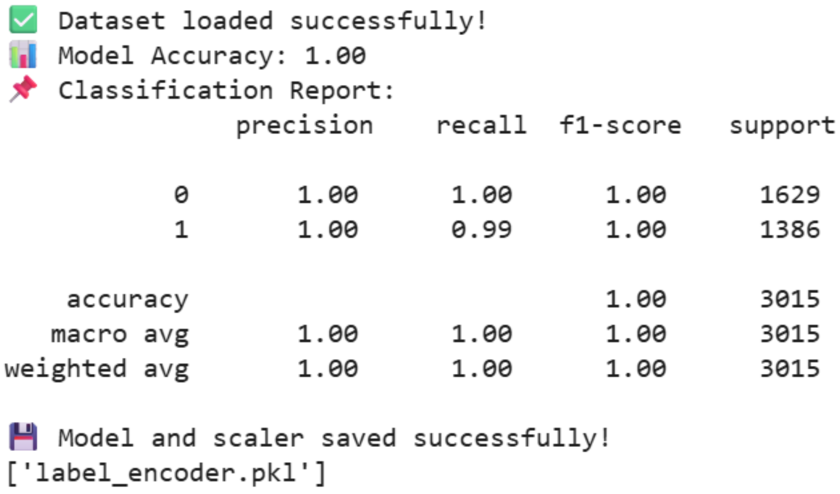
As shown in *Figure 5.14,Figure 5.14* The KNN classifier was trained with k=3, optimized to adapt to smaller training samples. This value balances bias and variance in the model.



```
# **Step 9: Train KNN Model (Adaptive k)**
k = min(3, len(X_train))
knn = KNeighborsClassifier(n_neighbors=k)
knn.fit(X_train, y_train)

# **Step 10: Make Predictions**
y_pred = knn.predict(X_test)

# **Step 11: Evaluating Model Performance**
accuracy = accuracy_score(y_test, y_pred)
print(f"📊 Model Accuracy: {accuracy:.2f}")
print("📌 Classification Report:\n", classification_report(y_test, y_pred))
```

Figure 5.14: Model Training and Evaluation

After training, predictions were generated for the test data and evaluated using accuracy score and a classification report. The model achieved 99% accuracy, with high precision and recall for both "Good" and "Bad" classes as indicated in *Figure 5.15* below.



```
✅ Dataset loaded successfully!
📊 Model Accuracy: 1.00
📌 Classification Report:
               precision    recall  f1-score   support

           0       1.00      1.00      1.00      1629
           1       1.00      0.99      1.00      1386

    accuracy                           1.00      3015
   macro avg       1.00      1.00      1.00      3015
weighted avg       1.00      1.00      1.00      3015

💾 Model and scaler saved successfully!
['label_encoder.pkl']
```

Figure 5.15: Model Accuracy and Classification Report

e. Model Serialization

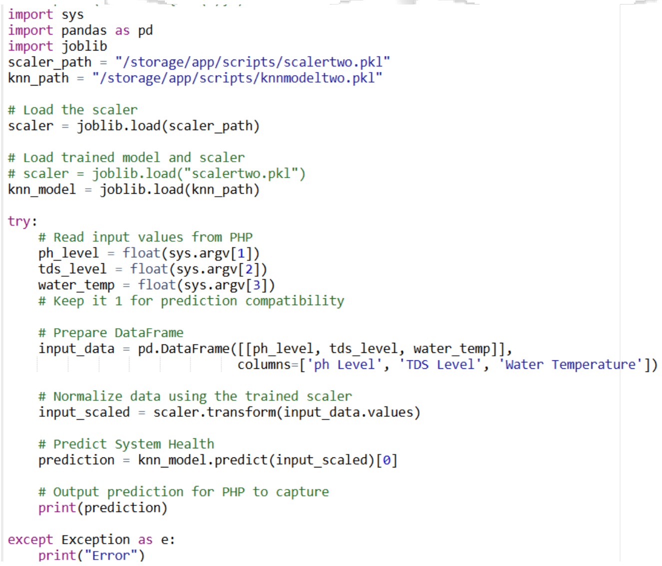
The trained model, scaler, and label encoder were serialized using joblib, enabling seamless deployment for real-time predictions as shown in *Figure 5.16*.

```
# **Step 12: Save the Model and Scaler**
joblib.dump(knn, "knnmodeltwo.pkl")
joblib.dump(scaler, "scalertwo.pkl")
print("💾 Model and scaler saved successfully!")

# **Step 13: Save Label Encoder for Future Use**
joblib.dump(label_encoder, "label_encoder.pkl")
```

Figure 5.16: Model Serialization

f. Real-Time Prediction via Python Integration

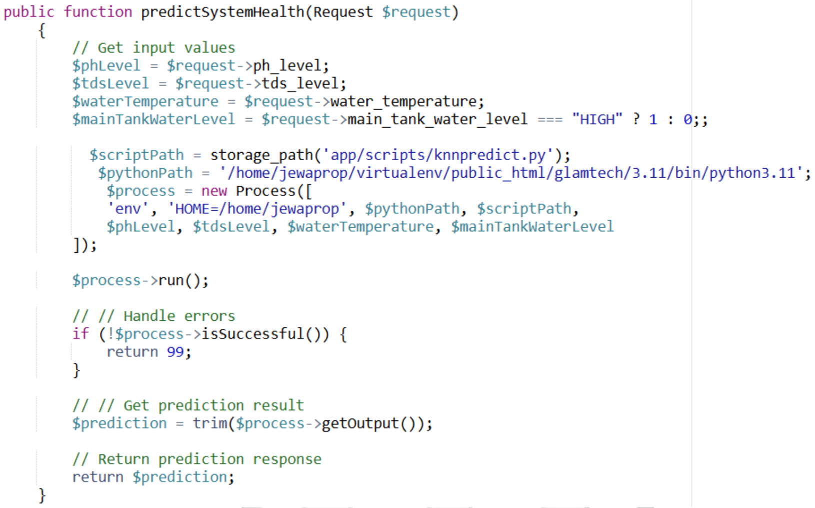
A Python script (predict.py) was then developed to handle the prediction process. This script loaded the trained KNN model and the corresponding scaler before receiving input values from Laravel through command-line arguments using sys.argv. The received sensor readings were structured into a Pandas DataFrame and normalized using the stored scaler. Once preprocessed, the data was passed through the model for prediction, and the predicted value was printed as shown in Figure 5.17. This output was captured by Laravel for further decision-making and system responses.



```
import sys
import pandas as pd
import joblib
scaler_path = "/storage/app/scripts/scalertwo.pkl"
knn_path = "/storage/app/scripts/knnmodeltwo.pkl"

# Load the scaler
scaler = joblib.load(scaler_path)

# Load trained model and scaler
# scaler = joblib.load("scalertwo.pkl")
knn_model = joblib.load(knn_path)

try:
    # Read input values from PHP
    ph_level = float(sys.argv[1])
    tds_level = float(sys.argv[2])
    water_temp = float(sys.argv[3])
    # Keep it 1 for prediction compatibility

    # Prepare DataFrame
    input_data = pd.DataFrame([[ph_level, tds_level, water_temp]],
                              columns=['ph Level', 'TDS Level', 'Water Temperature'])

    # Normalize data using the trained scaler
    input_scaled = scaler.transform(input_data.values)

    # Predict System Health
    prediction = knn_model.predict(input_scaled)[0]

    # Output prediction for PHP to capture
    print(prediction)

except Exception as e:
    print("Error")
```

Figure 5.17: Code to incorporate the trained model (knnpredict.py)

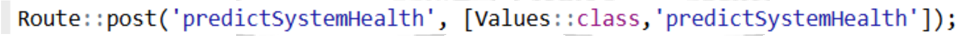
In Laravel, a controller method was implemented to handle prediction requests as shown in Figure 5.18.



```
public function predictSystemHealth(Request $request)
    {
        // Get input values
        $phLevel = $request->ph_level;
        $tdsLevel = $request->tds_level;
        $waterTemperature = $request->water_temperature;
        $mainTankWaterLevel = $request->main_tank_water_level === "HIGH" ? 1 : 0;;

          $scriptPath = storage_path('app/scripts/knnpredict.py');
           $pythonPath = '/home/jewaprop/virtualenv/public_html/glamtech/3.11/bin/python3.11';
            $process = new Process([
            'env', 'HOME=/home/jewaprop', $pythonPath, $scriptPath,
            $phLevel, $tdsLevel, $waterTemperature, $mainTankWaterLevel
        ]);

        $process->run();

        // // Handle errors
        if (!$process->isSuccessful()) {
            return 99;
        }

        // // Get prediction result
        $prediction = trim($process->getOutput());

        // Return prediction response
        return $prediction;
    }
```

Figure 5.18: Function to predict system health

This method extracted sensor values from incoming HTTP requests and constructed a command to execute the Python script, passing the sensor readings as arguments. The command was executed using shell_exec(), and the script's output was retrieved as the predicted system health status. This prediction was then returned as a JSON response to be used within the Laravel application. A route was defined in Laravel to handle these requests as shown in Figure 5.19.



```
Route::post('predictSystemHealth', [Values::class,'predictSystemHealth']);
```

Figure 5.19: Route to predict system health method

Chapter 6: Discussion of Results

6.1 Introduction

This chapter discusses the results obtained from implementing and testing the Solar-Powered Cyber-Physical System (CPS) for Aquaponics Optimization in Urban Environments. Key performance aspects, including sensor accuracy, automation efficiency, energy sustainability, and predictive analytics, were evaluated to assess the system's effectiveness. The first objective, reviewing relevant technologies, was addressed through an extensive literature review, identifying IoT sensors, solar energy, automation, and machine learning as critical components. The second objective, identifying system requirements, guided the selection of low-power sensors, efficient water regulation mechanisms, and a solar-powered energy source, ensuring feasibility in resource-constrained urban environments. The third objective, developing the CPS, was achieved by integrating real-time monitoring, automated water pump control, and a web-based dashboard, enhancing decision-making and reducing manual intervention. The fourth objective, system testing, validated the system's performance, with results confirming high sensor accuracy, efficient automation, and effective energy management. The K-Nearest Neighbors (KNN) algorithm successfully predicted system imbalances, allowing timely corrective actions. By intergrating machine learning and renewable energy sources, this CPS presents a sustainable and scalable solution for aquaponics management in resource-constrained urban environments, addressing key challenges related to food security, water quality control, and energy efficiency.

6.2 Water Quality Monitoring and Control

This research focused on an aquaponics system optimized for tilapia and kales, with water quality parameters aligned to their ideal growth conditions. For tilapia, the optimal pH range is 6.5–8.5, while kales thrive in pH levels between 6.0–7.5. The optimal temperature for tilapia is within 22–30°C, ensuring healthy growth, while kales require moderate temperatures for nutrient absorption. Additionally, the recommended TDS level for tilapia ranges from 1000 to 1500 ppm, ensuring suitable water quality for fish health, while kales benefit from a range of 500 to 1200 ppm for proper development. These parameters guided both the sensor monitoring strategy and the corrective actions employed. The CPS successfully monitored key water quality parameters, including pH, temperature, and TDS, providing real-time data crucial for maintaining optimal aquaponics conditions. The sensor performance aligns with prior studies like Goddek et al. (2019) and Zou et al. (2020), who emphasize the critical role of stable pH and temperature in aquaponics productivity. The sensors provided real-time data, enabling precise monitoring of aquaponics conditions. The pH sensor detected fluctuations effectively, allowing timely adjustments to maintain optimal conditions for both fish and plants. The temperature sensor functioned reliably, ensuring that water temperature remained within the ideal range.

Compared to earlier IoT-based monitoring solutions Adewumi et al. (2021, our implementation demonstrated similarly high sensor accuracy and responsiveness. However, unlike some works that rely on chemical pH adjustments, this research employed freshwater dilution for pH correction, a more sustainable approach supported by Kim et al. (2019). This method mitigates the potential ecological harm caused by chemical dosing, representing a merit in environmental sustainability not always addressed in previous studies. The machine learning model, K-Nearest Neighbors (KNN), achieved a high accuracy of 0.99 as shown in *Figure 5.15*, which compares favorably to Gutiérrez et al. (2018), who reported improved robustness by hybridizing KNN with decision trees. While our KNN-only model is simpler and computationally less intensive, the slight dip in recall for one class suggests room for improvement. Future work could involve refining the training dataset and experimenting with more advanced machine learning models such as Random Forest or Neural Networks to further enhance predictive accuracy.

6.3 pH Adjustment Analysis

During testing, the system encountered instances where pH levels deviated significantly from the ideal range. For example, a recorded pH value of 11.7, far above the optimal 7.5, required correction to maintain suitable water conditions. Instead of using acid dosing, dilution with fresh water was employed to adjust pH levels. Since TDS influences buffering capacity, adding water with lower TDS levels helped neutralize alkalinity without chemical additives. The system's approach to pH correction by dilution rather than acid dosing aligns with sustainability goals highlighted in Kim et al. (2019) and Adewumi et al. (2021). This contrasts with conventional methods that often overlook the long-term microbial and environmental impacts of chemical additives.

By gradually introducing fresh water, the system This allowed parameters to stabilize naturally within the recommended range for optimal fish and plant growth. This approach reduced dependency on chemical additives, making the system more sustainable and minimizing potential harm to aquatic life. Future improvements could involve real-time TDS monitoring to determine optimal dilution rates dynamically.

6.4 Automation of Water Pump Operations

The automated water pump system responded efficiently to changes in system health, consistent with findings by Espinosa et al. (2020), who advocate IoT integration for resource optimization. The integration of a water float switch ensured that the main tank maintained adequate water levels, preventing system failures due to low water supply. The ESP32 microcontroller executed control commands with minimal latency, demonstrating reliable real-time automation. However, occasional delays in actuation were observed when network connectivity was unstable, suggesting the need for a more robust communication protocol or an offline fail-safe mechanism. To prevent overflow, the pump operation was regulated by a continuous monitoring cycle. Every 3 seconds, the system checked the system health status. If the status remained bad, the pump continued running, ensuring that water replenishment was sustained until conditions stabilized. The pump only stopped once the sensor readings indicated that the water level had reached the optimal range. The pump's runtime was estimated based on its flow rate to ensure precise water delivery. With a flow rate of 240 L/H (4 L/min), the required runtime was calculated using the formula:To evaluate the pump's ability to deliver the required water volume, its operational duration was estimated based on the flow rate. The pump specifications indicate a flow rate of 240 L/H (liters per hour), which translates to 4 L/min.

Using the formula:

$$t = \frac{V}{Q}$$

Equation 6.1: Pump operational duration

where:

t = runtime (minutes)

V = required water volume (liters)

Q = pump flow rate (liters per minute)

For instance, using *Equation 6.1*, if the system requires 50 liters of water to maintain equilibrium, the estimated runtime is:

$$t = \frac{50}{4} = 12.5\text{minutes}$$

Since the system continuously evaluated the water level every 3 seconds, adjustments were made dynamically, ensuring that the pump stopped precisely when optimal levels were reached. The calculated pump runtime based on flow rate allowed precise water delivery, preventing overflow and conserving water. The system could benefit from integrating flow sensors for real-time feedback, an approach supported by recent studies Baganz et al., (2021), to dynamically adjust runtime and reduce energy consumption, an important advancement over fixed-timing controls common in earlier designs.

6.5 Solar Power Efficiency and Sustainability

The energy subsystem utilizing an 18V, 5W solar panel and 12V, 7.2Ah battery, provides a sustainable power source but reveals limitations in output under suboptimal sunlight. With the system's estimated power requirement at approximately 12.8W under normal operation, the panel generates only 5W, which is significantly lower than the system's daily energy demand. This constraint aligns with observations by Somerville et al. (2014) and Adewumi et al. (2021), who emphasize the need for hybrid or higher-capacity solar setups for reliable off-grid operation. While the battery capacity allowed nearly 48 hours of autonomy, the solar panel's insufficient wattage limits recharging efficiency, especially in cloudy conditions. This exposes a trade-off between system portability and energy sufficiency, a common challenge in urban CPS applications. Future iterations should explore hybrid energy solutions, such as combining solar with wind power or higher-capacity solar setups for reliable off-grid operation, as recommended by Baganz et al. (2021).

6.6 Web-Based Dashboard Performance

The web-based dashboard successfully displayed real-time sensor data and allowed users to remotely monitor system performance. The user interface was intuitive, enabling quick access to critical information. However, minor delays in data updates were noted, particularly during peak network traffic. Future enhancements could involve implementing data caching mechanisms and optimizing cloud server communication.

6.7 System Limitations and Improvement Areas

The main limitations of the research include the short monitoring period, restricting long-term performance evaluation. Additionally, while the KNN algorithm provided useful predictions, more advanced machine learning models could improve accuracy. The reliance on solar power alone posed occasional challenges, highlighting the need for alternative energy sources in low-sunlight conditions. Sensor calibration was necessary to maintain data accuracy, and occasional network disruptions impacted real-time data transmission. The research conducted two interviews with key stakeholders to obtain focused, high-quality insights from experts in aquaponics systems. Interviewees were selected based on their extensive knowledge and hands-on experience, ensuring the relevance and impact of the data collected. However, as the research primarily relied on real-time sensor data and system performance metrics, extensive qualitative interviews were unnecessary. Instead, the interviews served as a supplementary data source to validate system effectiveness rather than a primary method of analysis.

Despite these limitations, the research contributes to the field by demonstrating a practical, integrated CPS that balances sustainability, automation, and predictive analytics for urban aquaponics. Future research should pursue hybrid energy systems, as suggested by Baganz et al. (2021, more robust communication protocols, and adaptive machine learning methods (Wang et al., 2019) to optimize system resilience and efficiency.

6.8 Research Significance and Conclusion

This research addressed critical challenges in maintaining optimal water quality and automation within urban aquaponics systems, especially under resource-constrained conditions. By integrating cyber-physical systems (CPS) with IoT-based real-time monitoring, the research demonstrated improvements in system sustainability, operational efficiency, and scalability. Unlike many prior studies that relied heavily on chemical interventions for pH control, this research revealed that fresh water dilution is a more sustainable and less disruptive alternative, aligning with findings by Kim et al. (2019) but providing practical validation in an urban aquaponics context. The application of the K-Nearest Neighbors (KNN) algorithm for predictive maintenance yielded high accuracy (0.99), indicated that even relatively simple machine learning models can provide reliable decision support in aquaponics management. This finding corroborates earlier work by Gutiérrez et al. (2018), who highlighted the potential of hybrid machine learning approaches, yet this research confirms that straightforward models can be effective when properly trained and integrated.

The research outcomes clearly demonstrate that real-time sensor data significantly enhances water quality management, while automated control of water pumps improves system resilience, findings consistent with Espinosa et al. (2020). Additionally, the viability of solar power as a renewable energy source was validated, although limitations due to panel capacity suggest the need for hybrid solutions, supporting recommendations from Adewumi et al. (2021). Overall, this research contributes to the field by providing an integrated CPS framework that optimizes urban food production without excessive resource consumption. It extends the current body of knowledge by emphasizing sustainable alternatives and practical automation strategies tailored for urban settings. In conclusion, integrating advanced monitoring, automation, and renewable energy within aquaponics can empower urban farmers to increase productivity, reduce environmental impact, and enhance food security. Future research should focus on refining predictive analytics through more advanced machine learning models, exploring hybrid renewable energy configurations, and conducting longer-term performance assessments to fully realize the potential of sustainable urban aquaponics systems.

Chapter 7: Conclusion and Recommendation

7.1 Conclusion

The thesis successfully developed and tested a Cyber-Physical System (CPS) for optimizing aquaponics in resource-constrained metropolitan environments. The system integrated real-time water quality monitoring, automated pump control, and solar power for sustainable energy use. Despite some limitations, the CPS demonstrated effectiveness in enhancing the efficiency and sustainability of aquaponics systems.

Key conclusions from the research include:

i. Water Quality Monitoring - The CPS reliably monitored critical water quality parameters including pH, temperature, and total dissolved solids (TDS), enabling timely adjustments to maintain optimal conditions for both plants and fish.

ii. Automation of Water Pump Operations - The integration of the ESP32 microcontroller and water float switch ensured that the water pump responded promptly to fluctuating water conditions, preventing system failures and maintaining stable operations.

iii. Solar Power Efficiency - The solar panel and battery system provided a sustainable energy source, although performance was affected during cloudy periods.

iv. Web-Based Dashboard Performance - The dashboard successfully displayed real-time data to users, enhancing remote monitoring capabilities, despite minor delays under high network traffic conditions.

v. Machine Learning for Predictive Analytics - The K-Nearest Neighbors (KNN) algorithm was used to predict system health based on collected sensor data, demonstrating potential for predictive maintenance and early intervention.

7.2 Research Contributions

This research contributes to the field of smart agriculture and urban food production by developing an IoT-enabled CPS for aquaponics that enhances automation and real-time monitoring. It demonstrates the feasibility of solar-powered automation in urban agricultural settings, ensuring sustainability and energy efficiency. Additionally, the research showcases the application of machine learning, specifically the KNN algorithm, in predictive system health analysis, enabling proactive management of water quality and system performance. Furthermore, it provides an open-source framework that future researchers and practitioners can build upon, fostering innovation and further advancements in smart aquaponics systems.

7.3 Recommendations for Future Work

To enhance the effectiveness and reliability of the CPS for aquaponics, the following recommendations are proposed. Future studies should conduct long-term monitoring to assess system stability and optimize automation parameters. Integrating a hybrid power system, such as solar combined with grid power or battery backup, can improve reliability during low sunlight conditions. Exploring advanced predictive analytics, including deep learning models like LSTMs or Random Forest, could enhance the accuracy of system health predictions. Additionally, implementing an offline mode or edge computing capabilities would strengthen network resilience and ensure system functionality in areas with unstable internet connectivity. To boost accessibility and user engagement, the development of a mobile application that provides real-time alerts is also recommended

7.4 Final Remarks

The developed Cyber-Physical System offers significant potential to optimize aquaponics through automation, real-time monitoring, and predictive analytics. While the system effectively addressed key challenges in urban aquaponics, opportunities exist for further enhancements to improve efficiency, resilience, and scalability. By addressing the identified limitations and implementing the recommended improvements, future iterations of this system can provide even greater benefits to urban agricultural practitioners and researchers.

REFERENCES

A Guide to Ideal Water Pump Placement in Aquaponics—Go Green Aquaponics. (2024, March 5). https://gogreenaquaponics.com/blogs/news/where-to-place-the-water-pump-in-your-aquaponics-system

Abdi, A. H., Mohamed, A. A., & Mohamed, F. H. (2024). Enhancing food security in sub-Saharan Africa: Investigating the role of environmental degradation, food prices, and institutional quality. Journal of Agriculture and Food Research, 17, 101241. https://doi.org/10.1016/j.jafr.2024.101241

Abikoye, O., Bajeh, A., Bamidele, A., Oloduowo, A., Mojeed, H., AbdulRaheem, M., Oladipo, I., & Salihu, S. (2021). *Application of Internet of Thing and Cyber Physical System in Industry 4.0 Smart Manufacturing* (pp. 203–217). https://doi.org/10.1007/978-3-030-66222-6_14

Abu Hatab, A., Cavinato, M. E. R., Lindemer, A., & Lagerkvist, C.-J. (2019). Urban sprawl, food security and agricultural systems in developing countries: A systematic review of the literature. Cities, 94, 129–142. https://doi.org/10.1016/j.cities.2019.06.001

Adewumi, J. R., Olorunfemi, O., & Babajide, F. (2021). "Hybrid solar energy storage solutions for sustainable aquaponics systems." *Renewable Energy*, 178, 345–358.

Al-Ali, A. R., Al Nabulsi, A., Mukhopadhyay, S., Awal, M. S., Fernandes, S., & Ailabouni, K. (2019). IoT-solar energy powered smart farm irrigation system. *Journal of Electronic Science and Technology*, *17*(4), 100017. https://doi.org/10.1016/j.jnlest.2020.100017

Alkhayyal, M., & Mostafa, A. (2024). Recent Developments in AI and ML for IoT: A Systematic Literature Review on LoRaWAN Energy Efficiency and Performance Optimization. *Sensors*, *24*(14), Article 14. https://doi.org/10.3390/s24144482

Alselek, M., Alcaraz-Calero, J. M., Segura-Garcia, J., & Wang, Q. (2022). Water IoT monitoring system for aquaponics health and fishery applications. *Sensors*, *22*(19), Article 7679. https://doi.org/10.3390/s22197679

Amolong, G. (2024, August 29). Building a Deep Reinforcement Learning Bitcoin Trading Bot with TensorForce. Medium. https://medium.com/@gaille.amolong1/building-a-deep-reinforcement-learning-bitcoin-trading-bot-with-tensorforce-f7bfd83ee166

Analog pH Sensor / Meter Kit. (2021). Pixel Electric Company Limited. https://www.pixelelectric.com/sensors/load-pressure-flow-vibration/water-tds-ph-flow-level-sensor/analog-ph-sensor-meter-kit/

Aquaponics, G. G. (n.d.). What is Aquaponics and How Does it Work? Go Green Aquaponics. Retrieved July 26, 2024, from https://gogreenaquaponics.com/blogs/news/what-is-aquaponics-and-how-does-it-work

Aquaponics, G. G. (2024, February 16). *Why is pH Important in Aquaponics?* Go Green Aquaponics. https://gogreenaquaponics.com/blogs/news/the-importance-of-ph-in-aquaponics

Aquaponic Systems. (2024). Hydroponics Africa. Retrieved September 30, 2024, from https://www.hydroponicsafrica.org/aquaponic-systems/

Baganz, D., Junge, R., & Portella, M. C. (2021). "Aquaponics as an Educational Tool for Sustainable Development Goals (SDGs): A Review." *Sustainability*, **13(4)**, 1885.

Bashan, A., & Kordova, S. (2021). Globalization, quality and systems thinking: Integrating global quality Management and a systems view. *Heliyon*, *7*(2), e06161. https://doi.org/10.1016/j.heliyon.2021.e06161

Basir, R., Qaisar, S., Ali, M., Aldwairi, M., Ashraf, M., Mahmood, A., & Gidlund, M. (2019). Fog Computing Enabling Industrial Internet of Things: State-of-the-Art and Research Challenges. Sensors, 19, 4807. https://doi.org/10.3390/s19214807

Blynk: A low-code IoT software platform for businesses and developers. (2024). https://blynk.io

Bradley, J., & Atkins, E. (2014). Optimization and Control of Cyber-Physical Vehicle Systems. *Sensors (Invited Paper) Special Issue Cyber-Physical Systems (Urlhttp://Www.Mdpi.Com/Journal/Sensors/Special_issues/Wsn_cyber_physical_system), 15*. https://doi.org/10.3390/s150923020

Brunckhorst, J. (2023, September 18). Destructive creation: When feedback loops go wrong. *Medium*. https://janetbrunckhorst.medium.com/destructive-creation-when-feedback-loops-go-wrong-18520fd72fa1

Chakraborty, S., & Aithal, P. S. (2023). *Let Us Create an IoT Inside the AWS Cloud* (SSRN Scholarly Paper 4400278). https://doi.org/10.2139/ssrn.4400278

Channa, A. A., Munir, K., Hansen, M., & Tariq, M. F. (2024). Optimisation of Small-Scale Aquaponics Systems Using Artificial Intelligence and the IoT: Current Status, Challenges, and Opportunities. *Encyclopedia*, *4*(1), Article 1. https://doi.org/10.3390/encyclopedia4010023

Choudhary, A. (2024, April 17). *Introduction, Definitions, Homeostasis, Components and Types of Feedback systems*. https://www.pharmaguideline.com/2022/01/introduction-definitions-homeostasis.html

Conductivity TDS Meter & Sensor—Apure. (2021, October 16). https://apureinstrument.com/water-quality-analysis/conductivity-tds/

Dawa, M., Lausa, S., & Tibon, M. (2022). Internet of things (IoT) based aquaponics management system adaptive to climate change. 2502, 050004. https://doi.org/10.1063/5.0108681

Dey, N., Ashour, A. S., Shi, F., et al. (2018). *Medical cyber-physical systems: A survey*. *Journal of Medical Systems*, *42*(74). https://doi.org/10.1007/s10916-018-0921-x

Diaz, J. M., Webb, S. T., Warner, L. A., & Monaghan, P. (2018). Barriers to community garden success: Demonstrating framework for expert consensus to inform policy and practice. Urban Forestry & Urban Greening, 31, 197–203. https://doi.org/10.1016/j.ufug.2018.02.014

Difference between Cyber-Physical System(CPS) and Embedded System. (2023, March 29). GeeksforGeeks.https://www.geeksforgeeks.org/difference-between-cyber-physical-systemcps-and-embedded-system/

Dijkgraaf, K. H., Goddek, S., & Keesman, K. J. (2019). Modeling innovative aquaponics farming in Kenya. *Aquaculture International*, *27*(6), 1395–1422. https://doi.org/10.1007/s10499-019-00397-z

DS18B20 Digital Temperature Sensor. (2021). Pixel Electric Company Limited. https://www.pixelelectric.com/sensors/temp-humidity-gas-environmental/temperature-humidity/ds18b20-digital-temperature-sensor/

Du Toit, M. J., Rendón, O., Cologna, V., Cilliers, S. S., & Dallimer, M. (2022). Why Home Gardens Fail in Enhancing Food Security and Dietary Diversity. Frontiers in Ecology and Evolution, 10. https://doi.org/10.3389/fevo.2022.804523

Dutta, A., Tamang, P., Dahal, P., Prajapati, R., & K.C., S. (2018, September 27). *IoT based Aquaponics Monitoring System*.

ESP32S DevKIT WIFI + BLE Module—Microcontroller. (2023). https://www.pixelelectric.com/iot-and-wireless/esp-wifi-modules/esp32s-devkit-wifi-ble-module/

Equifinality—An overview | ScienceDirect Topics. (n.d.). Retrieved August 5, 2024, from https://www.sciencedirect.com/topics/psychology/equifinality

Extremum Seeking Control—MATLAB & Simulink. (n.d.). Retrieved August 11, 2024, from https://www.mathworks.com/help/slcontrol/ug/extremum-seeking-control.html

Forrester, J. W. (1994). System dynamics, systems thinking, and soft OR. *System Dynamics Review*, *10*(2–3), 245–256. https://doi.org/10.1002/sdr.4260100211

García-Valls, M., Dubey, A., & Botti, V. (2018). Introducing the new paradigm of Social Dispersed Computing: Applications, Technologies and Challenges. *Journal of Systems Architecture*, *91*, 83–102. https://doi.org/10.1016/j.sysarc.2018.05.007

Gamkrelidze, R. (2013). Principles of Optimal Control Theory. Springer Science & Business Media.

Getricity. (2024). Aquaponics and solar: A sustainable symbiosis. https://getricity.com/blog/aquaponics-and-solar-sustainable-symbiosis

Grafana: Real-Time Data Visualization and Monitoring—Webhosting, VPS Hosting a Dedikované Servery. (2024). https://www.mydreams.cz/en/hosting-wiki/1002-grafana-real-time-data-visualization-and-monitoring.html

Habib, M. K., & Chimsom, C. I. (2022). *CPS: Role, characteristics, architectures and future potentials*. In *Proceedings of the 3rd International Conference on Industry 4.0 and Smart Manufacturing*. https://www.sciencedirect.com/science/article/pii/S1877050922000000

Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*, *20*, 101621. https://doi.org/10.1016/j.rineng.2023.101621

Hätönen, J. (2004). *Hierarchical systems theory*. In *Report 145* (Session 12). Systems Engineering Laboratory, University of Oulu. https://neocybernetics.com/report145/Chapter12.pdf

Harsha, H., Sundar, G., & Ramya, S. (2022). The real-time monitoring system for aquaponics using Aquapony. *International Research Journal of Modernization in Engineering, Technology and Science*, *4*(7), 348. https://www.irjmets.com

Hayes, A. (2024, July 31). *Autoregressive Integrated Moving Average (ARIMA) Prediction Model*. Investopedia. https://www.investopedia.com/terms/a/autoregressive-integrated-moving-average-arima.asp

Hespanha, J. P. (2005). Lecture notes on LQR/LQG controller design. https://staff.uz.zgora.pl/wpaszke/materialy/kss/lqrnotes.pdf

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. *MIS Quarterly*, *28*(1), 75-105.

How to Do Thematic Analysis | A Complete Step-by-Step Guide. (2021, May 5). https://www.projecteditinghelp.com/data-analysis-service/qualitative-data-analysis-service/thematic-analysis/how-to-do-thematic-analysis/

Humaizi, A. (2024, April 28). Cyber Physical System in Industrial Control System. *Medium*. https://medium.com/@maizi5469/cyber-physical-system-in-industrial-control-system-11931fe31f89

Hydroponics Africa. (n.d.). *Growing fish and vegetables together: Natural, sustainable and rewarding*. https://www.hydroponicsafrica.org/aquaponic-systems/

Ibrahim, L. A., Shaghaleh, H., El-Kassar, G. M., Abu-Hashim, M., Elsadek, E. A., & Alhaj Hamoud, Y. (2023). Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency. *Water*, *15*(24), Article 24. https://doi.org/10.3390/w15244310

Insights, S. (2023, May 17). *Top 10 Cyber-Physical Systems Examples in 2023 & 2024*. StartUs Insights. https://www.startus-insights.com/innovators-guide/cyber-physical-systems/

Inc, E. T. (2024). *MQTT vs HTTP: Which is Better Suited for the Internet of Things (IoT)?* www.Emqx.Com. https://www.emqx.com/en/blog/mqtt-vs-http

Integrating with Home Assistant via MQTT and Setting Up Automations. (2023\4.). Atmocube. Retrieved September 9, 2024, from https://atmotube.com/atmocube-support/integrating-home-assistant-via-mqtt

Ibrahim, L. A., Shaghaleh, H., El-Kassar, G. M., Abu-Hashim, M., Elsadek, E. A., & Alhaj Hamoud, Y. (2023). Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency. *Water*, *15*(24), Article 24. https://doi.org/10.3390/w15244310

Janssen, H. G., Davies, I. G., Richardson, L. D., & Stevenson, L. (2018). Determinants of takeaway and fast food consumption: A narrative review. *Nutrition Research Reviews*, *31*(1), 16–34. https://doi.org/10.1017/S0954422417000178

Januario, F., Cardoso, A., & Gil, P. (2019). A Distributed Multi-Agent Framework for Resilience Enhancement in Cyber-Physical Systems. *IEEE Access*, *PP*, 1–1. https://doi.org/10.1109/ACCESS.2019.2903629

Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2023). An integrated outlook of Cyber–Physical Systems for Industry 4.0: Topical practices, architecture, and applications. *Green Technologies and Sustainability*, *1*(1), 100001. https://doi.org/10.1016/j.grets.2022.100001

Jayne, T. S., Chamberlin, J., & Headey, D. D. (2014). Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food Policy*, *48*, 1–17. https://doi.org/10.1016/j.foodpol.2014.05.014

Kang, W., Kapitanova, K., & Son, S. (2012). RDDS: A Real-Time Data Distribution Service Physical Systems. IEEE Transactions on Industrial Informatics, 8, 393–405. https://doi.org/10.1109/TII.2012.2183878

Karimanzira, D., & Rauschenbach, T. (2018). Optimal utilization of renewable energy in aquaponic systems. *Energy and Power Engineering*, *10*(6), 164-171. https://doi.org/10.4236/epe.2018.106018

Kim, H., Lee, S., & Park, J. (2019). "Non-chemical pH regulation strategies for aquaponics sustainability." Non-chemical pH regulation strategies for aquaponics sustainability., 15, 100216.

Kok, C., Kusuma, I., Koh, Y., Tang, H., & Lim, A. (2024). Smart Aquaponics: An Automated Water Quality Management System for Sustainable Urban Agriculture. Electronics, 13, 820. https://doi.org/10.3390/electronics13050820

Laforest, M. (2023, September 19). *Smart indoor aquaponics gardens: For everyone and the environment*. Onua World. https://onuaworld.com/blogs/news/smart-indoor-aquaponics-gardens-for-everyone-and-the-environment?_pos=4&_psq=aquaponics&_ss=e&_v=1.0

Laravel vs Node.js: Making the Right Choice. (2024, February 26). Simplilearn.Com. https://www.simplilearn.com/laravel-vs-node-js-article

Latash, M. L. (2012). 4—Instructive examples. In M. L. Latash (Ed.), Fundamentals of Motor Control (pp. 55–68). Academic Press. https://doi.org/10.1016/B978-0-12-415956-3.00004-X

Linear-Quadratic-Gaussian (LQG) Design—MATLAB & Simulink. (n.d.). Retrieved August 11, 2024, from https://www.mathworks.com/help/control/getstart/linear-quadratic-gaussian-lqg-design.html

Lqr Control: Applications & Advantages | StudySmarter. (n.d.). StudySmarter UK. Retrieved August 11, 2024, from https://www.studysmarter.co.uk/explanations/engineering/aerospace-engineering/lqr-control/

Mahfuz, N., & Al-Mayeed, S. (2020). *Smart Monitoring and Controlling System for Aquaculture of Bangladesh to Enhance Robust Operation* (p. 1133). https://doi.org/10.1109/TENSYMP50017.2020.9230748

Mahmoud, M. M. M., Darwish, R., & Bassiuny, A. M. (2023). Development of an economic smart aquaponic system based on IoT. *Journal of Engineering Research*. https://doi.org/10.1016/j.jer.2023.08.024

Maulini, R., Sahlinal, D.*, & Arifin, O. (2022). Monitoring of pH, ammonia (NH_3), and temperature parameters in aquaponic water in the 4.0 Revolution era. *IOP Conference Series: Earth and Environmental Science*, *1012*, Article 012087. https://doi.org/10.1088/1755-1315/1012/1/012087

Maruti, C., & Chow, S. (2024, January 24). *Real-time data processing for ML with Striim and BigQuery*. Google Cloud Blog. https://cloud.google.com/blog/topics/partners/real-time-data-processing-for-ml-with-striim-and-bigquery

Mbuthia, M., Francis, K., Aayush, M., & Ran, G. (2022, March 30). *Mapping the impact of* *urbanization on vegetation in Nairobi, the 'green city in the sun* https://www.3ieimpact.org/blogs/mapping-impact-urbanization-vegetation-nairobi-green-city-sun

Mchunu, N., Lagerwall, G., & Senzanje, A. (2019). Aquaponics model specific to South African conditions. *South African Journal of Agricultural Extension*, *47*(1), 73–91.

Mella, A. (2024, May 30). *Harnessing the power of Tableau to visualize sensor data | Viam*. https://www.viam.com/post/harnessing-the-power-of-tableau-to-visualize-sensor-data

Micro Water submersive Pump. (2021). Pixel Electric Company Limited. https://www.pixelelectric.com/more-categories/other-accessories/pump/micro-water-submersive-pump/

Miquel, T. (2022). State space modelling. HAL Id: hal-02987750. https://cel.hal.science/hal-02987750v3

Mosbah, M. (2024, June 5). *WorldFish and Norway Spearhead Cutting-Edge Solar Powered Aquaponics Solution*. WorldFish. https://worldfishcenter.org/blog/worldfish-and-norway-spearhead-cutting-edge-solar-powered-aquaponics-solution

Murdan, A., & Joyram, A. (2021). An IoT based solar powered aquaponics system. 1–6. https://doi.org/10.1109/ECAI52376.2021.9515023

New paper: Strengthening food and nutrition security in Nairobi's informal settlements – ACRC. (2024, February 8). https://www.african-cities.org/new-paper-strengthening-food-and-nutrition-security-in-nairobis-informal-settlements/

Netherlands Enterprise Agency. (2020, April 22). *Experimenting with soilless food production: A successful business case*. Agroberichten Buitenland. https://www.agroberichtenbuitenland.nl/landeninformatie/kenia/achtergrond/successful-business-case/experimenting-with-soilless-food-production

Noor, U. (2024, August 5). *Solar Power and Aquaculture—Sustainable Solutions for Seafood Production(2024)*.8MSolar. https://8msolar.com/solar-power-and-aquaculture-sustainable-solutions-for-seafood-production/

Obirikorang, K. A., Sekey, W., Gyampoh, B. A., Ashiagbor, G., & Asante, W. (2021). Aquaponics for Improved Food Security in Africa: A Review. *Frontiers in Sustainable Food Systems*, *5*. https://doi.org/10.3389/fsufs.2021.705549

Omondi, S., Kosura, W., & Jirström, M. (2017). The role of urban-based agriculture on food security: Kenyan case studies: Urban-based agriculture and food security. *Geographical Research*, *55*, 231–241. https://doi.org/10.1111/1745-5871.12234

Ospina, D. (2019, December 19). Beyond Design Thinking: The Systemic Design Thinking Framework. *Medium*. https://conductal.medium.com/beyond-design-thinking-the-systemic-design-thinking-framework-8d4952271222

Parajuli, S., Narayan Bhattarai, T., Gorjian, S., Vithanage, M., & Raj Paudel, S. (2023). Assessment of potential renewable energy alternatives for a typical greenhouse aquaponics in Himalayan Region of Nepal. *Applied Energy*, *344*, 121270. https://doi.org/10.1016/j.apenergy.2023.121270

Paul, B., Agnihotri, S., Kavya, B., Tripathi, P., & Babu, N. C. (2024). Sustainable smart aquaponics farming using IoT and data analytics. *Journal of Information Technology Research*, *15*(1).

Pekeş, B. (2024, January 25). Understanding General System Theory. *Medium*. https://medium.com/@baturalppekes/understanding-general-system-theory-83321d64eb20

PlantedPerfection. (2023, August 4). Overcoming Common Challenges in Urban Gardening: Tips and Tricks for Success. Medium. https://medium.com/@PlantedPerfection/overcoming-common-challenges-in-urban-gardening-tips-and-tricks-for-success-98620551b8e9.

PBS Terra (Director). (2023, June 29). How This Aquaponics Farmer Is Reinventing Urban Agriculture [Video recording]. https://www.youtube.com/watch?v=_YmkWODcqbA

Podder, M. S., & Majumder, C. B. (2016). The use of artificial neural network for modelling of phycoremediation of toxic elements As(III) and As(V) from wastewater using *Botryococcus braunii*. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, *155*, 130–145. https://doi.org/10.1016/j.saa.2015.11.011

Pohshna, C., Singh, N., Ajaykumar, K., & Khose, S. (2024). *Aquaponics: An Approach to Sustainable Agriculture*. *6*, 245–248.

Radanliev, P., De Roure, D., Van Kleek, M., Santos, O., & Ani, U. (2021). Artificial intelligence in cyber physical systems. *AI & SOCIETY*, *36*(3), 783–796. https://doi.org/10.1007/s00146-020-01049-0

Raisin, S. N., Jamaludin, J., Jamal Mohamad, F. A., Hazwani, N., & Naeem, B. (2020). *Cyber-Physical System (CPS) Application- A REVIEW*. 52–65. https://doi.org/10.26760/rekaelkomika.v1i2.52-65

Random Forest: A Complete Guide for Machine Learning. (2024, March 8). Built In. https://builtin.com/data-science/random-forest-algorithm

Real Time Monitoring. (2024). MultiTech IoT Wiki. https://multitech.com/iot-wiki/real-time-monitoring/

Reidel, S. R. (2023, July 23). *Automation in aquaponics: Reducing labor and increasing profitability*. https://www.sciencedirect.com/science/article/pii/S0168169920301234

Reinforcement Learning: What It Is and How It Works. (2024, July 17). What Is Reinforcement Learning? A Comprehensive Guide | Grammarly. https://www.grammarly.com/blog/what-is-reinforcement-learning/

Reporter, B. (2018, July 13). *How I'm making millions from aquaponics farming on my balcony*. Bizna. https://biznakenya.com/aquaponics-farming-in-kenya/

Rodrigues Da Silva, R., Silva Teixeira, E. L., Murilo, A., & Dias Santos, M. M. (2017). A hardware-in-the loop platform for designing and testing of electric power assisted steering. *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics*

Society, 5113 5118. IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society. https://doi.org/10.1109/IECON.2017.8216884

Santosh, D. T., & Shukla, C. (2024). Innovations in Aquaponics: Components, Operations, and Economic Viability (pp. 208–222).

Serôdio, C., Mestre, P., Cabral, J., Gomes, M., & Branco, F. (2024). Software and Architecture Orchestration for Process Control in Industry 4.0 Enabled by Cyber-Physical Systems Technologies. *Applied Sciences*, *14*(5), Article 5. https://doi.org/10.3390/app14052160

Silveira, R. M. C., Alves, F. P. R. S., Fontaine, A., & Santana, E. E. C. (2019). A Web-Service to Monitor a Wireless Sensor Network. In J. Miller, E. Stroulia, K. Lee, & L.-J. Zhang (Eds.), *Web Services – ICWS 2019* (pp. 126–146). Springer International Publishing. https://doi.org/10.1007/978-3-030-23499-7_9

Sen, S., Maiti, S., Manna, S., Roy, B., & Ghosh, A. (2023). Smart Prediction of Water Quality System for Aquaculture Using Machine Learning Algorithms. *Journal of Current Trends in Computer Science Research, 2836–8495.*

Solar Learning Center. (2024). 5 ways that solar energy benefits the environment. In *The pros and cons of rooftop solar in 2024.* Solar Learning Center. https://www.solar.com/learn/benefits-of-solar-energy-to-the-environment/

Solanki, B., & Pal, S. (2020). *Balcony gardening of vegetable crops* (Article ID: 30158). Department of Vegetable Science, Faculty of Horticulture, Bidhan Chandra Krishi Viswavidyalaya; Division of Vegetable Crops, ICAR-Indian Institute of Horticultural Research. Retrieved from https://www.researchgate.net/publication/341778484_Balcony_Gardening_of_Vegetable_Crops

Song, Z., Mishra, A. R., & Saeidi, S. P. (2023). Technological capabilities in the era of the digital economy for integration into cyber-physical systems and the IoT using decision-making approach. *Journal of Innovation & Knowledge*, *8*(2), 100356. https://doi.org/10.1016/j.jik.2023.100356

Sotelo, D., Favela-Contreras, A., Kalashnikov, V. V., & Sotelo, C. (2020). Model Predictive Control with a Relaxed Cost Function for Constrained Linear Systems. *Mathematical Problems in Engineering*, *2020*(1), 7485865. https://doi.org/10.1155/2020/7485865

Storr, W. (2013, August 30). Closed-loop System and Closed-loop Control Systems. Basic Electronics Tutorials. https://www.electronics-tutorials.ws/systems/closed-loop-system.html

Support Vector Machine (SVM) Algorithm. | by Sumbatilinda | Medium. (2024, May 1). https://medium.com/@sumbatilinda/support-vector-machine-svm-algorithm-064566b5d411

Taha, M. F., ElMasry, G., Gouda, M., Zhou, L., Liang, N., Abdalla, A., Rousseau, D., & Qiu, Z. (2022). Recent advances of smart systems and Internet of Things (IoT) for aquaponics automation: A comprehensive overview. Chemosensors, 10(8), 303. https://doi.org/10.3390/chemosensors10080303The sewage headache that won't go away. (2023, June 20). Nation. https://nation.africa/kenya/health/the-sewage-headache-that-won-t-go-away-4275596

The State of Food Security and Nutrition in the World 2024. (2024). FAO; IFAD; UNICEF; WFP; WHO; https://doi.org/10.4060/cd1254en

VR, A. (2023, July 5). *Solar-Powered IoT Solutions: Transforming Energy Management*. Republic Of Solar. https://arka360.com/ros/solar-powered-iot-solutions-energy-management/

Water Level Sensor Float Switch. (2021.). Pixel Electric Company Limited. Retrieved September 8, 2024, from https://www.pixelelectric.com/category/water-level-sensor-float-switch/

What Is Optimal Control? (n.d.). Retrieved August 11, 2024, from https://www.mathworks.com/discovery/optimal-control.html

What is the k-nearest neighbors algorithm? | IBM. (2021, October 4). https://www.ibm.com/topics/knn

Wilson, S., & Jardon, V. (2024). *Mathematical Modeling of System Dynamics*. Retrieved August 11, 2024, from https://opentext.ku.edu/controlsystems/chapter/chapter-1/

Yang, S.-C., & Wang, Y.-L. (2011). System Dynamics Based Insider Threats Modelin. *International Journal of Network Security & Its Applications*, *3*. https://doi.org/10.5121/ijnsa.2011.3301

Yanes, A. R., Martinez, P., & Ahmad, R. (2020). Towards automated aquaponics: A review on monitoring, IoT, and smart systems. *Journal of Cleaner Production*, *263*, 121571. https://doi.org/10.1016/j.jclepro.2020.121571

Yau, S. R., Jalani, J.*, Sadun, A. S., Mohd Rejab, S., & John, J. (2025). Development of an aquaponics farming technology system using Arduino based on Internet of Things. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *45*(2), 11-24. https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index

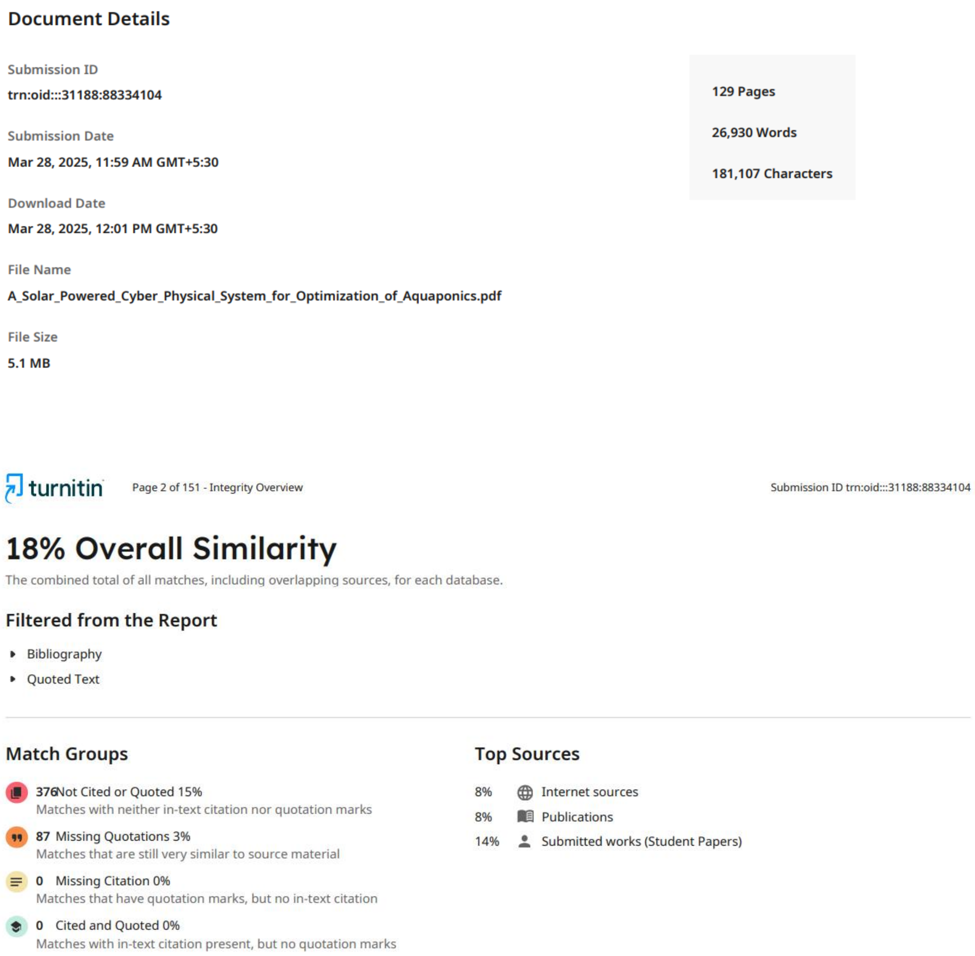
Young, L. C. (n.d.). Fundamental Concepts and Problems of Optimal Control Theory. https://apps.dtic.mil/sti/tr/pdf/AD0707621.pdf

Zainal Alama, M. N. H., Kamaruddin, M. J., Samsudin, S. A., Othman, R.*, Mohammad Radzi, N. H., Abiodun Emmanuel, A., & Zainal Abidin, M. S. (2023). Smart farming using a solar-powered aquaponics system for sustainable food production. *Malaysian Journal of Science*, *42*(1), 68-77.

Zhang, Bao & Ahmed, Salah. (2020). Systems Thinking—Ludwig Von Bertalanffy, Peter Senge, and Donella Meadows. 10.1007/978-3-030-43620-9_28.

Zou, X., Chen, L., & Zhang, W. (2020). "IoT-based aquaponics monitoring for urban farming." Journal of Smart Agriculture and Environment, 8(2), 122–134.

Appendix A: Similarity Report



Document Details

Submission ID
trn:oid:::31188:88334104

Submission Date
Mar 28, 2025, 11:59 AM GMT+5:30

Download Date
Mar 28, 2025, 12:01 PM GMT+5:30

File Name
A_Solar_Powered_Cyber_Physical_System_for_Optimization_of_Aquaponics.pdf

File Size
5.1 MB

129 Pages

26,930 Words

181,107 Characters

turnitin Page 2 of 151 - Integrity Overview Submission ID trn:oid:::31188:88334104

18% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Quoted Text

Match Groups

376 Not Cited or Quoted 15%
Matches with neither in-text citation nor quotation marks

87 Missing Quotations 3%
Matches that are still very similar to source material

0 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

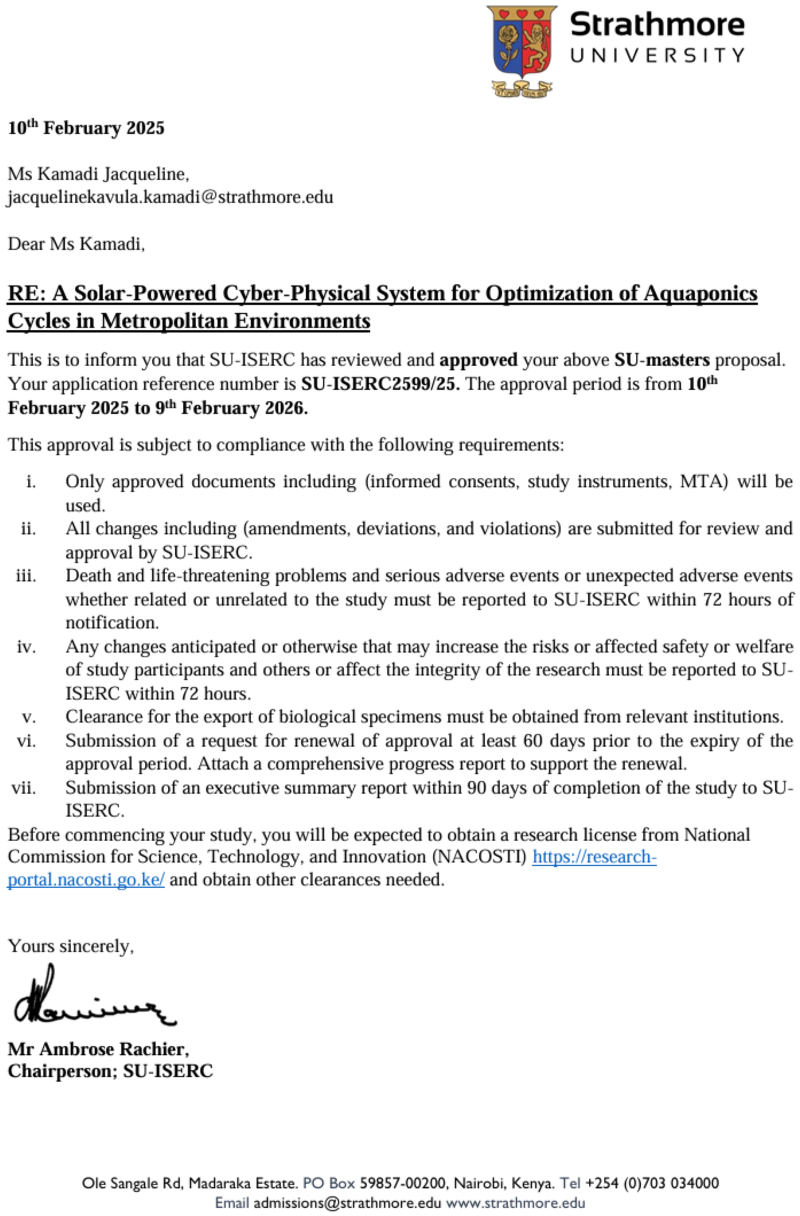
0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

8%	Internet sources
8%	Publications
14%	Submitted works (Student Papers)

Figure A.1: Similarity Report

Appendix B: Ethical Clearance Confirmation



Strathmore
UNIVERSITY

10th February 2025

Ms Kamadi Jacqueline,
jacquelinekavula.kamadi@strathmore.edu

Dear Ms Kamadi,

RE: A Solar-Powered Cyber-Physical System for Optimization of Aquaponics Cycles in Metropolitan Environments

This is to inform you that SU-ISERC has reviewed and **approved** your above **SU-masters** proposal. Your application reference number is **SU-ISERC2599/25.** The approval period is from **10th February 2025 to 9th February 2026.**

This approval is subject to compliance with the following requirements:

i. Only approved documents including (informed consents, study instruments, MTA) will be used.
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 72 hours of notification.
iv. Any changes anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 72 hours.
v. Clearance for the export of biological specimens must be obtained from relevant institutions.
vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) https://research-portal.nacosti.go.ke/ and obtain other clearances needed.

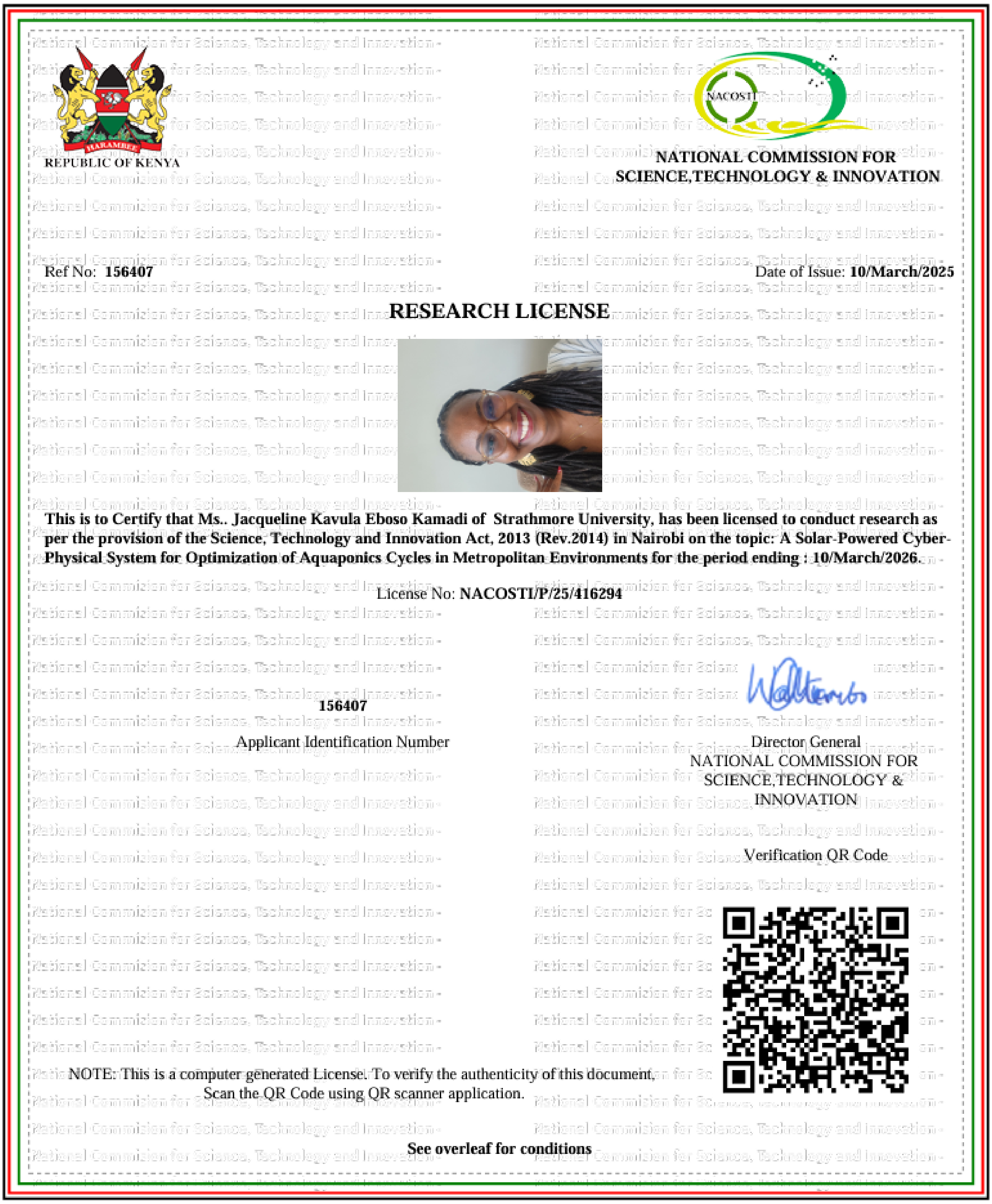
Yours sincerely,

Mr Ambrose Rachier,
Chairperson; SU-ISERC

Ole Sangale Rd, Madaraka Estate. PO Box 59857-00200, Nairobi, Kenya. Tel +254 (0)703 034000
Email admissions@strathmore.edu www.strathmore.edu

Figure B.1: Ethical Clearance Confirmation

Appendix C: Research License



REPUBLIC OF KENYA

NATIONAL COMMISSION FOR
SCIENCE,TECHNOLOGY & INNOVATION

Ref No: **156407**

Date of Issue: **10/March/2025**

RESEARCH LICENSE

This is to Certify that Ms.. Jacqueline Kavula Eboso Kamadi of Strathmore University, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Nairobi on the topic: A Solar-Powered Cyber-Physical System for Optimization of Aquaponics Cycles in Metropolitan Environments for the period ending : 10/March/2026.

License No: **NACOSTI/P/25/416294**

156407
Applicant Identification Number

Director General
NATIONAL COMMISSION FOR
SCIENCE,TECHNOLOGY &
INNOVATION

Verification QR Code

NOTE: This is a computer generated License. To verify the authenticity of this document,
Scan the QR Code using QR scanner application.

See overleaf for conditions

Figure C.1: Research License

Appendix D: Timeline of Activities

This section outlines the timeline of the research project, detailing the key milestones and deadlines from the start to the completion of the thesis.

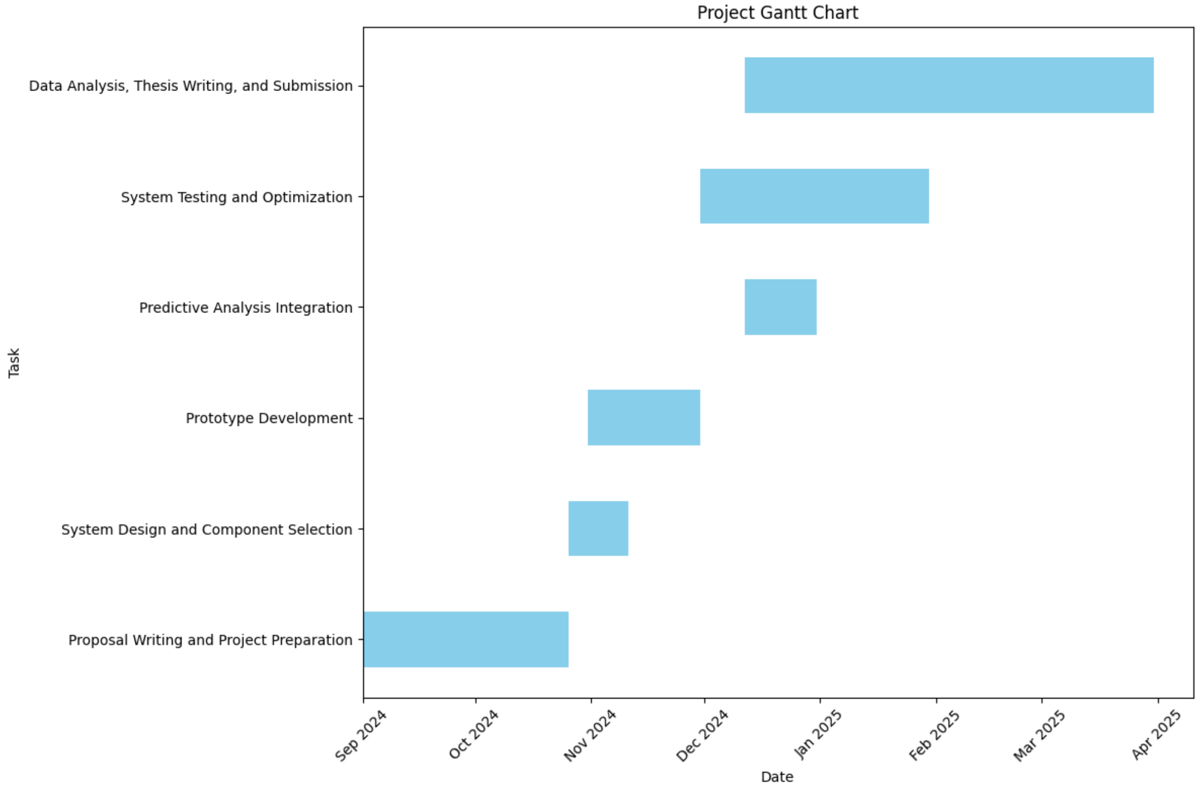


Figure D.1: Timeline of Activities Gantt Chart

Appendix E: Budget

The budget appendix provides a detailed breakdown of the estimated costs associated with the research project. These include the costs of materials, software licenses, hardware components and any other expenses related to the development and testing of the IoT system. The budget will also account for potential contingencies.

Table 2

Table E.1: Direct Costs

Item	**Quantity**	**Cost per Item (Ksh)**	**Total (Ksh)**
ESP32S DevKIT WIFI + BLE Module (30Pin)	1	1,400.00	1400
DFRobot Gravity Analog TDS Sensor module	1	2,500.00	2500
Water Level Sensor Float Switch	1	500	500
pH Sensor	1	3,350.00	3350
Temperature sensor	1	100	100
Micro Water submersible Pump	2	1,200.00	2400
TP4056 Lithium Battery Charger	1	100	100
Solar Charge Controller	1	1,000.00	1000
Sealed lead acid battery 12V 7Ah	1	1500	1500
Solar Cell, 18V	1	1300	1300
Jumper wires	4	150	600
LM2596 DC-DC Buck/Step-down Converter	1	500	500
LCD 20X4 (2004) Yellow Serial Backlight with IIC	1	800	800
4 Channel Relay Module	1	300	300
Total Direct Costs			**Ksh 16,350.00**

Table 3

Table E.2: Indirect Costs

Item	**Cost (Ksh)**
Contingency (10% of Direct Costs)	1,635.00
Transportation and Logistics	1,000.00
Miscellaneous (e.g., administrative fees)	500.00
Total Indirect Costs	3,135.00

Table 4

Table E.3: Software Licences

Item	**Quantity**	**Cost per License (Ksh)**
Arduino IDE (Open Source)	N/A	0.00
Cloud-based Subscription	1	2,500.00
Total Software Licence Costs		2,500.00

Table 5

Table E.4: Grand Total

Category	Total Cost (Ksh)
Direct Costs	16,350.00
Indirect Costs	3,135.00
Software Licenses	2,500.00
Grand Total Estimated Cost	**21,985.00**

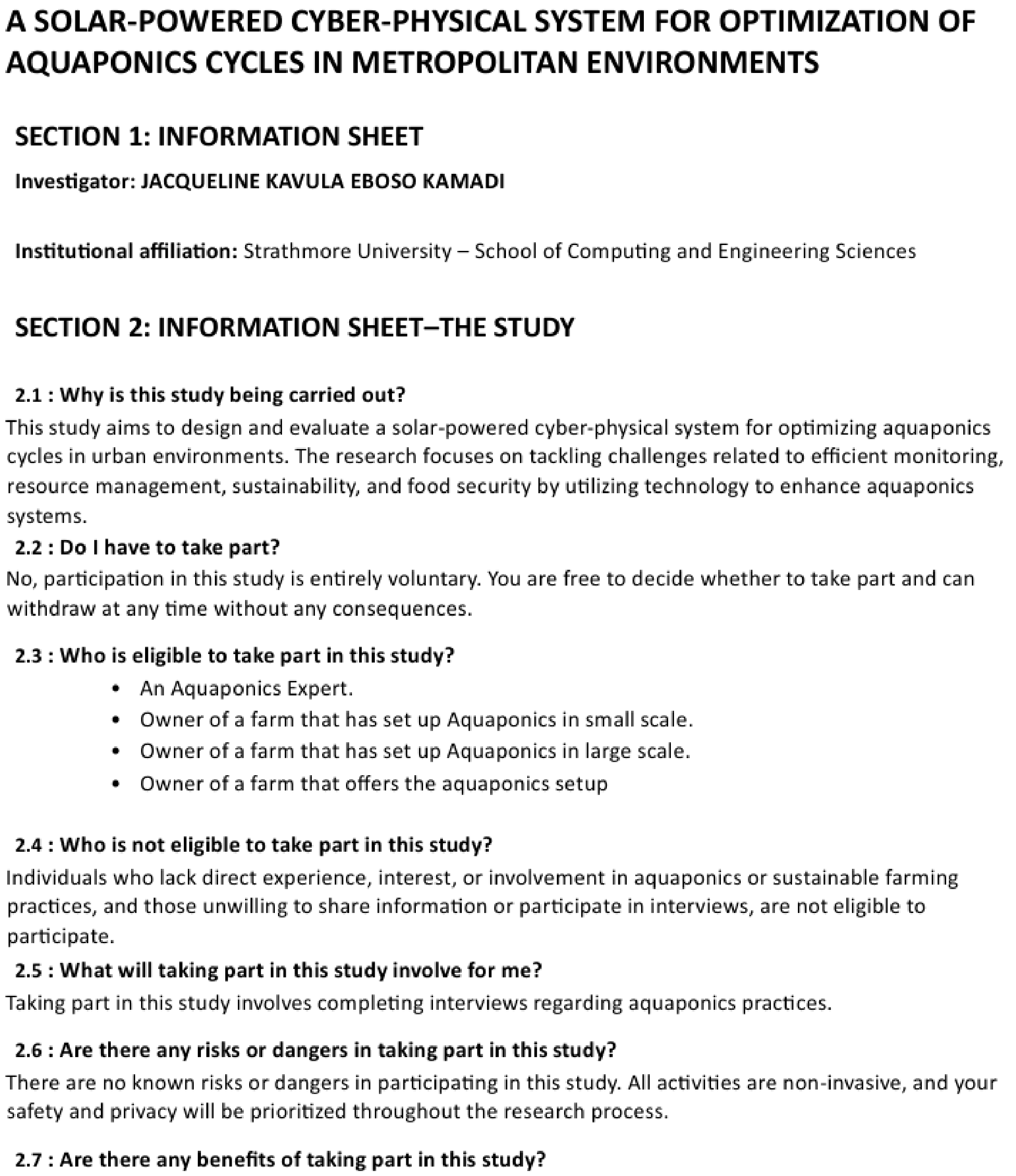
Appendix F: Consent Form and Data Collection Tools

This appendix provides an overview of the data collection tools and technologies employed in this research. As the research focuses on an IoT-based system without human participants, no consent forms will be required. The section describes the IoT sensors and cloud-based storage methods used to collect, log, and analyze data.

F-1: Consent Form

This section contains the consent forms signed by research participants, indicating their voluntary participation in the research. The forms outline the research objectives, participant rights, data confidentiality, and agreement to be part of the research.

F-1.1: Consent Form from Robert Mwakio



A SOLAR-POWERED CYBER-PHYSICAL SYSTEM FOR OPTIMIZATION OF AQUAPONICS CYCLES IN METROPOLITAN ENVIRONMENTS

SECTION 1: INFORMATION SHEET

Investigator: JACQUELINE KAVULA EBOSO KAMADI

Institutional affiliation: Strathmore University – School of Computing and Engineering Sciences

SECTION 2: INFORMATION SHEET–THE STUDY

2.1 : Why is this study being carried out?

This study aims to design and evaluate a solar-powered cyber-physical system for optimizing aquaponics cycles in urban environments. The research focuses on tackling challenges related to efficient monitoring, resource management, sustainability, and food security by utilizing technology to enhance aquaponics systems.

2.2 : Do I have to take part?

No, participation in this study is entirely voluntary. You are free to decide whether to take part and can withdraw at any time without any consequences.

2.3 : Who is eligible to take part in this study?

- An Aquaponics Expert.
- Owner of a farm that has set up Aquaponics in small scale.
- Owner of a farm that has set up Aquaponics in large scale.
- Owner of a farm that offers the aquaponics setup

2.4 : Who is not eligible to take part in this study?

Individuals who lack direct experience, interest, or involvement in aquaponics or sustainable farming practices, and those unwilling to share information or participate in interviews, are not eligible to participate.

2.5 : What will taking part in this study involve for me?

Taking part in this study involves completing interviews regarding aquaponics practices.

2.6 : Are there any risks or dangers in taking part in this study?

There are no known risks or dangers in participating in this study. All activities are non-invasive, and your safety and privacy will be prioritized throughout the research process.

2.7 : Are there any benefits of taking part in this study?

Participants will help advance sustainable farming technologies and resource optimization in urban environments. The study may also offer valuable insights into efficient aquaponics systems, benefiting participants in their practices.

2.8 : What will happen to me if I refuse to take part in this study?

If you choose not to participate, there will be no negative consequences. Your decision will be respected, and no further contact regarding this study will occur.

2.9 : Who will have access to my information during this research?

Access to your information will be strictly limited to the principal investigator, Jacqueline Kavula Eboso Kamadi, and authorized members of the research team at Strathmore University. Data will be stored securely and used solely for the purposes of this study, in compliance with data protection regulations.

2.10 : Who can I contact in case I have further questions?

You can contact me, **JACQUELINE KAVULA EBOSO KAMADI**, at Strathmore University, School of Engineering and Computing Sciences, or by e-mail **jacquelinekavula.kamadi@strathmore.edu**, or by phone (**+254 742912874)**. You can also contact my supervisor, Dr. **ALLAN OMONDI**, at Strathmore University, School of Engineering and Computing Sciences, Nairobi, or by e-mail (**aomondi@strathmore.edu**) or by phone (**+254 720714365**)

If you want to ask someone independent anything about this research, please contact:

The Secretary–Strathmore University Institutional Ethics Review Board, P. O. BOX 59857, 00200, Nairobi, email ethicsreview@strathmore.edu

I, ______________________________, have had the study explained to me. I have understood all that I have read and have had explained to me and had my questions answered satisfactorily. I understand that I can change my mind at any stage.

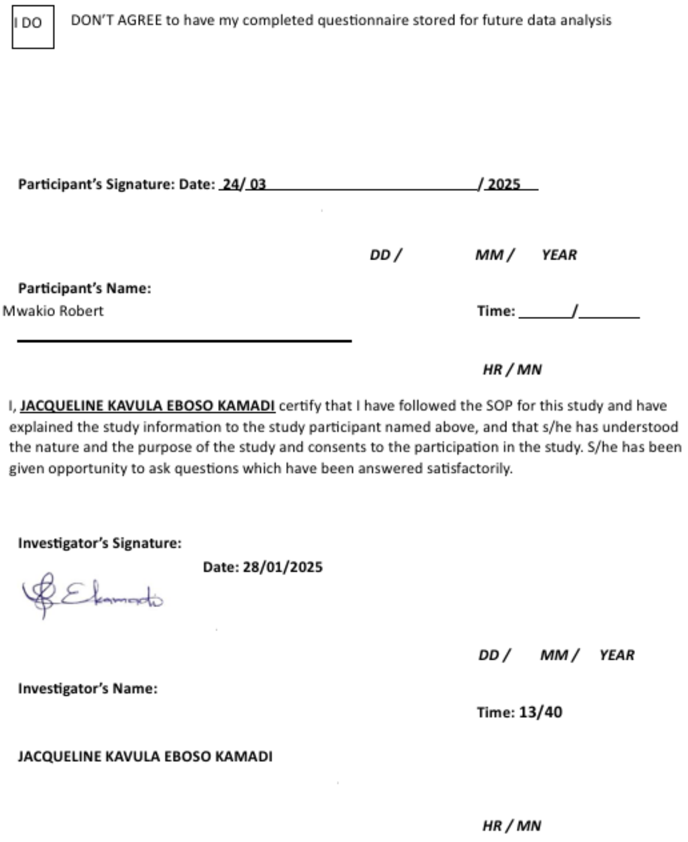
Please tick the boxes that apply to you;

Participation in the research study

🟩 I AGREE to take part in this research

☐ I DO DON’T AGREE to take part in this research

🟧 AGREE to have my completed questionnaire stored for future data analysis



I DO DON’T AGREE to have my completed questionnaire stored for future data analysis

Participant’s Signature: Date: 24/ 03 / 2025

DD / MM / YEAR

Participant’s Name:
Mwakio Robert

Time: ____/____

HR / MN

I, **JACQUELINE KAVULA EBOSO KAMADI** certify that I have followed the SOP for this study and have explained the study information to the study participant named above, and that s/he has understood the nature and the purpose of the study and consents to the participation in the study. S/he has been given opportunity to ask questions which have been answered satisfactorily.

Investigator’s Signature:

Date: 28/01/2025

DD / MM / YEAR

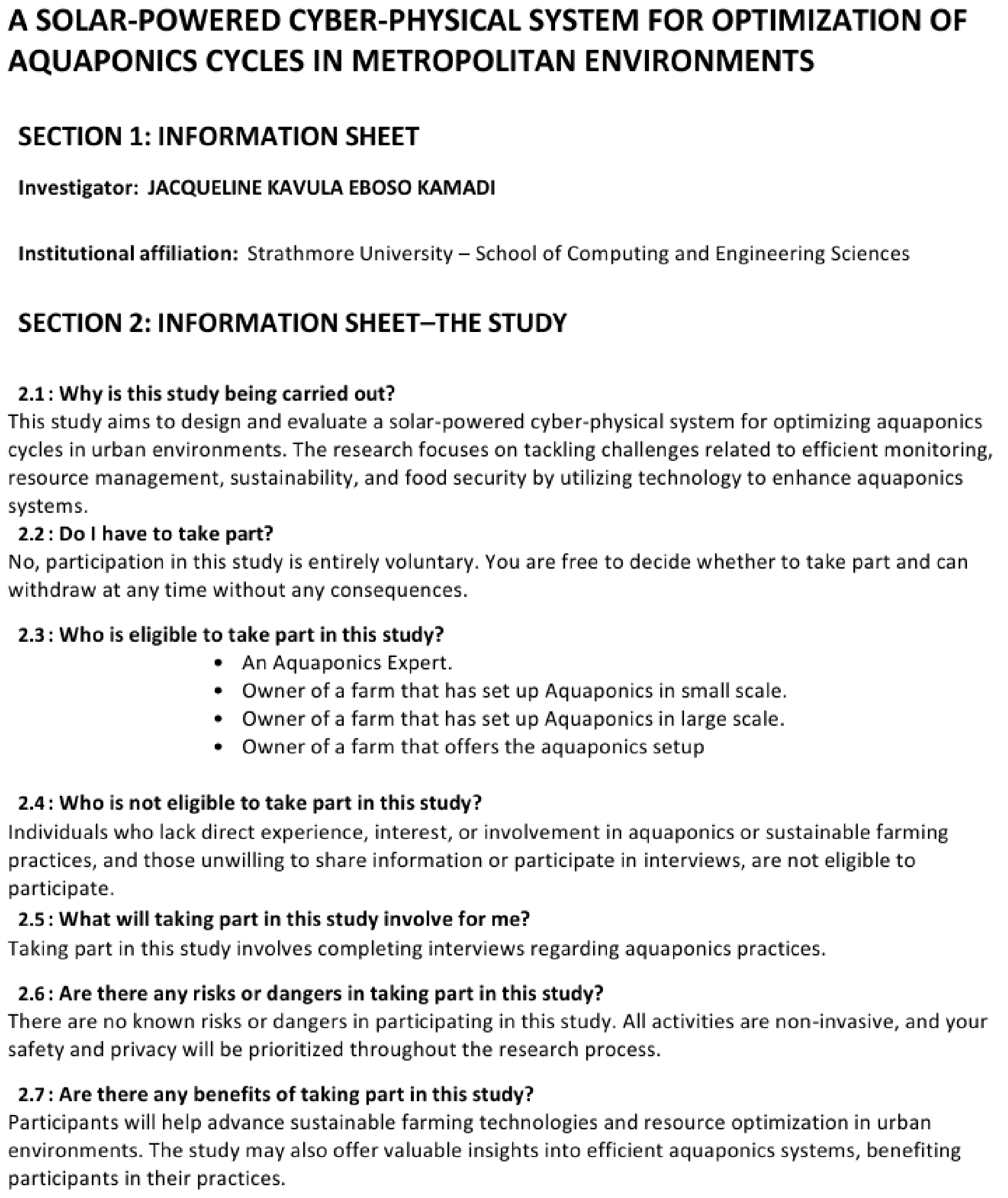
Investigator’s Name:

Time: 13/40

JACQUELINE KAVULA EBOSO KAMADI

HR / MN

F-1.2: Consent Form from Geoffrey Ngugi – City Shamba Representative



A SOLAR-POWERED CYBER-PHYSICAL SYSTEM FOR OPTIMIZATION OF AQUAPONICS CYCLES IN METROPOLITAN ENVIRONMENTS

SECTION 1: INFORMATION SHEET

Investigator: JACQUELINE KAVULA EBOSO KAMADI

Institutional affiliation: Strathmore University – School of Computing and Engineering Sciences

SECTION 2: INFORMATION SHEET–THE STUDY

2.1 : Why is this study being carried out?

This study aims to design and evaluate a solar-powered cyber-physical system for optimizing aquaponics cycles in urban environments. The research focuses on tackling challenges related to efficient monitoring, resource management, sustainability, and food security by utilizing technology to enhance aquaponics systems.

2.2 : Do I have to take part?

No, participation in this study is entirely voluntary. You are free to decide whether to take part and can withdraw at any time without any consequences.

2.3 : Who is eligible to take part in this study?

- An Aquaponics Expert.
- Owner of a farm that has set up Aquaponics in small scale.
- Owner of a farm that has set up Aquaponics in large scale.
- Owner of a farm that offers the aquaponics setup

2.4 : Who is not eligible to take part in this study?

Individuals who lack direct experience, interest, or involvement in aquaponics or sustainable farming practices, and those unwilling to share information or participate in interviews, are not eligible to participate.

2.5 : What will taking part in this study involve for me?

Taking part in this study involves completing interviews regarding aquaponics practices.

2.6 : Are there any risks or dangers in taking part in this study?

There are no known risks or dangers in participating in this study. All activities are non-invasive, and your safety and privacy will be prioritized throughout the research process.

2.7 : Are there any benefits of taking part in this study?

Participants will help advance sustainable farming technologies and resource optimization in urban environments. The study may also offer valuable insights into efficient aquaponics systems, benefiting participants in their practices.

2.8 : What will happen to me if I refuse to take part in this study?

If you choose not to participate, there will be no negative consequences. Your decision will be respected, and no further contact regarding this study will occur.

2.9 : Who will have access to my information during this research?

Access to your information will be strictly limited to the principal investigator, Jacqueline Kavula Eboso Kamadi, and authorized members of the research team at Strathmore University. Data will be stored securely and used solely for the purposes of this study, in compliance with data protection regulations.

2.10 : Who can I contact in case I have further questions?

You can contact me, **JACQUELINE KAVULA EBOSO KAMADI**, at Strathmore University, School of Engineering and Computing Sciences, or by e-mail **jacquelinekavula.kamadi@strathmore.edu**, or by phone **(+254 742912874)**. You can also contact my supervisor, Dr. **ALLAN OMONDI**, at Strathmore University, School of Engineering and Computing Sciences, Nairobi, or by e-mail (**aomondi@strathmore.edu**) or by phone (**+254 720714365**)

If you want to ask someone independent anything about this research, please contact:

The Secretary–Strathmore University Institutional Ethics Review Board, P. O. BOX 59857, 00200, Nairobi, email ethicsreview@strathmore.edu

I, Geoffrey Ngugi, have had the study explained to me. I have understood all that I have read and have had explained to me and had my questions answered satisfactorily. I understand that I can change my mind at any stage.

Please tick the boxes that apply to you;

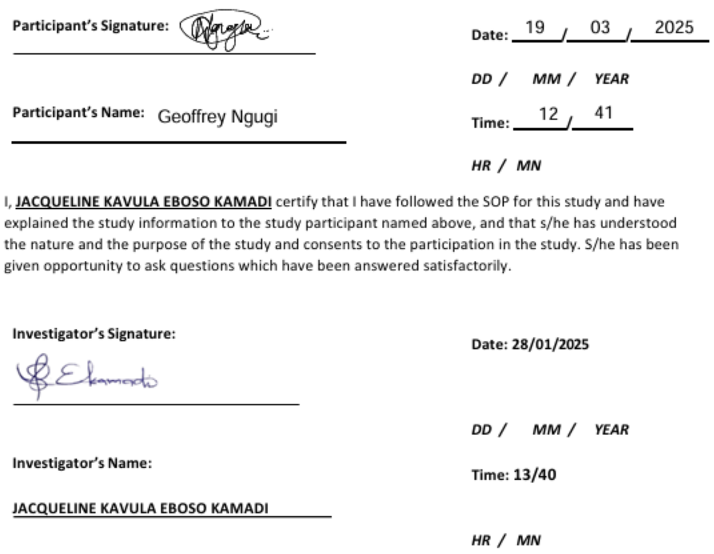
Participation in the research study

☑ I AGREE to take part in this research

☐ DON'T AGREE to take part in this research

☑ AGREE to have my completed questionnaire stored for future data analysis

☐ DON'T AGREE to have my completed questionnaire stored for future data analysis



Participant's Signature:

Date: 19 / 03 / 2025

DD / MM / YEAR

Participant's Name: Geoffrey Ngugi

Time: 12 / 41

HR / MN

I, **JACQUELINE KAVULA EBOSO KAMADI** certify that I have followed the SOP for this study and have explained the study information to the study participant named above, and that s/he has understood the nature and the purpose of the study and consents to the participation in the study. S/he has been given opportunity to ask questions which have been answered satisfactorily.

Investigator's Signature:

Date: 28/01/2025

DD / MM / YEAR

Investigator's Name:

Time: 13/40

JACQUELINE KAVULA EBOSO KAMADI

HR / MN

F-2: Interview Guide

F-2.1: Interview Guide for Balcony Aquaponics Practitioners (e.g., Robert Mwakio)

Personal Background

1. What inspired you to start an aquaponics system on your balcony?
2. How long have you been practicing aquaponics?

System Setup and Management

3. What specific components did you include in your balcony aquaponics system (e.g., fish species, plants, equipment)?

4. Can you describe the size and capacity of your system?

5. What challenges did you face in the initial setup, and how did you overcome them?

Operations and Maintenance

6. How do you manage water quality and nutrient levels in your system?

7. What technologies (e.g., sensors, automation) do you use to monitor your system?

8. How often do you need to perform maintenance on your setup?

Yield and Productiveness

9. What types of fish and plants have you found to be most successful in your setup?

10. How do you measure the success of your aquaponics system in terms of yield?

Community and Knowledge Sharing

11. Have you shared your experiences or knowledge with others interested in starting aquaponics? If so, how?

12. What resources (e.g., books, online courses, community groups) did you find helpful when starting your aquaponics journey?

F-2.2: Interview Guide for Larger Aquaponics Setup (e.g., Grandeur Africa)

Company Overview

1. Can you provide an overview of your aquaponics setup, including the size and scale of operations?
2. What types of fish and plants are primarily cultivated in your systems?

Operational Challenges

3. What are the major challenges you face in running a larger aquaponics setup compared to smaller systems?

4. How do you ensure sustainability and efficiency in your operations?

Technology and Innovation

5. What technologies do you implement in your aquaponics system (e.g., automation, monitoring systems)?

6. How has technology improved your operational efficiency and product yield?

Market and Distribution

7. Who are your main customers, and how do you distribute your products?

8. How do you determine market demand for your aquaponics products?

Future Perspectives

9. What future trends do you see in aquaponics, particularly in urban environments?

10. What advice would you give to new practitioners looking to scale their aquaponics systems?

F-2.3: Interview Guide for Supplier of Aquaponics Setup (e.g., Hydroponics Africa)

Company Profile

1. Can you describe your role in the aquaponics supply chain?
2. What products and services do you offer to aquaponics practitioners?

Product Supply and Quality

3. What factors do you consider when selecting equipment and supplies for aquaponics systems?

4. How do you ensure the quality and reliability of the products you supply?

Customer Engagement

5. What types of clients do you typically work with (e.g., individuals, businesses, schools)?

6. How do you provide support and guidance to your customers when setting up their aquaponics systems?

Challenges and Solutions

7. What challenges do your customers commonly face when starting or managing their aquaponics systems?

8. How do you assist in addressing these challenges?

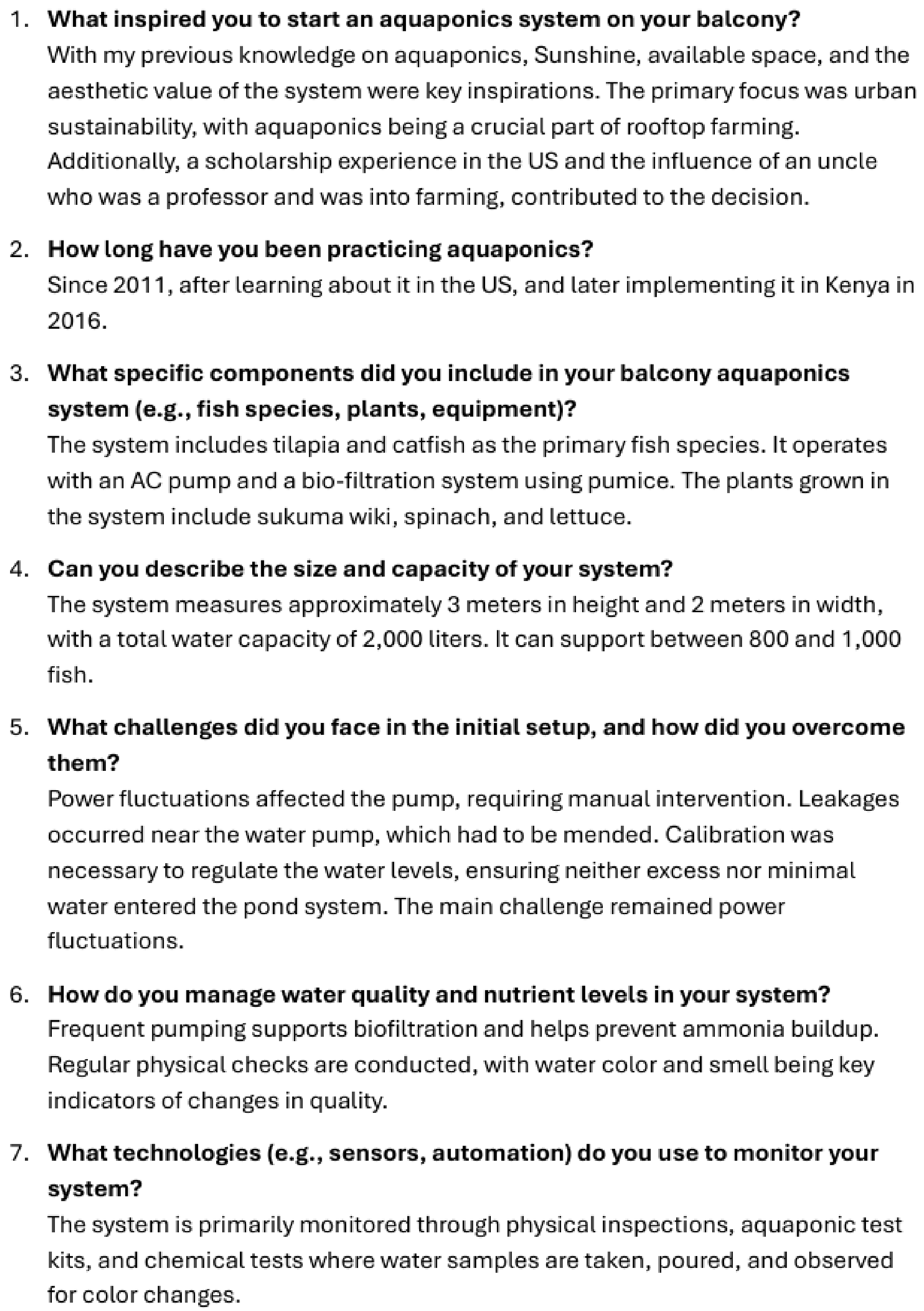
Industry Insights

9. What trends do you observe in the aquaponics industry in Kenya and beyond?

10. How do you foresee the future of aquaponics and hydroponics impacting food security in urban areas?

F-3: Interview Responses and Analysis

F-3.1: Responses from Balcony Aquaponics Practitioners (Robert Mwakio)



1. **What inspired you to start an aquaponics system on your balcony?**
   With my previous knowledge on aquaponics, Sunshine, available space, and the aesthetic value of the system were key inspirations. The primary focus was urban sustainability, with aquaponics being a crucial part of rooftop farming. Additionally, a scholarship experience in the US and the influence of an uncle who was a professor and was into farming, contributed to the decision.
2. **How long have you been practicing aquaponics?**
   Since 2011, after learning about it in the US, and later implementing it in Kenya in 2016.
3. **What specific components did you include in your balcony aquaponics system (e.g., fish species, plants, equipment)?**
   The system includes tilapia and catfish as the primary fish species. It operates with an AC pump and a bio-filtration system using pumice. The plants grown in the system include sukuma wiki, spinach, and lettuce.
4. **Can you describe the size and capacity of your system?**
   The system measures approximately 3 meters in height and 2 meters in width, with a total water capacity of 2,000 liters. It can support between 800 and 1,000 fish.
5. **What challenges did you face in the initial setup, and how did you overcome them?**
   Power fluctuations affected the pump, requiring manual intervention. Leakages occurred near the water pump, which had to be mended. Calibration was necessary to regulate the water levels, ensuring neither excess nor minimal water entered the pond system. The main challenge remained power fluctuations.
6. **How do you manage water quality and nutrient levels in your system?**
   Frequent pumping supports biofiltration and helps prevent ammonia buildup. Regular physical checks are conducted, with water color and smell being key indicators of changes in quality.
7. **What technologies (e.g., sensors, automation) do you use to monitor your system?**
   The system is primarily monitored through physical inspections, aquaponic test kits, and chemical tests where water samples are taken, poured, and observed for color changes.

8. **How often do you need to perform maintenance on your setup?**
   Maintenance is conducted every three weeks, focusing on algae buildup. Algae are removed, dissolved in water, and pumped out to maintain system balance.

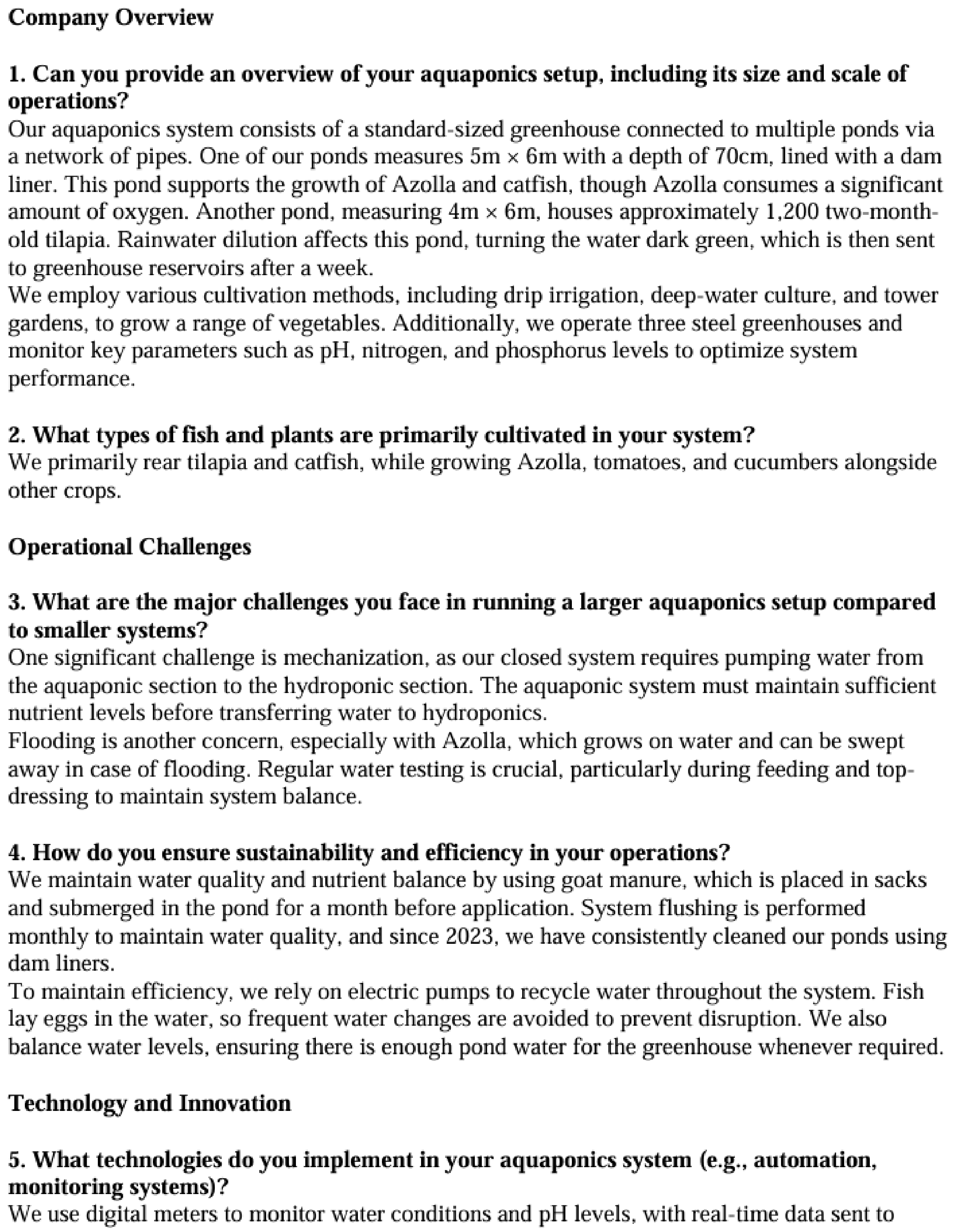
9. **What types of fish and plants have you found to be most successful in your setup?**
   Tilapia and catfish have been the most successful fish species, while kale and spinach grow best due to their fast growth rates.

10. **How do you measure the success of your aquaponics system in terms of yield?**
    Success is measured by the amount of fish harvested, with individual fish weighing at least 400 grams. Additionally, weekly kale harvests serve as a performance indicator.

11. **Have you shared your experiences or knowledge with others interested in starting aquaponics? If so, how?**
    Yes, knowledge is shared through books, Hydroponics, the future of farming in Africa, training sessions, YouTube videos, TV interviews, and participation in Facebook groups.

12. **What resources (e.g., books, online courses, community groups) did you find helpful when starting your aquaponics journey?**
    Online resources, particularly DIY guides from the internet, were the most helpful in learning and setting up the system.

F-3.2: Responses from Larger Aquaponics Setups (City Shamba)



Company Overview

1. Can you provide an overview of your aquaponics setup, including its size and scale of operations?

Our aquaponics system consists of a standard-sized greenhouse connected to multiple ponds via a network of pipes. One of our ponds measures 5m × 6m with a depth of 70cm, lined with a dam liner. This pond supports the growth of Azolla and catfish, though Azolla consumes a significant amount of oxygen. Another pond, measuring 4m × 6m, houses approximately 1,200 two-month-old tilapia. Rainwater dilution affects this pond, turning the water dark green, which is then sent to greenhouse reservoirs after a week.

We employ various cultivation methods, including drip irrigation, deep-water culture, and tower gardens, to grow a range of vegetables. Additionally, we operate three steel greenhouses and monitor key parameters such as pH, nitrogen, and phosphorus levels to optimize system performance.

2. What types of fish and plants are primarily cultivated in your system?

We primarily rear tilapia and catfish, while growing Azolla, tomatoes, and cucumbers alongside other crops.

Operational Challenges

3. What are the major challenges you face in running a larger aquaponics setup compared to smaller systems?

One significant challenge is mechanization, as our closed system requires pumping water from the aquaponic section to the hydroponic section. The aquaponic system must maintain sufficient nutrient levels before transferring water to hydroponics.

Flooding is another concern, especially with Azolla, which grows on water and can be swept away in case of flooding. Regular water testing is crucial, particularly during feeding and top-dressing to maintain system balance.

4. How do you ensure sustainability and efficiency in your operations?

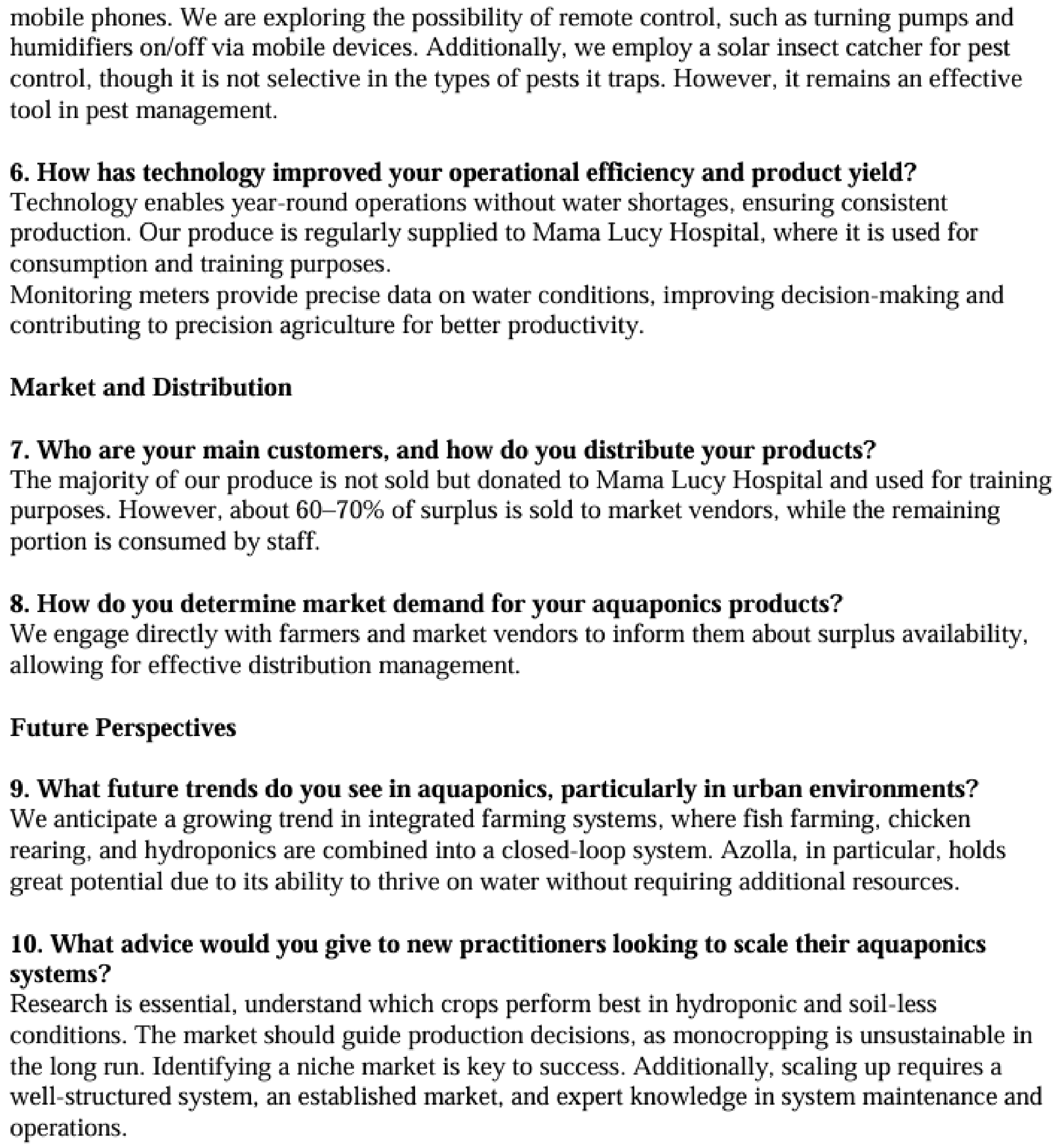
We maintain water quality and nutrient balance by using goat manure, which is placed in sacks and submerged in the pond for a month before application. System flushing is performed monthly to maintain water quality, and since 2023, we have consistently cleaned our ponds using dam liners.

To maintain efficiency, we rely on electric pumps to recycle water throughout the system. Fish lay eggs in the water, so frequent water changes are avoided to prevent disruption. We also balance water levels, ensuring there is enough pond water for the greenhouse whenever required.

Technology and Innovation

5. What technologies do you implement in your aquaponics system (e.g., automation, monitoring systems)?

We use digital meters to monitor water conditions and pH levels, with real-time data sent to



mobile phones. We are exploring the possibility of remote control, such as turning pumps and humidifiers on/off via mobile devices. Additionally, we employ a solar insect catcher for pest control, though it is not selective in the types of pests it traps. However, it remains an effective tool in pest management.

6. How has technology improved your operational efficiency and product yield?
Technology enables year-round operations without water shortages, ensuring consistent production. Our produce is regularly supplied to Mama Lucy Hospital, where it is used for consumption and training purposes.
Monitoring meters provide precise data on water conditions, improving decision-making and contributing to precision agriculture for better productivity.

Market and Distribution

7. Who are your main customers, and how do you distribute your products?
The majority of our produce is not sold but donated to Mama Lucy Hospital and used for training purposes. However, about 60–70% of surplus is sold to market vendors, while the remaining portion is consumed by staff.

8. How do you determine market demand for your aquaponics products?
We engage directly with farmers and market vendors to inform them about surplus availability, allowing for effective distribution management.

Future Perspectives

9. What future trends do you see in aquaponics, particularly in urban environments?
We anticipate a growing trend in integrated farming systems, where fish farming, chicken rearing, and hydroponics are combined into a closed-loop system. Azolla, in particular, holds great potential due to its ability to thrive on water without requiring additional resources.

10. What advice would you give to new practitioners looking to scale their aquaponics systems?
Research is essential, understand which crops perform best in hydroponic and soil-less conditions. The market should guide production decisions, as monocropping is unsustainable in the long run. Identifying a niche market is key to success. Additionally, scaling up requires a well-structured system, an established market, and expert knowledge in system maintenance and operations.

F-4: Sensors Data Collection Tools

The data for this research will be gathered using IoT sensors and supporting hardware, outlined as follows:

i. **Temperature Sensor**: This will be employed to monitor environmental conditions within the system.

ii. **pH Sensor**: This will be used to measure the acidity or alkalinity of the water to maintain a suitable environment for both plants and aquatic life.

iii. **TDS Sensor**: This will be used to monitor the concentration of dissolved solids in the water to assess and manage water quality.

iv. **Motor Control System**: The motor's operation will be controlled based on temperature readings from the sensors.

v. **ESP32 Microcontroller**: The ESP32 microcontroller will be responsible for collecting sensor data and transmitting it to the cloud for logging and analysis.

vi. **Solar Power Management System**: The IoT system will be powered by solar energy, utilizing a solar panel and lithium battery setup.

Cloud-Based Data Logging and Storage

i. **Cloud Storage**: All collected data will be transmitted and stored in a cloud-based platform. This approach enables real-time data access, backup, and ensures scalability for data analysis. The cloud service will be configured to store sensor data securely and make it accessible for monitoring and predictive analysis.

ii. **Data Logging**: Data from the sensors will be continuously logged in the cloud at predefined intervals. The logging frequency and data formats are standardized to facilitate efficient data processing and future analysis.

Data Visualization and Predictive Analysis Tools

i) **Real-Time Monitoring**: Data visualization dashboards will be integrated with the cloud platform, enabling real-time monitoring of sensor readings and motor activity. These dashboards provide a user-friendly interface to interpret the data.

ii) **Predictive Analysis Tools**: Predictive analysis software will be used to analyze the sensor data stored in the cloud.

Appendix G: Repository for Source Code, Data, and Other Artifacts

To store the source code for the IoT devices, the monitoring module, and other relevant data and artifacts, this link: https://github.com/Jacqueline777/166570-MASTERS-IT will be used as a comprehensive resource for all the software and data developed during the research.

Appendix H: Data Management Plan

All collected data will be transmitted and securely stored on a cloud-based platform, allowing for real-time access, backup, and scalability for future analysis. The cloud service will continuously log sensor data at predefined intervals in standardized formats to ensure efficient processing. Interested parties can request access to this sensor data by contacting me at **jacquelinekavula.kamadi@strathmore.edu**, and I will provide guidelines for responsible data use.

Appendix I: Outputs Management Plan

The outputs management plan outlines my intention to deploy the developed solar-powered cyber-physical system in an urban balcony garden to illustrate its practical application in optimizing aquaponics cycles. This deployment will serve as a demonstration of how technology can be effectively integrated into limited urban spaces to promote sustainable food production.

Different members of the community can benefit from this solution in various ways.

1. **Urban Gardeners**: Individuals with limited space can adopt the system to grow fresh produce efficiently, contributing to improved food security and nutrition.
2. **Schools and Learning Institutions**: The system can serve as a practical educational tool to teach students about sustainable agriculture, renewable energy, and resource optimization.
3. **Community Groups and Urban Farming Initiatives**: These groups can use the system as a model for larger-scale urban farming projects, fostering collaboration and collective food production efforts.
4. **Policy Makers and NGOs**: The solution can inform policy on urban agriculture and support initiatives addressing food security and environmental sustainability in urban settings.

I aim to present the findings at relevant conferences to foster collaboration and knowledge exchange within the urban agriculture community. Additionally, I intend to publish a peer-reviewed paper detailing the methodologies, results, and implications of the research, thereby contributing to the academic discourse on integrating technology in urban gardening practices.