WATER-USE EFFICIENCY, PLANT, AND FISH GROWTH PERFORMANCE ON THE SIMPLIFIED AQUAPONIC PRODUCTION SYSTEM OF INCITIS-FOOD

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A PROJECT REPORT SUBMITTED TO THE DEPARTMENT OF AQUACULTURE AND FISHERIES MANAGEMENT, FACULTY OF RENEWABLE NATURAL RESOURCES, UNIVERSITY OF IBADAN, IBADAN, OYO STATE, NIGERIA, IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF A BACHELOR DEGREE IN AQUACULTURE AND FISHERIES MANAGEMENT.

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CERTIFICATION

This is to certify that this project work was carried out by ONWUMAH OZIOMA PEACE (214606) at the Department of Aquaculture and Fisheries Management, University of Ibadan, under my supervision.

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DEDICATION

I wholeheartedly dedicate this project to God Almighty, whose guidance, wisdom, and mindfulness have been my constant source of strength throughout this journey, and to my family members, whose unwavering support I could always rely on.

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ABSRACT

Urban food production systems integrating aquaponics offer a sustainable approach to addressing food security and resource management challenges. This study evaluated water use efficiency, plant growth performance, and fish growth in a model urban aquaponic system under the Incitis-Food project. The research compared a recirculating aquaponic system (RAS) with a stagnant renewal fish production system to assess their impacts on water quality, nutrient utilization, and overall productivity. Understanding these dynamics is essential for improving resource efficiency and optimizing production in urban agriculture.

The study was conducted using four fish tanks (two RAS, two stagnant), three hydroponic grow beds (NFT, GB, DWC), and a sump tank. Water quality parameters—including conductivity, total dissolved solids (TDS), temperature, and dissolved oxygen (DO)—were monitored at multiple system points, with data collection occurring in both fish tanks and hydroponic grow beds to evaluate nutrient retention and loss. Fish growth performance was assessed using length-weight relationships and a condition factor, measured biweekly to track development over time. Plant growth was evaluated through biometric measurements, including plant height, number of leaves, stem girth, leaf dimensions, and fruit yield, with data collected across different species (tomato, bell pepper, and leafy garden egg). Data analysis involved correlation and regression analysis to determine relationships between water quality, fish growth, and plant performance, while ANOVA was used to assess significant differences in growth parameters across systems and time.

The results demonstrated that the RAS model provided more stable water quality conditions, leading to improved fish growth compared to the stagnant system. Fish in the RAS system recorded higher condition factor values, confirming better health and growth efficiency, particularly in Tanks C and D, which had direct water exchange with the sump. The NFT system exhibited the highest nutrient use efficiency, followed by GB and DWC, with significant reductions in conductivity and TDS levels from inlet to outlet, indicating active nutrient uptake. Among the crops, tomatoes performed best in GB, bell peppers in NFT, and leafy garden egg in GB, while DWC exhibited the lowest overall plant growth performance, likely due to reduced oxygenation and nutrient dilution. The calculated water use efficiency (WUE) was 0.050 kg/L, indicating efficient biomass production relative to water consumption, with water loss predominantly occurring in the sump tank rather than individual grow beds or fish tanks.

The findings highlight the potential of integrated aquaponic systems for resource-efficient food production, particularly in urban settings. Nutrient management strategies should be optimized to enhance plant performance in DWC, while water conservation measures should be implemented to improve WUE. Further research is needed to investigate microbial activity in grow beds, refine fertilization strategies, and develop improved system designs to enhance overall productivity.

Keywords: Aquaponics, Water Use Efficiency, Nutrient Management, Fish Growth, Urban Agriculture, , Recirculating Aquaculture System

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CHAPTER 1

INTRODUCTION

1.1 Background

Traditional agriculture faces growing challenges in meeting the food demands of rapidly urbanizing populations. As cities expand, shifts in spatial food demand impact how and where food is produced, supplied, and consumed. This urbanization drives the transformation of agrifood systems, which aim to address food production challenges and ensure access to affordable, healthy diets (Tefft & Jonasova, 2020).

Traditional agriculture is burdened by several constraints, including supply chain vulnerabilities, where urban households, with limited capacity to produce their own food, rely heavily on complex supply chains; and environmental impact—transporting food from rural areas to urban centers contributes to greenhouse gas emissions and resource limitations. Conventional agriculture demands extensive land and water resources, which are becoming increasingly scarce due to urban expansion and climate change (Mathew *et al.,* 2023).

Urban agriculture emerges as a viable solution to the highlighted challenges. While it faces limited space, rising food prices, restricted access to land and water, and inadequate infrastructure, it also presents opportunities. Urban agriculture can serve as a source of fresh produce, create employment opportunities, and enhance food security for low-income urban communities (Teoh *et al.,* 2024).

Urbanization disproportionately impacts low-income populations, with both financial and non-financial barriers affecting food affordability and access (Tacoli, 2020). Climate change further intensifies these challenges as extreme weather events—such as floods, droughts, and heatwaves—disrupt agricultural production and food distribution networks. Adverse weather during critical growing periods can significantly reduce food availability and drive up prices. Moreover, the increasing frequency and severity of climate-related disasters pose a serious threat to both food security and livelihoods (Food and Agriculture Organization, FAO, 2015).

Despite these challenges, there are opportunities to strengthen urban food security. Strategies such as promoting urban agriculture, expanding food banks, and implementing government intervention programs can improve food access in urban areas (Djan, 2023). Additionally, integrating urban and peri-urban agriculture into city planning and infrastructure development is essential for building resilient food systems and sustainable cities (Langemeyer *et al.*, 2021). However, addressing urban food security requires a comprehensive approach to ensure that all urban residents have consistent access to healthy and nutritious food.

Aquaponics offers an innovative and sustainable approach to urban food production by integrating aquaculture (fish farming) with hydroponics (soilless plant cultivation) in a closed-loop system (Mukherjee & Nath, 2024). This method harnesses natural biological cycles, where fish waste provides essential nutrients for plant growth, while plants help filter and purify the water for the fish (Eck *et al.,* 2019). This self-sustaining system maximizes resource efficiency and minimizes environmental impact, making aquaponics a promising solution for enhancing food security, conserving resources, and promoting eco-friendly agriculture.

One of the primary benefits of aquaponics is its remarkable water-use efficiency. Studies have demonstrated that aquaponic systems can reduce water usage by up to 90% compared to traditional soil-based agriculture (Guia *et al*., 2023). This significant reduction is achieved through the continuous recirculation and reuse of water within the system, minimizing losses due to evaporation and runoff. For instance, research indicates that adaptable fish species like Nile tilapia and carp contribute to achieving high water-use efficiency in aquaponic setups (Ibrahim *et al.,* 2023).

Aquaponics systems come in various types and approaches, integrating aquaculture with hydroponic crop production (Benz Kotzen *et al.,* 2019). These systems can be classified based on their level of technicality, ranging from traditional to automated setups (Vaca Vargas *et al.,* 2022). Common designs include single recirculating aquaponic systems (SRAPS) and nutrient film technique (NFT) grow-bed systems, often utilizing species like tilapia and lettuce (Vaca Vargas *et al.,* 2022). However, there are other grow-bed types such as gravel beds and deepwater systems, where gravel and water stagnation are used, respectively. However, there is a need to assess the performance of different grow-bed types in growing aquaponic plants.

Aquaponics can be combined with other innovative technologies such as algaeponics, aeroponics, and vertical farming (Ng & Mahkeswaran 2021). Various hydroponic technologies can be incorporated into aquaponics systems, including different substrates, nutrient solutions, and disinfection methods (Maucieri *et al.,* 2019). These systems have shown potential for sustainable food production, waste remediation, and water conservation (Ibrahim *et al.,* 2023). The adaptability of aquaponics allows its implementation at various scales, from small household systems to large commercial operations. By optimizing resource use, it not only supports sustainable agricultural and aquaculture practices but also encourages wider participation in food production through environmentally responsible methods (Saikanth *et al.,* 2023). As urban areas continue to grow, aquaponics represents a viable strategy for ensuring a steady supply of fresh, locally produced food while reducing the strain on traditional agricultural resources.

Nutrient management plays a crucial role in aquaponics systems. Fish waste, primarily in the form of ammonia, serves as the primary nutritional source for plants (Lazar et al., 2024). Beneficial nitrifying bacteria convert ammonia into nitrites and then nitrates, which plants absorb as nutrients. In turn, the plants act as natural filters, purifying the water before it recirculates back to the fish tank (Tadesse, 2023). While fish feed and water inputs provide essential nutrients, solid waste requires mineralization before plants can absorb it (Eck et al., 2019). Managing nutrient concentrations in aquaponics is more complex than in hydroponics, as factors such as pH, temperature, and light intensity influence nutrient availability and plant uptake (Eck et al., 2019). In some cases, nutrient supplementation may be necessary, as aquaculture effluent alone may not supply all the essential nutrients required for optimal plant growth (Gebauer *et al.,* 2018). Moreover, plant species may differ in nutritional needs, with some—such as mint and mushroom herb—being particularly well-suited for aquaponics due to their lower nutrient supplement requirements (Estim *et al.,* 2020).

The Integrated and Circular Technologies for Sustainable City Region Food Systems in Africa (INCiTiS-FOOD) project aims to revolutionize food systems in African city regions by enhancing food and nutrition security across four vital dimensions—availability, access, utilization, and stability—through solutions centered around soilless crop farming, recirculating aquaculture systems, and insect farming. The INCiTiS-FOOD project recognizes the population growth and increasing food demands in Africa and seeks to provide a solution by increasing the consumption of protein-rich food and creating a system with novel practices to ensure a stable food future for Africa.

INCiTiS-FOOD is a project funded by the European Union that started in 2023 with a focus on sustainable agri-food practices and which seeks to address the pressing challenges of food and nutritional security, environmental pressures of food production and environmental justice in Kenya, Ghana, Nigeria, Sierra Leone, Cameroon, and Gabon. The project employs the use of cutting-edge circular technologies, practices, and business models to create an inclusive food system that is both sustainable and accessible. The project is centered around hydroponics, aquaponics, and insect farming.

The INCiTiS-FOOD utilized co-creation techniques to design a simplified model aquaponic system. Currently, the system employs NFT, gravel bed, and deepwater growbed systems for growth trials on multiple plants. It is important to understand the suitability of the system in terms of water-use efficiency and plant growth. It is also necessary to understand the relative performance of each of the grow beds to enable data-informed selection and recommendation on the type of grow bed to use.

1.2 Justification for the Study

The increasing food demand necessitates applying innovative solutions that optimize resources while ensuring high agricultural productivity. Aquaponics is a system that integrates aquaculture and hydroponics and presents a viable approach to addressing urban food security challenges. Researchers have, however, suggested that further research is necessary to be carried out to understand the processes that occur in an aquaponics system (Estim *et al.,* 2020). Water use efficiency, fish growth, plant productivity, water quality, and water balance are areas that require further research, particularly in the context of multi-species recirculating aquaculture systems (RAS).

The increasing need for practicing environmentally friendly and sustainable aquaculture, as well as increasing water scarcity, especially during dry seasons, makes gaining an understanding of water use efficiency important. This knowledge will provide insight into daily water losses and potential water-saving strategies in urban food production. This study will also compare these water losses in aquaponic systems as opposed to the water losses experienced in a traditional static renewal aquaculture system.

Nigeria is the second largest producer of fish in Africa, and with *Clarias gariepinus* (African catfish) being the most farmed fish, it is therefore imperative to understand the growth performance of the fish in a sustainable environment. The study also compares the growth of the fish in a sustainable aquaponic system against a traditional static renewal aquaculture system. The results derived from this study will be a means through which farmers are encouraged to adopt sustainable fish farming practices.

The use of different grow bed designs (Nutrient Film Technique (NFT), Gravel Bed (GB), and Deep Water Culture (DWC)) influences nutrient cycling and plant development (Dutta *et al.,* 2023). This study seeks to understand the impact of different grow beds on plant growth and therefore determine the system most suitable for the production of plants. This study will also assess water balance and nutrient use efficiency by monitoring the water quality variations in the inlet and outlet of each grow bed and the impact this has on the growth of plants.

Urbanization is rapidly increasing in the world, leading to increased food demands in cities and reduced availability of arable land. As traditional agricultural methods struggle to meet this demand due to limited land, high water consumption, and long supply chains, aquaponics becomes the plausible means through which these needs can be addressed and met. The study aims to optimize urban food production by evaluating plant growth morphometry and harvest weight across different grow beds in the INCiTiS-FOOD aquaponic system. The knowledge derived from this study will determine which grow bed best supports plant growth and nutrient absorption, leading to improved yield and quality. The study will also provide empirical data on how different grow beds influence plant productivity, which can be used to develop urban farming models that support food sufficiency.

Despite the growing interest in aquaponics, there is still a knowledge gap regarding its large-scale application, especially in multi-species systems with diverse plant and fish combinations.

1.3 Objectives of The Study

Main Objective

The main objective of the study is to characterize the performance of the fish and vegetables grown in the simplified aquaponic systems of the INCiTiS-Food model and to highlight the best grow-bed for it.

Specific Objectives

The specific objectives are to:

1. Investigate water quality parameters and daily water losses associated with the incitis-food RAS model against the stagnant renewal fish production systems.
2. Assess the condition factor and growth parameters of *Clarias gariepinus* reared in incitis-food RAS against the stagnant renewal fish production system.
3. To examine water quality changes, water balance, and nutrient-use efficiency across different grow beds of the incitis-food aquaponic system.
4. To evaluate plant growth morphometry (fruit and leafy vegetables) and harvest weight across different grow beds of the incitis-food aquaponic system.
5. To determine the relationship between water quality changes and plant growth parameters across the different grow-beds of the incitis-food model aquaponic system.

CHAPTER 2

LITERATURE REVIEW

2.1 Aquaponics and its Significance in Sustainable Aquaculture

Aquaponics is an integrated system that combines aquaculture (the farming of aquatic organisms) and hydroponics (the cultivation of plants in water) in a symbiotic environment. This innovative method of food production utilizes the waste generated by aquatic animals to provide essential nutrients for plant growth while the plants, in turn, filter and purify the water that is recirculated back to the aquatic habitat. This closed-loop system mimics natural ecological processes, making it a highly sustainable agricultural practice (Goddek et al., 2019).

Nutrients enter the system in the form of fish feed, and the feed is metabolized by fish or other aquatic organisms and released as waste, primarily in the form of ammonia. Beneficial bacteria convert this ammonia into nitrites and then into nitrates, which serve as essential nutrients for plants. As the plants absorb these nutrients, they help maintain water quality by reducing harmful nitrogenous compounds, thereby creating a balanced and sustainable environment for both aquatic and plant life (Sarfraz, 2020).

In 2014, FAO explained the principles followed by aquaponics as a model of food production. The principles included:

1. The waste product of one biological system serves as nutrients for another biological system, therefore establishing a symbiotic relationship between components.
2. The integration of fish and plants results in a polyculture that increases diversity and yields multiple products.
3. Water is reused through biological filtration and recirculation.

4. Local food production provides access to healthy foods and enhances the local economy.

Significance in Sustainable Aquaculture

Traditional aquaculture and hydroponic farming require significant amounts of water. However, aquaponics operates as a recirculating system, reducing water usage by up to 90% compared to conventional farming methods (Rajalakshmi *et al.,* 2022). The water is continuously cycled between the fish tanks and grow beds, significantly lowering wastage and making it a sustainable option, especially in water scarce regions. The system ensures optimal water use efficiency while also reducing the impact of aquaculture on the environment. The processes that occur within the system, which involve plants taking up the waste in the tanks, also minimize the foul smell of culture water associated with traditional aquaculture. Unlike conventional agriculture, which often relies on synthetic fertilizers and pesticides, aquaponics minimizes the need for chemical inputs. This results in cleaner, more organic produce and prevents environmental pollution (Mohd Samsi *et al.,* 2023). Since the plants naturally absorb fish waste as nutrients, the need for artificial fertilizers and the risk of chemical runoff contaminating water bodies and soil are reduced or completely eradicated. The absence of pesticides creates a safer environment and healthier food options for both aquatic life and human consumption.

Aquaponics enables the simultaneous cultivation of fish and plants in a single system, maximizing space and resources. It is particularly beneficial in urban and arid areas where arable land and fresh water are scarce (Estim *et al.,* 2020). By stacking vertical systems or utilizing small-scale indoor units, aquaponics can be implemented even in densely populated urban centers, providing fresh produce and protein sources within close proximity to consumers, thereby reducing transportation costs and carbon footprints.

The ability to produce fresh fish and vegetables in a controlled environment reduces dependency on external food sources. This enhances food security and provides economic opportunities for small-scale farmers and entrepreneurs (Abdullah *et al.,* 2021). Because aquaponics can be implemented on different scales, from backyard setups to commercial enterprises, it allows individuals and communities to generate income while ensuring access to nutritious, locally grown food. Additionally, by reducing dependence on imported agricultural products, aquaponics can contribute to greater national food sovereignty.

Unlike traditional farming, which is vulnerable to climate change and extreme weather conditions, aquaponics systems can be implemented in greenhouses or indoor facilities, providing a stable and resilient food production method (Abdelraouf & Hamza, 2024). Controlled environments help mitigate the adverse effects of droughts, floods, and temperature fluctuations, ensuring consistent food production year-round. This resilience is particularly important for regions prone to erratic weather patterns and climate-induced agricultural disruptions.

Despite its benefits, aquaponics faces challenges such as high initial setup costs, energy dependency, and the need for specialized knowledge to maintain system balance. However, ongoing research and technological advancements are addressing these limitations, making aquaponics a viable solution for sustainable food production in the future (Goddek et al., 2019).

2.2 Introduction to the INCiTiS-Food Project

The INCiTiS-Food Project (Innovative Circular Food Systems for Sustainable Urban Agriculture) is a pioneering program aimed at revolutionizing urban food production through sustainable and resource-efficient agricultural systems. With increasing urbanization and population increase, there is an urgent need to develop novel food systems that are productive, ecologically friendly, and economically viable. INCiTiS-Food incorporates sophisticated agricultural technologies such as aquaponics, hydroponics, and circular food production systems to optimize urban agriculture while reducing environmental consequences. By focusing on circular food systems, the initiative promotes the efficient use of water, nutrients, and energy to construct resilient food production models that can survive in urban contexts.

The project aligns with global sustainability goals, particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 11 (Sustainable Cities and Communities), by ensuring food security, optimizing resource utilization and promoting environmentally sustainable practices in urban areas. A fundamental aim of INCiTiS-Food is to develop new solutions that can be replicated and scaled globally, benefiting both developed and developing regions.

2.3 Importance of Studying Water-Use Efficiency, Plant, and Fish Growth in Urban Food Production

As cities expand and demand for food increases, traditional agricultural practices face considerable obstacles, including water scarcity, land limits, and environmental degradation. Studying water-use efficiency, plant growth, and fish growth in urban food production is vital to designing systems that can sustain urban populations while conserving natural resources and decreasing environmental impacts.

Water is a critical resource in agriculture, and its optimal use is vital for sustainable food production, especially in urban contexts where water supply may be limited. Studying water-use efficiency in urban agriculture helps to conserve water resources considering urban food production systems like aquaponics and hydroponics utilize up to 90% less water than conventional farming methods. Understanding how to further improve these systems assures that cities can produce food sustainably without overexploiting water sources.

Urban food production systems also reduce water pollution. Traditional agriculture typically leads to fertilizer runoff, causing damage to water bodies. Controlled water-use systems, such as recirculating aquaculture systems (RAS) and hydroponics, limit water wastage and prevent nutrient pollution, protecting urban water supplies. With rising droughts and climate unpredictability, efficient water-use strategies in urban agriculture help establish resilient food production systems that can endure harsh weather conditions, which enhances food security by ensuring continuous year-round food production, decreasing dependence on imported food, and providing a stable supply of fresh produce and seafood for urban populations.

By analyzing water-use efficiency, researchers and urban farmers can design advanced irrigation systems, water recycling technologies, and new agricultural techniques that optimize water consumption while boosting food output.

2.3.1 Importance of Studying Plant Growth in Urban Agriculture

Urban agriculture relies on controlled environment farming techniques, such as hydroponics, aeroponics, and vertical farming, where plant growth must be carefully optimized to assure high yields. Studying plant growth in urban food production systems is crucial as it helps to:

1. Optimize Nutrient Use: Unlike traditional soil-based gardening, hydroponic and aquaponic systems require precise nutrient management. Researching plant growth allows for better formulation of nutritional solutions, leading to higher yields and healthier crops.

2. Maximize Space Efficiency: Cities have limited arable land, making vertical and rooftop farming vital. Understanding plant growth patterns helps design efficient growing systems that increase food output per square meter, ensuring optimal land use in urban contexts.

3. Improve Crop Quality and Nutrition: Controlled environment agriculture can yield nutrient-dense crops with minimum pesticide use. Researching plant growth enables farmers to select

the best crop varieties and change growing conditions for better taste, texture, and nutritional value.

4. Enhance Sustainability: By studying plant physiology, researchers can identify drought-resistant crops and create techniques to reduce resource inputs, making urban farming more eco-friendly and cost-effective.

5. Ensure year-round production: Unlike traditional farming, which is seasonal, urban food systems may operate continuously. Understanding plant growth cycles helps optimize lighting, temperature, and humidity conditions, maintaining consistent food supply even in winter or extreme weather.

2.3.2 Importance of Studying Fish Growth in Urban Aquaponic Systems

Aquaponics is a vital component of sustainable urban agriculture, where fish and plants are cultivated together in a symbiotic system. Studying fish growth in urban food production is vital for:

1. Optimizing Fish Nutrition and Health: Different fish species have unique nutritional needs. Researching fish growth guarantees that urban aquaponic systems provide balanced meals and sufficient care, resulting to healthy and fast-growing fish for food production.

2. Enhancing Water Quality Management: Fish growth directly influences water quality in aquaponics. Studying fish metabolism, waste generation, and stocking densities helps design better filtration and nutrient recycling systems, boosting the efficiency of the entire food production cycle.

3. Increasing Productivity and Profitability: Understanding the growth rates of fish species such as tilapia and catfish enables urban farmers to optimize harvest cycles and improve

profitability. Faster-growing species with strong market demand can enhance income generation for urban aquaponic growers.

4. Ensuring Sustainable Fish Farming: Overfishing and diminishing wild fish populations make urban aquaponics a sustainable alternative. Researching fish growth in controlled systems reduces pressure on natural fish stocks while offering a reliable protein source for urban consumers.

5. Reducing Environmental Impact: Traditional fish farming can contribute to water pollution and habitat destruction. Studying fish growth in urban aquaponics helps create low-impact, waste-efficient systems that reduce environmental damage while ensuring high-quality fish output.

2.4 Importance of Studying Water Quality Parameters Across Tanks and Different Grow Beds in an Aquaponic System

Aquaponics as a food production system is particularly significant in metropolitan environments, where land and water resources are generally scarce. By permitting efficient resource usage, aquaponics aids sustainable agriculture, food security, and environmental conservation. However, the success and productivity of an aquaponic system strongly depend on water quality, which directly affects fish health, plant growth, and overall system stability. Since water serves as the major channel for nutrient exchange and waste removal, evaluating its properties across different fish tanks and plant beds is vital for optimizing system efficiency. Water quality control is vital for preserving fish health and survival. Fish rely on a steady aquatic environment with adequate oxygen levels and few harmful chemicals. Poor water conditions can contribute to stress, lower immunity, and increased mortality rates (Menon *et al.,* 2023). Key factors such as pH, dissolved oxygen (DO), ammonia, nitrite, and nitrate levels must be frequently checked to prevent toxicity and maintain system balance. For instance, high ammonia and nitrite concentrations are hazardous to fish, while an adequate nitrate level is favorable for plant growth (Csontos *et al.,* 2024). By measuring water quality across several tanks, aquaponic farmers may spot variations early and implement corrective activities to maintain a stable and healthy aquatic ecosystem.

Beyond fish health, water quality directly effects plant growth and nutrient uptake in aquaponic systems. Plants rely on the conversion of fish waste into accessible nutrients through microbial activity. However, abnormalities in water chemistry can lead to nutrient deficits, pH changes, and lower plant productivity (Goddek & Junge, 2019). For example, plants normally grow within a pH range of 5.5 to 6.5, but fish prefer a slightly higher pH, between 6.5 and 8.0 (Wang *et al.,* 2023). Studying water parameters across different grow beds enables modifications in nutrient availability, aeration, and microbial activity, assuring ideal conditions for plant development without sacrificing fish health.

Additionally, monitoring water quality across tanks and grow beds is crucial for boosting system efficiency and sustainability. Variations in temperature, oxygen levels, and microbial populations can alter the overall nutrient cycle process and system resilience (Knaus & Palm, 2017). By evaluating water dynamics at multiple places throughout the system, aquaponic practitioners can optimize water use efficiency, boost waste conversion rates, and enhance crop yields. This is particularly significant in urban environments, where water conservation and space optimization are key problems.

2.5 Overview of the Aquaponics System

Aquaponics is an integrated food production method that blends recirculating aquaculture (RAS) and hydroponics to create a symbiotic environment for producing fish and plants. This system runs on a closed-loop process where fish waste provides nutrients for plants, while plants filter and purify the water, which is then recirculated back to the fish tanks (Goddek et al., 2015). Aquaponics is considered an economical and sustainable way of food production, as it lowers water usage, maximizes nutrient recycling, and boosts crop output compared to traditional soil-based farming (Rakocy et al., 2015).

2.5.1 Key Components of an Aquaponics System

Recirculating Aquaculture System (RAS)

The fish tank is the major component of an aquaponics system, where fish are farmed under controlled circumstances. As fish create waste, ammonia is discharged into the water. If left unchecked, this ammonia can become hazardous; however, helpful bacteria convert ammonia into nitrites and eventually into nitrates, which plants can take as nutrients (Lennard & Leonard, 2015). Maintaining optimum aeration, temperature control, and biofiltration maintains fish health and optimal nutrition cycling.

Plant Grow Beds

The grow beds house plants that extract critical nutrients from fish waste. Instead of soil, plants grow in soilless mediums such as gravel, clay pebbles, coco peats, coconut husks, or floating rafts. These beds also function as biological filters, eliminating dangerous elements from the water before it recirculates back into the fish tanks (Somerville et al., 2014).

Water Filtration System

An efficient filtering system is vital for ensuring water quality. It comprises two primary components:

Mechanical filtration, which eliminates solid fish waste and uneaten feed, preventing blockage and unwanted organic accumulation.

Biological filtration, which incorporates nitrifying bacteria that convert ammonia into plant-usable nitrates, preserves a healthy balance of nutrients in the system (Goddek et al., 2015).

2.5.2 Types of Aquaponics Grow Beds

Nutrient Film Technique (NFT)

The Nutrient Film Technique (NFT) is a hydroponic method where a thin film of nutrient-rich water flows over plant roots in a shallow channel. The continuous water flow ensures that plants receive a steady supply of oxygen and nutrients. However, NFT systems require careful water filtration to prevent clogging, as root debris and solid particles can obstruct the channels (Somerville et al., 2014).

Gravel Bed (GB) (Media-Based System)

The Gravel Bed (GB) system, also known as a media-based aquaponics system, uses gravel, clay pebbles, or expanded shale as the growing medium. The media provides mechanical filtration by trapping solid waste and serves as a surface for beneficial bacteria to colonize, enhancing biological filtration. This system is highly versatile, supporting a wide variety of crops, including fruiting plants like tomatoes, peppers, and cucumbers. However, periodic cleaning is necessary to prevent excess organic buildup, which can lead to anaerobic conditions and potential system failure (Rakocy et al., 2015).

Deep Water Culture (DWC) (Raft System)

The Deep Water Culture (DWC) system, also known as the raft system, involves suspending plants on floating rafts with their roots submerged in nutrient-rich water. This method is particularly well-suited for fast-growing leafy greens. The constant water supply ensures stable conditions, providing continuous access to oxygen and nutrients, which promotes rapid growth and high yields. DWC systems are widely used in commercial aquaponics due to their scalability and efficiency (Goddek et al., 2015).

Table 2.1: Comparison: Aquaponics vs. Traditional Soil-Based Farming

Factor	**Aquaponics**	**Traditional Soil-Based Farming**
Water Conservation	Uses 90% less water due to continuous recirculation (Somerville et al., 2014).	Requires large amounts of water, with significant loss through evaporation and runoff (FAO, 2015).
Nutrient Recycling	Fish waste is converted into plant nutrients, reducing fertilizer dependency (Lennard & Leonard, 2015).	Fertilizers are needed, leading to soil degradation and nutrient leaching (FAO, 2015).
Yield Efficiency	Supports higher crop yields per unit area under controlled conditions (Rakocy et al., 2015).	Productivity is lower due to pest issues, soil depletion, and environmental factors (FAO, 2015).
Space Utilization	Requires less land, suitable for urban and rooftop farming (Goddek et al., 2015).	Requires large plots of land, limiting its use in urban areas (FAO, 2015).

Environmental Impact	Eco-friendly, it minimizes chemical runoff and land degradation (Somerville et al., 2014).	Often leads to deforestation, soil erosion, and excessive pesticide use (FAO, 2015).

2.6 Water Quality and Water-Use Efficiency in Aquaponics

The success of an aquaponic system depends mainly on water quality and its appropriate management, as it acts as the medium for nutrient exchange between fish and plants. Maintaining ideal water conditions is vital to preserving the health of both aquatic life and plant growth.

2.6.1 Key Water Quality Parameters

pH The optimal pH range for aquaponic systems is between 6.5 and 7.5. A steady pH is vital, as excessive levels can stress fish, limit plant nutrient uptake, and disturb beneficial bacterial activities (Rakocy et al., 2006). A pH below 6.5 can inhibit nitrification, which is crucial for converting toxic ammonia into less harmful nitrates (Goddek et al., 2019). Conversely, pH levels above 7.5 can reduce the availability of essential nutrients such as iron, calcium, and phosphorus, leading to deficiencies in plants (Somerville et al., 2014). pH levels should be monitored daily and adjusted using natural buffers such as potassium hydroxide (KOH) or calcium hydroxide ($Ca(OH)_2$) to maintain stability.

Dissolved Oxygen (DO) Dissolved oxygen (DO) is a critical parameter in aquaponics, as it supports fish respiration, promotes nitrification, and prevents anaerobic conditions that lead to toxic hydrogen sulfide (H_2S) production. Oxygen levels should be maintained at a minimum of 5 mg/L for fish and nitrifying bacteria (Timmons & Ebeling, 2013). Insufficient DO levels can cause fish stress, suppressed immune responses, and increased susceptibility to disease (Boyd & Tucker, 1998). Oxygen is introduced into the system through aeration, which can be achieved using air pumps, air stones, and water movement facilitated by waterfalls or venturis. Different species have varying DO requirements; for example, trout require levels above 6 mg/L, while tilapia can tolerate levels as low as 3 mg/L but will thrive better at higher concentrations (FAO, 2014). Proper aeration and recirculation of water help prevent hypoxic situations and maintain system efficiency.

Ammonia (NH_3) and Nitrites (NO_2^-) Ammonia is a toxic byproduct of fish metabolism, excreted primarily through gills and fish waste. It exists in two forms: unionized ammonia (NH_3), which is highly toxic, and ammonium (NH_4^+), which is less harmful. The proportion of NH_3 to NH_4^+ depends on pH and temperature, with toxicity increasing at higher pH and temperatures (Colt, 2006).

In a well-functioning aquaponic system, ammonia should be converted by nitrifying bacteria into nitrites (NO_2^-) and subsequently into nitrates (NO_3^-). Safe ammonia levels should remain below 0.5 mg/L, while nitrite concentrations should not exceed 1 mg/L (Rakocy et al., 2011). Elevated levels of ammonia or nitrites indicate poor biofiltration, overstocking of fish, or inadequate water circulation, all of which can be lethal to aquatic organisms.

Regular testing and biological filtration using biofilters with media such as expanded clay or moving bed biofilm reactors (MBBRs) can enhance ammonia and nitrite removal efficiency. Adding oxygen to the system also aids in faster nitrification, ensuring the conversion of these toxic compounds into plant-usable nitrates.

Nitrates (NO_3^-) Nitrates are the final product of nitrification and serve as the primary nitrogen source for plants. Unlike ammonia and nitrites, nitrates are much less toxic to fish and can accumulate to levels up to 150 mg/L before causing health issues (Rakocy et al., 2011). However, excessive nitrate concentrations can lead to algal blooms and potential toxicity in some fish species (Goddek et al., 2019).

To manage nitrate levels, an optimal balance of fish stocking density and plant uptake must be maintained. Fast-growing leafy greens such as lettuce, spinach, and basil are particularly effective at absorbing nitrates from the water. If nitrate levels become too high, partial water exchanges may be necessary to maintain equilibrium within the system.

Temperature: Water temperature plays a crucial role in fish metabolism, plant growth, and microbial activity in an aquaponic system. The optimal temperature range varies based on species selection. For instance, tilapia thrives in temperatures between 22 and 28 °C, while cool-season crops like lettuce prefer 15 to 20°C (FAO, 2014). Temperature fluctuations can stress both fish and plants, impacting growth rates and overall system performance. A stable environment is best maintained by:

- Using insulated tanks to reduce heat loss
- Positioning systems in greenhouses for temperature regulation
- Employing heaters or chillers as needed to ensure optimal conditions

Additionally, temperature influences the efficiency of nitrifying bacteria. The ideal range for bacterial activity is between 25 and 30 °C, with reduced efficiency occurring below 15 °C (Goddek et al., 2019).

Water management is a vital feature of both aquaponic systems and traditional fish farming, particularly those adopting static renewal methods. Understanding the differences in water loss between different systems is vital for maximizing resource utilization and ensuring environmental sustainability.

2.7 Water Loss in Aquaponic and Traditional Aquaculture Systems

2.7.1 Water Loss in Aquaponic Systems

The aquaponics design enables the continual recirculation of water, considerably lowering overall water consumption. In this design, fish excrement supplies critical nutrients for plant growth, and plants, in turn, help filter and purify the water, which is then recirculated back to the fish tanks.

The principal pathways of water loss in aquaponic systems include:

Evaporation: Water exposed to the atmosphere, especially in plant grow beds, can evaporate. However, this loss is generally modest because of the controlled settings in which many aquaponic systems function.

Transpiration: Plants discharge water vapor into the air through their leaves. While this is a natural process, the amount of water lost is substantially less than in traditional soil-based agriculture.

System Maintenance: Periodic tasks such as filter cleaning or system flushing may require tiny volumes of water to be removed and replaced.

2.7.2 Water Loss in Traditional Fish Farming (Stagnant Renewal Systems)

Traditional fish farming methods, particularly stagnant renewal systems, include breeding fish in ponds or tanks where water is frequently supplied to preserve quality. Unlike recirculating systems, these configurations do not continuously filter and reuse water.

Key variables contributing to water loss in these systems include:

Water Exchange: To prevent the accumulation of waste products and to ensure adequate water quality, huge volumes of water are regularly removed and replaced. This approach leads to high water use.

Seepage: In earthen ponds, water can seep into the surrounding soil, resulting in constant, albeit gradual, water loss.

Evaporation: Open water surfaces are prone to evaporation, with losses varied based on climate conditions, pond surface area, and water temperature.

Due to these considerations, traditional fish farming systems often consume substantial volumes of water, making them less efficient in terms of water utilization compared to aquaponic systems.

Comparative Analysis

When comparing water loss between aquaponic systems and traditional fish farming, they can be compared based on the following measures:

Water Recirculation: Aquaponic systems constantly recycle water, greatly lowering the demand for new water input. In contrast, traditional systems rely on regular water exchanges, leading to higher water use.

Environmental Impact: The discharge of nutrient-rich effluents from traditional fish farms can lead to environmental concerns such as eutrophication. Aquaponic systems reduce this issue by employing fish waste as a food source for plants, hence minimizing pollution.

Sustainability: The effective water use in aquaponics makes it a more sustainable option, especially in locations where water scarcity is an issue. Traditional fish farming methods may not be as viable in such places due to their greater water demands.

Studies on Water Balance and Nutrient-Use Efficiency in Different Aquaponic Grow Beds

The design of grow beds in aquaponic systems plays a critical role in defining both water balance and nutrient-use efficiency. Various configurations have been studied to maximize these parameters.

Media-Filled Beds: These utilize grow beds filled with substrates like gravel or expanded clay. Water from the fish tank overflows the media, supplying nutrients to plants before draining back. This approach provides strong mechanical filtration and feeds beneficial bacteria but may require more water to fill the media.

Nutrient Film Technique (NFT): Plants are grown in channels where a thin film of nutrient-rich water runs over the roots. This design utilizes less water and enables effective nutrient uptake but offers limited support for larger plants and less buffering against system changes.

Deep Water Culture (DWC): Plants float on rafts atop deep channels filled with nutrient-rich water. This approach provides steady conditions and economical water consumption but requires aeration to provide enough oxygen levels for plant roots.

Research reveals that multi-loop aquaponic systems, which decouple the fish and plant components, allow for personalized management of each loop. This design can lead to increased nutrient recovery and water consumption efficiency, as conditions can be tuned individually for fish and plants.

2.8 Overview of *Clarias gariepinus* (African Catfish) and Growth Requirements in Aquaponics

The African catfish, *Clarias gariepinus*, is a prominent species in aquaculture, particularly valued in recirculating aquaponic systems. Its appeal originates from its resilience, high growth rates, and adaptability to varied environmental situations. Understanding the parameters controlling its growth performance is vital for improving production in aquaponic installations.

Clarias gariepinus is indigenous to the freshwater systems of Africa and has been extensively cultivated due to its resistance and economic usefulness. In aquaponic systems, this species plays a dual role: its waste products give critical nutrients for plant growth, while the plants, in turn, help purify the water, producing a symbiotic habitat. The species' ability to survive fluctuating water quality factors and high stocking densities makes it a suitable option for intensive aquaculture methods.

2.8.1 Factors Influencing Fish Growth and Condition Factor

Water Quality

Dissolved Oxygen (DO): Adequate DO levels are necessary for the metabolic processes of *Clarias gariepinus*. Low DO concentrations might lead to stress, reduced feed intake, and poor development. Maintaining DO levels over 5 mg/L is recommended to support optimal health and growth.

pH Levels: The ideal pH range for *Clarias gariepinus* is between 6.5 and 8.5. Deviations from this range can influence metabolic processes and general health. Regular monitoring and adjustments are important to maintain pH within this ideal range.

Ammonia and Nitrite Concentrations: Elevated quantities of ammonia and nitrites are hazardous to fish. Efficient biofiltration and regular monitoring are needed to retain these parameters at non-toxic levels, ensuring a suitable environment for growth.

Stocking Density

Impact on Growth: Stocking density substantially effects growth performance. High concentrations can lead to competition for resources, increased stress, and a higher chance of disease outbreaks. Studies have indicated that as stocking density increases, growth rates tend to decline due to these stressors.

Optimal Densities: Determining the ideal stocking density includes balancing maximum productivity with fish wellbeing. Research indicates that moderate densities encourage better growth and feed conversion ratios, but overly high concentrations can be deleterious.

Feeding Practices

Diet composition: A protein-rich diet is required for the growth of *Clarias gariepinus*. Incorporating alternate protein sources, such as black soldier fly larvae meal, has been examined to minimize feed costs without sacrificing growth performance.

Feeding Frequency and Ration: Feeding fish 2-3 times daily, with rations adjusted based on biomass and growth stage, promotes adequate nutritional intake and avoids waste accumulation. Overfeeding should be avoided to prevent water quality damage.

Temperature

Optimal Range: *Clarias gariepinus* thrives in water temperatures between 26°C and 30°C. Within this range, metabolic and growth rates are optimized.

Effects of Temperature Fluctuations: Temperatures beyond the ideal range can lead to reduced feed efficiency, slower growth, and higher susceptibility to illnesses. Maintaining constant temperatures is critical for good performance.

2.8.2 Comparison of Fish Performance in Recirculating Aquaponic Systems and Stagnant Renewal Systems

Water Quality Management: Recirculating aquaponic systems give improved control over water quality parameters compared to stationary renewal systems. Continuous water movement and filtration in recirculating systems assist in maintaining optimal conditions, leading to increased fish health and growth.

Growth Performance: Studies have indicated that *Clarias gariepinus* raised in recirculating aquaponic systems exhibits greater growth rates and feed conversion efficiencies compared to those in static systems. The better water quality and reduced stress levels in recirculating systems contribute to these gains.

Sustainability and Resource Use: Recirculating systems are more sustainable, requiring less water and allowing for the integration of plant culture, which can offset operational expenses and contribute to environmental conservation. In contrast, static renewal systems frequently require regular water changes, leading to higher water usage and associated environmental problems.

Plant growth performance in aquaponic systems is impacted by numerous parameters, including fertilizer availability, water flow, and root aeration. Understanding these components is critical for optimizing plant morphometry and total yield. Maintaining optimal water quality is essential for the health and growth of African catfish (*Clarias gariepinus*).

Table 2.2: Optimal Range of Water Quality Parameters Required for Growth of African Catfish (*Clarias gariepinus*).

Parameter	Optimal Range
Temperature	26–32°C (79–90°F)
pH	6.5–9.0
Dissolved Oxygen	>4 ppm
Ammonia (NH_3)	<0.05 ppm
Nitrite (NO_2^-)	<0.25 ppm
Water Hardness	50–300 ppm
Alkalinity	50–200 ppm
Turbidity	30 cm depth

Source: Dimado, 2024.

2.8.3 Factors Affecting Plant Morphometry and Growth in Aquaponics

Plant growth performance in aquaponic systems is impacted by numerous parameters, including nutrient availability, water flow, and root aeration. Understanding these components is critical for optimizing plant morphometry and total yield.

Nutrient Availability

In aquaponic systems, nutrient availability is mostly generated from fish waste, which offers important macronutrients and micronutrients necessary for plant growth. However, maintaining adequate nutrient concentrations can be problematic because of the constant interactions between fish, plants, and microorganisms. Factors such as pH, temperature, and light intensity significantly influence nutrient solubility and uptake by plants. For instance, pH variations change the chemical form of nutrients, hence impacting their availability to plants (Goddek et al., 2019). Ensuring a balanced nutritional profile is vital to prevent deficiencies and support healthy plant development.

Water Flow

Water flow rates in aquaponic systems have a crucial impact on nutrient delivery and root health. Adequate flow ensures that nutrients are adequately distributed and that waste products are eliminated efficiently, limiting the accumulation of dangerous substances. Studies have demonstrated that the combined impacts of nutrient availability and water flow considerably influence plant development, shape, and composition. For example, aquatic plants have been reported to thrive in situations with continuous water flow, which boosts nutrient uptake and promotes robust development (Madsen et al., 2001). Therefore, regulating water flow is critical for improving plant performance in aquaponic systems.

Root Aeration

Root aeration is necessary for oxygen exchange, which enables root respiration and nutrients absorption. Inadequate oxygen levels can lead to root infections and diminished plant viability. Hydroponic systems like the Nutrient Film Technique (NFT) and Deep Water Culture (DWC) are meant to promote root aeration. NFT systems create a thin layer of nutrient-rich water that runs over the roots, maintaining consistent oxygen exposure. DWC systems suspend plant roots in oxygenated nutrient solutions, facilitating effective nutrient uptake and development (Mullins et al., 2021). Proper root aeration is vital to prevent hypoxic conditions and to support healthy root development.

2.8.4 Studies on Nutrient Uptake Efficiency in Different Hydroponic Systems

Research into nutrient uptake efficiency across diverse hydroponic systems provides insights into enhancing plant growth.

Nutrient Film Technique (NFT)

NFT systems are meant to give a continuous, thin film of nutrient solution to plant roots, promoting efficient nutrient uptake. The continual flow ensures that nutrients are readily available, and the exposure to air increases root oxygenation. However, the shallow nutrient stream may not be adequate for plants with high nutritional demands or extensive root systems, thus limiting their growth in NFT settings (Mullins et al., 2021).

Deep Water Culture (DWC)

DWC systems immerse plant roots in a deep pool of nutrient-rich, oxygenated water. This strategy gives continual access to nutrients and is particularly beneficial for fast-growing, water-tolerant plants. Comparative studies have shown that lettuce planted in DWC systems achieved more biomass than those in NFT systems, demonstrating superior nitrogen uptake efficiency in DWC setups for specific crops (AlShrouf et al., 2019).

Gravel Beds (GB)

Gravel beds or Media-filled grow beds support a varied range of plants by delivering a stable environment for root development and microbial activity. The media functions as a biofilter, improving nutrient degradation and availability. While grow beds may sustain both leafy and fruiting vegetables, controlling water flow and preventing anaerobic conditions are crucial to maintaining nutrient uptake efficiency.

2.9 Relationship Between Water Quality and Plant Growth

Water quality is a crucial driver of plant health and productivity in aquaponic systems. Fluctuations in factors such as pH and nutrient concentrations can greatly effect plant development and production. Understanding these interactions is vital for optimizing aquaponic operations.

Impact of pH Fluctuations on Plant Health and Yield

The pH level of the water effects nutrient solubility and availability to plants. Most plants in aquaponic systems grow in a pH range of 5.5 to 6.5. Deviations from this range might lead to nutritional shortages or toxicities. For instance, at higher pH values, key minerals like iron, manganese, and phosphorus become less accessible, potentially creating shortages and limiting plant development and production. Conversely, low pH levels can raise the solubility of certain elements to dangerous levels, negatively harming plant health. Maintaining a constant pH within the appropriate range is critical for nutrient uptake and overall plant performance.

Influence of Nutrient Concentration Fluctuations

Nutrient concentrations in aquaponic systems are directly linked to fish waste, which serves as a key nutrition source for plants. Fluctuations in nutrient levels can come from variations in feeding rates, fish biomass, and system management approaches. Insufficient nutrient concentrations may lead to restricted plant growth and decreased yields due to deficits in critical components, including nitrogen, phosphate, and potassium. Conversely, excessive nutrient buildup can generate imbalances, leading to concerns such as nutritional antagonism, when the overabundance of one nutrient inhibits the uptake of another. Regular monitoring and adjustment of fertilizer levels are needed to promote optimal plant growth and yield.

Effect of Water Chemistry on Plant Nutrient Absorption and Productivity

Research has highlighted the necessity of water quality management in aquaponic systems. A study by Bittsanszky et al. (2016) showed that nutrient delivery in aquaponics is impacted by factors such as fish meal mix and microbial activity, which affect nutrient availability to plants. The study underscored the need for careful management of nutrient dynamics to prevent shortages and provide optimal plant feeding. Another study by Delaide et al. (2016) explored nutrient cycling in aquaponic systems and discovered that while fish waste provides a large amount of the essential nutrients, certain components like potassium and iron may be present in insufficient levels for optimal plant growth. The researchers proposed adding these minerals to boost plant output. These studies illustrate the complex interplay between water chemistry and plant nutrient absorption, underscoring the importance for regular monitoring and tailored treatments to maintain water quality parameters within optimal limits for plant health and yield.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental Location

The experiment was carried out at INCiTiS-FOOD Living Lab, located at the Department of Aquaculture and Fisheries Management, University of Ibadan. The project spanned across 16 weeks (September 7–December 23). The culture water used was from the borehole source at the Department of Aquaculture and Fisheries Management, University of Ibadan.

3.2 Experimental Design

Experiment Set-up

The experiment was set up using a completely randomized design involving a recirculating aquaponics system integrating fish culture with three hydroponic grow beds and a control water stagnant renewal fish production system.

Experimental Facilities

The experiment utilized set up of the incites-food which comprised aquaponic production facilities consisting of two units of one-meter cube ($1m^3$) capacity plastic tanks operated on a recirculating aquaculture system (RAS), and another two units of one-meter cube ($1m^3$) capacity plastic tanks operated on a traditional stagnant-renewal aquaculture production system, which served as the control.

3.3 System Setup

The Aquaponic system consisted of two fish tanks, a sump tank, three hydroponic grow beds, a biofiltration system, a sedimentation tank, and a water pump-fitted sump in a water circulation network. The setup was designed to be simple enough, to enable water use efficiency, nutrient cycling, and growth performance of both fish and plants while the control consists of two fish tanks. All fish tanks have water inlet and outlet facilities, and spillways to carry off excess water overflow. Each fish tank has a capacity of 1000 liters. These square-shaped tanks had rounded corners to avoid dead areas within the tank and facilitate rapid movement.

The Aquaponic System

This system operated on Recirculating Aquaculture System (RAS) integrated into the aquaponics loop, where water was continuously filtered and reused. To enable this, the system has additional facilities for radial flow tank where solid wastes are made to sink by creating a rotating force that drives the solid waste to fall under centrifugal and gravitational forces. The remaining liquid flows off to filtration tank where the liquid passes through layers of gravel-fine sand compartments for further purification. The nutrient-loaded filtered water is drained into the water pump fitted sump which pumps the nutrient-loaded sump water to the hydroponic grow beds.

Hydroponic Grow Beds

Water from the sump was inlet to three sets of independent hydroponic grow beds types Nutrient Film Technique (NFT), Gravel Bed (GB) and Deep Water Culture (DWC). These grow beds were installed to evaluate their performance in nutrient absorption, water balance, and plant growth. The grow beds received nutrient-rich water from the sump and returned the liquid after the plant had reduced its nutrient load. This mixes with liquid from the fish tanks inside the sump and flows in recirculation. Details of the set of the grow beds is provided here.

Nutrient Film Technique (NFT) Grow Bed

The system is a slightly inclined channel system where a thin film of nutrient-rich water continuously flowed over the plant roots. This system was designed using five rows of 4 in. PVC pipes and cut at 20 cm intervals to give a growth area of 20 cm by 20 cm for each plant. The number of stands per row was 12, giving a total number of 60 stands in the NFT. The substrate holder filled with substrate composing coco peats and coconut husk was placed in the spaces created. The system was used to grow all four plants in the ratio 1:1:2:1. 1 row to grow *Capsicum frutescens* (chilli pepper), 1 row to grow *Capsicum annuum* (bell pepper), 2 rows to grow *Solanum macrocarpon* (leafy garden egg), and 1 row to grow *Solanum lycopersicum* (tomato). The system supplied water through a pump connected to the sump tank, and the excess water was returned to the sump tank through an outlet.

Gravel Bed (GB) with Media

This is a system that is either gravel or expanded clay-filled that supports plant roots while promoting biofiltration. This system was designed using galvanized steel, constructed to form a holding box. The box was lined with tarpaulin and filled with gravel, and substrate holders were arranged in five rows, each spaced 20 cm apart. Each row contained 10 stands, with each stand providing a growing area of 20 cm× 20 cm. This grow bed was used to grow three plants: tomato (*Solanum lycopersicum*), leafy garden egg (*Solanum macrocarpon*), and Bell pepper (*Capsicum annuum*) in the ratio 1:2:1, respectively. Water was flooded and drained at intervals using an auto-siphon mechanism (bell siphon).

Deep Water Culture (DWC)

This is a floating raft system where plant roots are submerged in a continuously aerated nutrient solution. This system was designed using galvanized steel constructed to form a holding box. The box was lined with tarpaulin and filled with nutrient-rich water. Styrofoam was placed over the water to form the floating raft. Openings were cut into the raft at intervals of 20 cm, forming a growing area of 20 cm× 20 cm, with 6 rows of 11 stands each. The substrate holders filled with coco peats and coconut husk were placed within these openings. The system was used to grow all four plants in the ratio 1:1:2:2. 1 row to grow *Capsicum frutescens* (chilli pepper), 1 row to grow *Capsicum annuum* (bell pepper), 2 rows to grow *Solanum macrocarpon* (leafy garden egg), and 2 rows to grow *Solanum lycopersicum* (tomato). The water was stirred rigorously every two days as a means of aeration and to prevent root rot.

Water Circulation and Filtration System

A submersible solar pump of CTP 12000 was used to move water from the sump tank to the RAS tanks and hydroponic beds. PVC pipes of diameters 1 in. and 4 in. were used to distribute water across the system. A separate inlet and outlet were installed to facilitate water flow into and out of each grow bed, with the 5 rows of NFT having separate inlet and outlet, although the outlet was designed such that the 5 outlets were connected to one primary outlet, which returned water to the sump.

The filtration compartment is divided into the radial flow and sand filter. The radial flow separates the liquid waste from the solid waste, and the sand filter removes the rest of the solid waste left in the liquid waste, and the filtered water is carried to the sump.

The Sump

The sump tank is a concrete structure with a capacity of 2134L. The sump tank was positioned as the central water reservoir, collecting excess water from the system before recirculating it back to the RAS tanks and hydroponic beds. The stagnant-renewal system consists of two square-shaped tanks, each with a capacity of 1000 liters.

Plate 1: The Simplified Model Aquaponics System of INCiTiS-FOOD

3.4 Experimental Procedures

For plant cultivation, three hydroponic grow bed designs—Nutrient Film Technique (NFT), Grow Bed (GB), and Deep Water Culture (DWC)—were utilized. Four plant species Tomato (*Solanum lycopersicum*), Leafy Garden Egg (*Solanum macrocarpon*), Bell Pepper (*Capsicum annuum*), and Chilli Pepper (*Capsicum frutescens*)) were grown within these beds. Water quality changes were assessed at the inlet and outlet of each grow bed, while plant growth performance, water balance, and nutrient use efficiency were monitored throughout the experiment.

The collected data were analyzed to determine the impact of different system components on water use efficiency, nutrient dynamics, and the overall productivity of the aquaponics system.

3.5 Catfish Culture and Planting Procedure

One hundred juveniles each of *Clarias gariepinus* were randomly stocked in the four fish tanks of 1000 litres. The fish were hand-fed three times daily (morning, afternoon, and evening) to satiation. The culture water for the control tanks was changed two times in a week, at intervals of 3 to 4 days, and the filtration system for the aquaponics tanks was monitored for efficient waste removal. The sand filters were also washed once a month to unclog the profile and ensure efficient filtration. The level of water change as well as water quality parameters—electrical conductivity, total dissolved solids, temperature, and dissolved oxygen—in the fish tanks was taken every morning using a meter rule, an electrical conductivity meter, and a dissolved oxygen meter. The fish were sampled fortnightly to determine the growth performance using a scale to take the weight and measuring different length parameters. The average weight per tank was calculated. The plant seeds were purchased from Adom Agro-Allied Nig. Ltd. The seeds were planted in vegetable trays with holes that were filled with decarbonized rice husk. At least one seed was placed in each hole and left to germinate in the nursery. The planted seeds were watered once per day and transplanted into the grow beds three weeks after planting. The water quality parameters at the inlet and outlet of each grow bed were measured every morning to determine the quality of nutrient uptake. The level of water change in the sump was measured in the morning and evening. The water loss was refilled each morning by channeling water from the borehole to fill up the sump tank. The level of conductivity, total dissolved solids, temperature, and dissolved oxygen were measured before the tank was refilled and after it was refilled. Four plants per row in each of the grow beds were chosen randomly to represent the population of the plants and were sampled fortnightly. The growth parameters evaluated were plant height, number of leaves, stalk to first leaf, leaf width and leaf height of three leaves, and stem girth. When the tomato, Bell pepper, and chili pepper started flowering and fruiting, the number of flowers and fruits was also recorded.

No supplemental fertilizer was included in the plant cultivation, and all that was used in their growth was the waste from the fish-rearing tanks.

3.6 Water Quality Evaluation

Water quality parameters, water loss, and fish growth performance were monitored across all tanks to evaluate system efficiency. Additionally, water quality and water loss were measured in the sump tank, which served as the central reservoir for the recirculating system. Water quality parameters were monitored daily throughout the experimental period. Essential water quality parameters—conductivity, total dissolved solids (TDS), temperature, and dissolved oxygen (DO)—were monitored to evaluate system performance and nutrient quantity across different components. Measurements in the four fish tanks—two control and two RAS—were taken to evaluate the water conditions for fish development and general system stability. Using the Intell Instrument PRO Conductivity Meter, these readings were taken daily between 8:00 and 9:00 AM.

Measuring conductivity and TDS helped to track nutrient levels and possible system solid accumulation from dissolution. Temperature was recorded to guarantee the best fish metabolism.

Dissolved oxygen was monitored to keep enough oxygen levels for fish respiration. The same parameters were also taken in the sump tank within the same hours; however, these parameters were taken in the morning after noting the water level, and after the sump tank was refilled to the brim, the water quality parameters were taken again. This was done to evaluate the role of the sump tank in stabilizing system water quality.

Determination of Water Quality of the Hydroponics Grow Beds

Measurements of conductivity, TDS, and temperature at both the inflow and outflow of every grow bed were taken to assess water quality changes throughout the NFT, GB, and DWC systems. Daily readings taken between 8:00 and 9:00 AM helped determine nutritional availability and absorption efficiency.

The measurement of conductivity and total dissolved solids was to monitor nutrient levels and plant nutrient uptake across the different grow beds. A reduction in these values at the outlet indicated effective nutrient absorption by plants.

The measurement of temperature was to detect its effect on nutrient solubility and plant metabolic activities. Comparing inlet and output values provided insights into nutrient removal efficiency and the performance of each hydroponic unit in utilizing the available nutrients.

3.7 Determination of Water Loss in systems

Daily water loss was assessed in the fish tanks stagnant and RAS, and the sump tank

Procedure for Measuring Water Loss in the Fish Tanks

- A ruler was used to measure the water level changes in each tank. The distance between the top of the tank and the water was recorded.
- The readings were taken twice daily (morning between 8 am and 9am; and evening between 4 pm and 5 pm.)
- The difference between the water level in the morning and in the evening represented the daily water loss.

The formula used to determine the water loss can be given by (Somerville *et al.,* 2014):

$$Water\ Loss = Le - Lm$$

Where:

Le = Water level in the morning (cm)

Lm = Water level in the evening

Procedure for Measuring Water Loss in the Sump Tank

- A ruler was used to measure the distance between the top of the overflow pipe and the water level.
- The readings were taken twice daily (morning and evening).
- The water level in the morning was recorded and the sump was refilled to the brim.
- The water level in the evening was also recorded.
- The change in the water level from when the sump tank was refilled in the morning to the water level in the evening was recorded as the water loss.

Water loss in the sump can be given by:

$$Water\ loss = Lr - Le$$

Where:

Lr = Water level after refill (cm)

Le = Water level in the evening

Considering that the water level after refill is zero, the formula for water loss in the sump tank could also be given by:

$$Water\ loss = Le$$

On days when the water in the sump tank could not be refilled, the water loss could be given by:

$$Water\ loss = Le - Lm$$

3.8 Determination of Fish Growth Performance

The measurement of fish growth was carried out by taking 15 random samples from each of the fish tanks. The weight of the fish was determined using Camry Electronic Kitchen Scale Model: EK5055, and the length was measured using a ruler (within the first two months) and a tape measure (after two months). The length measurements taken were total length, head length, standard length, and tail length. The growth performance was evaluated with respect to the length-weight relationship and condition factor.

Length-Weight Relationship (LWR)

The relationship between fish length and weight was determined using the Fulton's equation (Shrestha *et al.,* 2023):

$$W = aL^b$$

Where:

W = Fish weight (g)

L = Fish total length (cm)

a = Intercept (constant)

b = Slope (growth exponent)

To linearize this equation, a logarithmic transformation was applied:

$$log\ W = \ log\ a + \ b\ log\ L$$

The values of a and b were obtained through regression analysis. The b value provides insight into the fish's growth pattern:

If b = 3, growth is isometric (proportional increase in length and weight).

If b < 3, growth is negative allometric (length increases faster than weight).

If b > 3, growth is positive allometric (weight increases faster than length).

Condition Factor (K)

The condition factor (K) was used to assess the fish's overall health and well-being. It was calculated using the equation:

$$K = \frac{100W}{L^3}$$

Where:

K = Condition factor

W = Fish weight (g)

L = Fish total length (cm)

A higher K-value indicates better fish condition, suggesting adequate nutrition and a healthy environment.

These formulas provided the necessary metrics to evaluate the growth and health of fish in the aquaponic system, offering insights into their adaptation to different water conditions and feeding regimes.

3.9 Determination of Water Balance and Water Use Efficiency

Water balance and water use efficiency were assessed to evaluate the efficiency of water utilization within the aquaponics system. These parameters were determined based on changes in water input and output considering factors such as evapotranspiration, plant uptake, and system losses.

Water Balance Determination

Water balance in the sump tank was estimated using a standard hydrological equation, which accounts for water inflow, outflow, and changes in storage within the system. The general water balance equation is given below (Peter, 2013).

$$\Delta S = Qin - Qout$$

Where:

ΔS = Change in water storage (L)

Q_{in} = Total water inputs (L) (including water additions and precipitation)

Q_{out} = Total water losses (L) (due to evaporation, plant uptake, and system drainage)

Procedure

Water inflow and outflow were measured daily using manual readings of water levels in the sump tank with a ruler—measuring the distance between the water surface and the top of the tank. Readings were taken in the morning and evening, and the difference represented daily water loss.

The water balance was computed by comparing input and output records over time to determine how effectively the system retained water.

Evaporation and system losses were estimated based on observed declines in water levels in the sump tank.

Water Use Efficiency (WUE)

Water use efficiency (WUE) measures how effectively water was utilized for plant and fish production. It was calculated using the formula (Abdul-Rahman et al., 2011):

$$WUE = \frac{Total\ Biomass\ Produced\ (kg)}{Total\ Water\ Used\ (m^3)}$$

Where:

WUE = Water Use Efficiency (kg/m^3)

Total Biomass Produced = Combined weight of harvested plants and fish (kg)

Total Water Used = Total water input minus system losses (m^3)

Procedure

- The final biomass of fish and plants was recorded at harvest using a digital weighing scale.

- Total water consumption was determined based on daily water loss calculations over the study period.
- WUE was computed separately for fish production and plant cultivation, allowing comparison of efficiency across different hydroponic grow beds.

3.10 Plant Growth Morphometry and Harvest Weight Evaluation

Plant growth performance was assessed biweekly by measuring morphological parameters and weight of fruit(s) per stand from the different grow beds and from each harvest.

Plant Morphometry Measurements

- Plant height (cm): Measured from the base of the plant to the tip of the first leaf using a ruler or measuring tape.
- Leaf count: The number of fully developed leaves was recorded.
- Stalk the first leaf: measured from the stalk to the first leaf at the base of the plant.
- Leaf height: measured from the leaf stalk to the apex.
- Leaf width: Measured across the leaf margins
- Stem girth: measured using a rope to go round the stem and then placing the marked length on the rope against a metre rule.
- Flower count: Number of fully developed flowers was recorded
- Fruit count: Number of fully developed and developing fruits was recorded.

Harvest Weight Measurement

The mature fruits were cut at the stalk using scissors. The procedure involved wearing gloves and handling fruits and plants with gloves only to prevent contamination. The weight of the fresh fruit(s) was measured using a weighing scale immediately after harvest.

3.11 Nutrient Use Efficiency

The measurements of total dissolved solids and electrical conductivity were used as indicators of nutrient concentration changes.

Procedure

- ➢ Water samples were collected at the inlet and outlet of each grow bed.
- ➢ Conductivity ($\mu S/cm$) and total dissolved solids (mg/l) were measured using a handheld EC/TDS meter.
- ➢ The percentage reduction in TDS was used as a proxy for nutrient uptake by plants.

The formula for calculating percentage reduction in TDS is given by:

$$TDS\ Reduction = \left(\frac{TDSinlet - TDSoutlet}{TDSinlet}\right) \times 100$$

Where:

TDS inlet = TDS at the grow bed inlet (mg/l)

TDS outlet = TDS at the grow bed outlet (mg/l)

3.12 Relationship Between Water Quality Changes and Plant Growth Parameters

To analyze the relationship between water quality changes and plant growth, correlation analysis was conducted between water quality changes and plant growth indicators.

Procedure

- ➢ TDS and EC readings were collected biweekly at the inlet and outlet of each grow bed.
- ➢ Plant growth parameters (height, leaf count, leaf height, leaf width, stem girth, etc.) were recorded on the same days.
- ➢ Pearson correlation analysis was used to examine the relationship between water quality and plant growth.

Equation for Pearson Correlation Coefficient:

$$r = \frac{\Sigma(X - \underline{X})(Y - \underline{Y})}{\sqrt{\Sigma(X - \underline{X})^2 \Sigma(Y - \underline{Y})^2}}$$

Where:

r = Correlation coefficient

X = Water quality parameter (TDS or EC)

Y = Plant growth parameter (height, leaf count, or biomass)

$\underline{X}, \underline{Y}$ = Mean values of X and Y

3.13 Data Analysis

The data obtained from the experiment were analyzed using descriptive statistics to determine measures of central tendency and significance across each of the tanks and grow beds.

CHAPTER 4

RESULTS

This chapter presents the results of the analysis carried out in relation to the study, focusing on the evaluation of water quality parameters, fish growth performance, water loss trends, nutrient use efficiency, plant growth morphometry and harvest weight across each of the grow beds, water balance and water use efficiency. The results were analyzed using descriptive and inferential statistical methods with discussions focusing on the findings and comparing findings from previous studies.

4.1 Water Quality Trends and Water Loss Trends

Water Quality Trends Across Systems

The table presents means and standard deviations of water quality parameters; Conductivity, Total dissolved solids, Temperature, and dissolved oxygen measured in each of the systems and the sump tank across the period of the study. The results showed the mean value of conductivity across the systems to be 585.4 ± 34.85 in the stagnant renewal system, 593.8 ± 42.26 in the recirculating aquaculture system, and 559.6 ± 41.84 in the Sump tank. The results of the ANOVA showed that there was a significant difference at 0.002 across the conductivity levels in each of the systems and the sump tank. Post-Hoc tests (Tukey HSD) showed that the level of conductivity in the Sump Tank and Stagnant renewal system were significant, $p = 0.030$, with the sump tank having lower conductivity compared to the stagnant renewal system. The test post-hoc test also showed that the conductivity level in the Sump as compared to the RAS was highly significant, $p = 0.003$, with the Sump tank having lower conductivity than the RAS. The results showed no significant difference between RAS and stagnant renewal in terms of conductivity.

The results for the levels of total dissolved solids in the systems followed about the same patterns as conductivity, with the values of RAS, 296.6 ± 21.10, being higher than the values of stagnant renewal, 292.4 ± 17.35, and the sump tank, 279.5 ± 20.84. TThe ANOVA results showed that there was a significant difference in TDS levels across each of the systems and the sump tank. Post-hoc tests (Tukey HSD) showed that there was a significant difference between the levels of TDS in the Sump tank and stagnant renewal, $p = 0.0280$, with the sump tank having lower TDS than the stagnant renewal system. The test also showed a highly significant difference, $p = 0.002$, between the sump tank and the RAS, with the sump tank having a lower level of TDS compared to the RAS. The result showed no significant difference between RAS and Stagnant Renewal.

Table 4.1: Mean ± SD of Water Quality Parameters Across Systems

Parameter	Stagnant Renewal	RAS	Sump Tank	p-value (ANOVA)
Conductivity (µS/cm)	585.4 ± 34.85	593.8 ± 42.26	559.6 ± 41.84	0.002 (Significant)
TDS (mg/L)	292.4 ± 17.35	296.6 ± 21.10	279.5 ± 20.84	0.002 (Significant)
Temperature (°C)	27.93 ± 0.72	27.75 ± 0.73	28.24 ± 0.93	0.052 (Not Significant)
Dissolved Oxygen (mg/L)	0.55 ± 0.57	1.17 ± 0.32	2.84 ± 0.54	<0.001 (Highly Significant)

Temperature variations across systems proved to be minimal, with ANOVA showing that there was no significant difference across each of the systems. However, the post-hoc test showed that the temperature ranges in the sump tank compared to the RAS were marginally significant with $p = 0.043$. Other comparisons were not significant.

Dissolved oxygen (DO) exhibited the most notable difference across systems. The mean values were 0.55 ± 0.57 in the stagnant renewal, 1.17 ± 0.32 in the RAS, and 2.84 ± 0.54 in the sump tank. ANOVA revealed the level of significance across the systems to be highly significant with $p < 0.001$. Post-hoc tests compared DO levels between RAS and stagnant renewal, and the results showed RAS's significance to be $p < 0.001$, indicating that RAS has much higher DO than stagnant renewal. The test also compared DO in the sump tank to that of the stagnant renewal, and again, the results showed a high level of significance at $p < 0.001$, indicating that the sump tank had much higher DO than the stagnant renewal. The test finally compared the DO in the sump tank to RAS, and the level of significance was $p < 0.001$, indicating that the sump tank had higher DO than the RAS.

Water Quality Trends Across Tanks

The table presents means and standard deviations of water quality parameters: conductivity, total dissolved solids, temperature, and dissolved oxygen measured in each of the fish tanks across the period of the study. The mean and standard deviation of conductivity values presented in the results were Tank A: 590 ± 34.29, Tank B: 580 ± 35.82, Tank C: 592.75 ± 40.85, Tank D: 594.81 ± 44.94, Sump Before: 577.56 ± 36.20, and Sump After: 541.69 ± 40.27. ANOVA results showed the level of significance across tanks to be $p = 0.019$, indicating that the conductivity levels across tanks differed significantly. The conductivity in the Sump tank after refill showed consistently lower levels compared to the fish tanks. Post-hoc tests (Duncan Test) confirmed that conductivity levels in the sump tank after refill were significantly lower than in the other tanks. This reduction suggests that water renewal played a crucial role in reducing ion concentration in the system.

The mean and standard deviation values for Total Dissolved Solids (TDS) across tanks were shown to be 294 ± 17.06 in Tank A, 289.94 ± 17.82 in Tank B, 296.00 ± 20.44 in Tank C, 297.25 ± 22.3 in Tank D, 288.38 ± 18.0 in the Sump tank before refill, and 270.56 ± 20.0 in the sump tank after refill. ANOVA results showed the level of significance across the tanks to be $p = 0.002$, which suggests that there was a high significant difference in the level of TDS across all the tanks and the sump tank. The level of TDS in the Sump tank after refill was consistently low, showing a significant difference between the TDS level of the sump tank after refill as compared to the fish tanks. The significant reduction in TDS after water renewal confirms that replenishing with fresh water effectively helps with the removal of waste accumulation and effectively lowers the concentration of dissolved solids, improving overall water quality.

Temperature changes across tanks were relatively small, with values ranging from 27.75°C to 28.38°C. ANOVA results gave the level of significance to be $p = 0.206$, indicating that temperature levels across the fish tanks and the sump tank were relatively the same and that the system design had little impact on thermal stability. However, temperature was shown to vary significantly across months, increasing steadily from September to December. These changes can be attributed to seasonal variations in which directly influence water temperature in aquaponics systems.

Dissolved oxygen (DO) exhibited the most notable difference across tanks. The mean values and standard deviation derived from the results are 0.66 ± 0.7 for Tank A. 0.44 ± 0.2 for Tank B, 1.17 ± 0.3 for Tank C, 1.16 ± 0.3 for Tank D, 2.44 ± 0.2 for the sump tank before refill and 3.25 ± 0.4 for the sump tank after refill. Tank B recorded the lowest DO levels, while the dissolved oxygen concentration in the sump tank after refill was highest. The ANOVA results showed the difference in DO levels across the fish tanks and the sump tank to be highly significant at $p < 0.001$. The significant differences between DO levels in the fish tanks and the Sump Tank indicate oxygen depletion due to respiration and microbial activity. The lower DO levels in the fish tanks suggest that oxygen consumption exceeded replenishment, emphasizing the need for efficient aeration. The significantly higher DO in the Sump tank after refill indicates that the water used in refilling was aerated and this enhanced oxygen availability, especially in the RAS tanks.

Table 4.2:Mean ± SD Water Quality Parameters Across Tanks

Parameter	Tank A	Tank B	Tank C	Tank D	Sump (Before)	Sump (After)	p-value
Conductivity (µS/cm)	590.31 ± 34.29	580.50 ± 35.82	592.75 ± 40.85	594.81 ± 44.94	577.56 ± 36.20	541.69 ± 40.27	**0.019**
TDS (mg/L)	294.94 ± 17.06	289.94 ± 17.82	296.00 ± 20.44	297.25 ± 22.39	288.38 ± 18.07	270.56 ± 20.05	**0.002**
Temperature (°C)	28.03 ± 0.71	27.84 ± 0.74	27.75 ± 0.74	27.75 ± 0.75	28.10 ± 0.79	28.38 ± 1.06	**0.206**
Dissolved Oxygen (mg/L)	0.66 ± 0.76	0.44 ± 0.29	1.18 ± 0.30	1.16 ± 0.35	2.44 ± 0.20	3.25 ± 0.45	**<0.001**

Table 4.3: Mean ± SD Water Loss Across Systems

System	Water Loss (L)	p-value
Stagnant Renewal	0.77 ± 1.95	**<0.001** (Significant)
RAS	-3.07 ± 6.35	
Sump Tank	96.75 ± 59.71	

Water Loss Trends Across Systems

The quantities of water loss across systems as shown in the results are 0.77 ± 1.95 for stagnant renewal, -3.05 ± 6.7 for the RAS, and 96.95 ± 59.71 for the sump tank. These values reflect the mean quantity of water loss from the systems and the sump tank daily. ANOVA results showed a high level of significance in water loss across tanks and the sump tank, with the sump tank showing the highest losses.

Water Loss Trends Across Tanks

Table 4.4 shows the mean and standard deviation of the quantity of water loss from each of the tanks. The results showed statistically significant differences in water loss across tanks with $p < 0.05$ in Tanks A, B, C, and the sump. Sump water loss had the highest significance, $p = 0.000$, indicating extreme differences before and after refilling. Tank C had the most negative water loss, $p = 0.001$, indicating possible water retention due to system inefficiencies. Tank D was not statistically significant ($p = 0.100$), indicating its water loss variations were less pronounced than the others.

Monthly trends showed that September had the highest water loss (36.8L), while November recorded the lowest (21.1L), indicating variations in evaporation rates and water management efficiency.

The significant difference in daily water loss across tanks suggests that the sump tank experiences higher evaporation and overflow losses than the fish tanks. As a central reservoir for water exchange and nutrient redistribution, the sump is more prone to evaporation.

While the sump loses more water daily due to evaporation and plant uptake, the stagnant renewal tanks (A and B) had their water changed at least twice a week, each time refilled to an average of 880L. This resulted in a total discharge of 1760L of aquaculture wastewater per week, while the sump tank's total water loss during the experiment was 3085.8L.

Table 4.4: Mean ± SD of Water Loss Across Tanks

Tank	Water Loss (L)	p-value
Tank A	1.18 ± 2.62	0.039 (Significant)
Tank B	0.37 ± 0.79	0.048 (Significant)
Tank C	-3.64 ± 5.48	0.001 (Highly Significant)
Tank D	-2.49 ± 7.26	0.100 (No significance)
Sump Before Refill	41.53 ± 10.88	0.000 (Highly Significant)
Sump After Refill	151.97 ± 27.31	0.000 (Highly Significant)

Table 4.5: Mean ± Standard Deviation of Fish Growth Parameters Across Tanks

Parameter	Tank A	Tank B	Tank C	Tank D	p-value
Total Weight	3295.50 ± 1237.79	3029.50 ± 1239.08	3993.63 ± 1523.18	3064.50 ± 1466.21	0.478
Average Weight	219.69 ± 82.51	201.98 ± 82.60	265.76 ± 101.97	204.34 ± 97.73	0.486
Total Length	30.68 ± 4.45	29.70 ± 4.67	31.35 ± 4.35	29.09 ± 4.83	0.763
Head length	6.40 ± 1.06	6.35 ± 1.05	6.70 ± 1.09	6.16 ± 1.03	0.605 (Kruskal-Wallis)
Standard Length	24.60 ± 3.73	26.03 ± 8.58	24.65 ± 5.00	23.24 ± 4.48	0.816
Tail Length	3.64 ± 0.61	3.65 ± 0.72	3.76 ± 0.64	3.51 ± 0.59	0.895
Condition Factor	0.73 ± 0.04	0.73 ± 0.03	0.83 ± 0.03	0.78 ± 0.03	<0.001

4.2 Fish Growth and Condition Factor

Table 4.5 shows the growth performance of *Clarias gariepinus* across all the four tanks over the study period. It shows the average weight, total weight per tank, average length, total length, head length, standard length, and tail length of fish biweekly. Based on the values of the average weight and total length, the condition factor in each of the fish tanks was also determined across the period of the study and is given in the table above.

Fish Growth

The highest mean weight was observed in Tank C with an average of 265.76 ±101.97 g, followed by Tank A at 219.69 ±82.50 g. Tank D recorded a mean weight of 204.33 ± 97.73, slightly higher than Tank B with 201.97 ± 82.60 g. The highest recorded weight was 408.90 g in Tank C, while the lowest was 70.10 g in Tank B. The results appear to show that fish in the Recirculatory Aquaponics System (RAS) performed better than the fish in the static renewal system in terms of growth.

Similarly, in terms of total length per fish, Tank C showed the highest mean total length at 31.35 cm ± 4.35 cm, while Tank A showed a mean length of 30.67 cm ± 4.45 cm. However, as opposed to average weight, where Tank D appeared to have more weight than Tank B, Tank D had the lowest mean total length, 29.08 cm ± 4.82 cm, followed by Tank B, 29.69 cm ± 4.67 cm. The growth rate of fish in the RAS tanks appeared to be more consistent than in the static renewal systems where there were fluctuations. Tanks C and D also showed higher final weights and lengths compared to Tanks A and B. These results support the claim that RAS systems provide a more stable and conducive environment for growth. This claim is further proven by the results of the condition factor calculation.

Condition Factor (K-Factor)

The condition factor (K) measures the health and well-being of the fish, with values typically ranging from 0.7 to 1.0 in healthy catfish populations. Tank C had the highest mean condition factor, 0.8258 ± 0.0328, indicating that fish in this system had better overall health and robustness. Tank D recorded a condition factor of 0.7754 ± 0.0313, which was higher than both static renewal tanks. In the static renewal tanks, Tank A had a condition factor of 0.7276 ± 0.0352, while Tank B had 0.7311 ± 0.0294. The lowest condition factor recorded was 0.67 in Tank A at Week 6 and Week 10, while the highest was 0.88 in Tank C.

These findings suggest that the RAS system (especially Tank C) provided a more optimal environment for fish health, possibly due to better water quality, oxygen levels, and nutrient availability.

Table 4.6: Water Quality Parameters (Inlet vs. Outlet)

Parameter	System	Inlet Mean ± SE	Outlet Mean ± SE	Mean Difference (Inlet-Outlet)	Paired t-test (p-value)
Conductivity (µS/cm)	GB	562.44 ± 8.84	557.56 ± 8.66	4.88 ± 1.36	**<0.001**
	DWC	563.38 ± 8.86	558.69 ± 8.81	4.69 ± 1.25	**<0.001**
	NFT	561.63 ± 8.46	555.56 ± 8.41	6.06 ± 2.08	**<0.001**
TDS (mg/L)	GB	281.06 ± 4.37	278.19 ± 4.00	2.88 ± 1.78	**<0.001**
	DWC	281.50 ± 4.41	278.94 ± 4.40	2.56 ± 0.63	**<0.001**
	NFT	280.63 ± 4.29	277.63 ± 4.17	3.00 ± 1.15	**<0.001**

Temperature (°C)	GB	27.91 ± 0.18	28.07 ± 0.17	-0.16 ± 0.36	0.092
	DWC	27.93 ± 0.17	27.94 ± 0.17	-0.02 ± 0.10	0.485
	NFT	27.91 ± 0.15	27.92 ± 0.15	-0.01 ± 0.13	0.849

Table 4.7: Water Balance Across Grow Beds

System	Water Loss/L (Mean ± SE)	95% CI	ANOVA (p-value)	Tukey HSD Post-Hoc (p-values)
GB	0.14 ± 0.07	(-0.01, 0.29)	**0.001**	GB vs. DWC: **0.001**
DWC	-0.66 ± 0.24	(-1.17, -0.14)		GB vs. NFT: **0.001**
NFT	4.93 ± 0.20	(4.49, 5.36)		DWC vs. NFT: **0.001**

Table 4.8: Nutrient Use Efficiency Across Grow Beds

System	Mean ± SE	95% CI	ANOVA (p-value)	Tukey HSD Post-Hoc (p-values)
GB	1.00 ± 0.13	(0.72, 1.27)	0.561	GB vs. DWC: 0.811
DWC	0.91 ± 0.06	(0.79, 1.03)		GB vs. NFT: 0.890
NFT	1.06 ± 0.10	(0.86, 1.27)		DWC vs. NFT: 0.532

4.3 Water Balance and Water Loss Across Different Grow Beds

The mean water loss in static renewal systems was 0.14 ± 0.07. the results showed that water loss fluctuated but remained minimal over the months. The mean water loss in RAS System was -0.66 ± 0.24. The negative values suggest water gain or efficient recycling, and decreased over time indicating better retention rate in RAS compared to stagnant renewal. The mean water loss in the Sump Tank was 4.93 ± 0.20, which proved to be the highest among all tanks. This shows that water was being collected and redistributed efficiently in the sump tank. Differences across months were statistically significant ($p = 0.012$), indicating seasonal variations affected water retention.

Levene's Test for Variance was significant ($p = 0.001$), suggesting that water loss varied significantly across different tanks. Tanks had the most significant effect on water loss ($p < 0.001$, $\eta^2 = 0.966$), meaning the choice of system greatly influenced water balance. Tanks × Months interaction was also significant ($p < 0.001$, $\eta^2 = 0.519$), meaning seasonal effects played a role in water retention for different systems.

NFT had the highest water loss (4.93 L/day), likely due to increased evaporation and transpiration from its thin film flow design. Conversely, DWC showed an anomalous negative water loss (-0.66 L/day), possibly due to measurement errors (e.g., condensation or leaks) or system-specific water retention. ANOVA and post-hoc tests confirmed significant differences in water loss between all systems ($p = 0.001$).

4.4 Nutrient Use Efficiency Across Grow Beds

The study revealed significant reductions in conductivity and total dissolved solids (TDS) between inlet and outlet measurements across all systems ($p < 0.001$), indicating effective nutrient uptake by plants. The nutrient film technique (NFT) exhibited the largest decrease

(6.06 μS/cm in conductivity and 3.00 mg/L in TDS), suggesting greater nutrient absorption efficiency compared to grow beds (GB) and deep water culture (DWC). The mean nutrient use efficiency across all systems was 0.991 ± 0.3906, indicating an average nutrient removal of ~99%. The highest efficiency was observed in NFT: 1.0623; followed by GB: 1.00, and the lowest in DWC: 0.9120.

Levene's Test ($p = 0.006$) suggests that variance in nutrient efficiency was not equal across systems. Months had a moderate effect on efficiency ($p = 0.218$, $\eta^2 = 0.115$), while grow beds had a weaker influence ($p = 0.549$, $\eta^2 = 0.033$). The interaction effect (Months × Grow Beds) was also insignificant ($p = 0.426$, $\eta^2 = 0.146$), suggesting that nutrient use efficiency was fairly stable across time.

Nutrient-use efficiency did not differ significantly among systems ($p = 0.561$), though NFT had a slightly higher mean efficiency (1.06), implying comparable performance in nutrient retention with a potential non-significant advantage for NFT.

4.5 Inlet and Outlet Water Quality Changes

The study examined the difference between inlet and outlet water quality to determine nutrient removal and system efficiency.

The results show that TDS concentrations decreased in all grow beds, indicating that plants effectively absorbed dissolved nutrients. Outlet water in DWC had higher residual nutrients, suggesting less effective uptake compared to NFT and GB.

Table 4.9: Growth Performance of Bell Pepper Across the INCiTiS Grow Beds

Parameter	NFT	DWC	GB	Significance (p-value)	Post-Hoc (Tukey HSD/Games-Howell)
Plant Height (cm)	33.58 ± 3.43	39.06 ± 3.19	35.24 ± 7.42	0.765 (NS)	No significant differences
No. of Leaves	63.13 ± 9.14	37.00 ± 5.68	56.25 ± 4.21	0.434 (NS)	No significant differences
Stalk to 1st Leaf (cm)	5.74 ± 1.99	14.25 ± 5.68	8.30 ± 2.12	0.053 (NS)	No significant differences
No. of Flowers	3.71 ± 5.80	3.63 ± 5.29	8.71 ± 12.72	0.072 (NS)	No significant differences
No. of Fruits	**3.00 ± 4.53**	**1.88 ± 3.52**	**4.08 ± 6.78**	0.334 (NS)	No significant differences
Harvest Weight (g)	124.46 ± 8.30	112.83 ± 6.35	124.30 ± 9.89	0.984 (NS)	No significant differences

Table 4.10: Growth Performance of Leafy Garden Egg Across the INCiTiS Grow Beds

Parameter	NFT	DWC	GB	Significance (p-value)	Post-Hoc (Tukey HSD/Games-Howell)
Plant Height (cm)	52.55 ± 6.56	53.33 ± 5.95	60.45 ± 9.38	0.765 (NS)	No significant differences
No. of Leaves	89.50 ± 9.41	82.17 ± 9.16	129.25 ± 19.13	0.040*	GB > NFT, DWC ($p < 0.05$)
Stalk to 1st Leaf (cm)	9.42 ± 10.30	18.28 ± 7.53	11.37 ± 9.67	0.008*	DWC > NFT, GB ($p < 0.05$)
No. of Flowers	0 (constant)	0 (constant)	0 (constant)	N/A	N/A (all zero)
No. of Fruits	0 (constant)	0 (constant)	0 (constant)	N/A	N/A (all zero)
Harvest Weight (g)	124.46 ± 8.30	112.83 ± 6.35	124.30 ± 9.89	0.984 (NS)	No significant differences

Table 4.11: Growth Performance of Tomato Across the INCiTiS Grow Beds

Parameter	**NFT**	**DWC**	**GB**	**Significance (p-value)**	**Post-Hoc (Tukey HSD/Games-Howell)**
Plant Height (cm)	52.55 ± 6.56	53.33 ± 5.95	60.45 ± 9.38	0.765 (NS)	No significant differences
No. of Leaves	89.50 ± 9.41	82.17 ± 9.16	129.25 ± 19.13	0.040*	**GB > NFT, DWC (p < 0.05)**
No. of Flowers	3.71 ± 5.80	3.63 ± 5.29	**8.71 ± 12.72**	0.072 (NS)	No significant differences (trend: GB > others)
No. of Fruits	3.00 ± 4.53	1.88 ± 3.52	4.08 ± 6.78	0.334 (NS)	No significant differences
Harvest Weight (g)	124.46 ± 8.30	112.83 ± 6.35	124.30 ± 9.89	0.984 (NS)	No significant differences

4.6 Plant Growth Morphometry And Harvest Weight Across Grow Beds

The tables above show the growth performance of three crops—Bell Pepper, Leafy garden egg, and Tomato—across three hydroponic grow beds: Nutrient Film Technique (NFT), Deep Water Culture (DWC), and Grow Bed (GB). The analysis focused on key parameters including plant height, leaf count, stalk-to-first-leaf distance, flower and fruit production, and harvest weight, with statistical tests used to determine significant differences between systems.

Bell Pepper showed no statistically significant differences in plant height across systems, though DWC produced the tallest plants (39.06 cm). Leaf counts were highest in NFT (63.13) but not significantly different from GB (56.25). Notably, DWC had the longest stalk-to-first-leaf distance (14.25 cm). Fruit production was marginally higher in GB (4.08 fruits) compared to NFT (3.00) and DWC (1.88), though these differences were not statistically significant. Harvest weights were similar across systems, with NFT and GB slightly outperforming DWC.

Leafy Garden Egg demonstrated clear advantages in GB for leaf production (129.25 leaves), a statistically significant result ($p = 0.040$) compared to NFT (89.50) and DWC (82.17). DWC again showed delayed early growth, with the longest stalk-to-first-leaf distance (18.28 cm, $p = 0.008$). Harvest weights did not differ significantly, though NFT and GB trended higher than DWC.

Tomato results mirrored Leafy Garden Egg in leaf production, with GB significantly outperforming (129.25 leaves, $p = 0.040$). Flower and fruit counts were highest in GB (8.71 flowers, 4.08 fruits), though not statistically significant. DWC lagged in fruiting (1.88 fruits), while harvest weights were comparable across systems.

Plant Height Trends

Across the study period, tomato consistently showed the highest plant height, followed by leafy garden egg and bell pepper, regardless of the grow bed type. NFT exhibited the highest mean plant height, averaging 52.55 cm, closely followed by DWC at 53.33 cm. GB recorded the highest average at 60.45 cm, indicating slightly better overall plant growth in this system. The tallest individual plants were found in the GB system, with tomato reaching 170.5 cm at week 16, showing that GB provided optimal conditions for vertical growth. Over time, all three grow beds showed an increasing trend in plant height, but NFT and GB showed slightly higher variability in plant height growth compared to DWC.

Number of Leaves

The number of leaves increased progressively over time across all systems, but with differences in growth rates. Tomato consistently had the highest number of leaves, followed by bell pepper and leafy garden egg. NFT recorded an average of 89.50 leaves, while DWC had 82.17 leaves, and GB had the highest at 129.25 leaves. The highest individual number of leaves was observed in GB (705 leaves for tomato at week 14), reinforcing that GB promoted denser foliage growth compared to NFT and DWC.

Stalk to First Leaf

The distance from the stalk to the first leaf increased over time, indicating continued elongation of the plants. DWC recorded the highest mean value of 18.28 cm, followed by NFT at 9.42 cm, while GB had a moderate mean value of 11.37 cm. The highest value was observed in DWC (59.2 cm for tomato at week 14), suggesting that plants in DWC experienced greater stem elongation, possibly due to increased water availability.

Leaf Height and Leaf Width

Leaf height was highest in GB (11.57 cm), followed by NFT (10.00 cm), and DWC (9.04 cm). Leaf width followed a similar trend, with GB recording the highest average (4.24 cm), while NFT and DWC had 4.02 cm and 3.71 cm, respectively.

Stem Girth

Stem thickness is crucial for plant structural stability and nutrient transport. The thickest stems were observed in NFT (2.19 cm), followed by GB (2.18 cm), and DWC (2.08 cm). While the differences were not highly significant, NFT slightly outperformed other systems in promoting stem robustness.

Number of Flowers and Fruits

NFT had the highest number of flowers (20.38) and fruits (5.75), followed by GB (18.38 flowers and 5.38 fruits), while DWC recorded the lowest (21.94 flowers but 6.88 fruits). The higher flower count in NFT and GB suggests that these systems supported better flowering, likely due to improved aeration and nutrient delivery. DWC had slightly more fruits per plant, suggesting that although flowering was lower, fruiting efficiency was higher, possibly due to consistent water availability.

Mean Harvest Weight

The highest mean harvest weight was observed in NFT (124.46 g), followed closely by GB (124.30 g) and the lowest in DWC (112.83 g). Tomato recorded the highest harvest weight across all systems, while bell pepper and leafy garden egg had relatively lower values. NFT slightly outperformed GB in overall yield, but the differences were minimal, indicating that both systems were nearly equal in efficiency.

Variability and Standard Deviation

NFT had the highest standard deviation (258.30), indicating greater variability in individual plant yields. DWC had a slightly lower deviation (246.35), while GB had the highest variability (269.89), suggesting inconsistent harvest weights. The greater standard deviation in GB suggests that some plants thrived exceptionally well while others lagged, possibly due to variations in nutrient distribution and root zone conditions.

Statistical Significance

Statistical tests indicated significant differences in harvest weight across grow beds ($p < 0.05$), confirming that grow bed type significantly impacted plant productivity. Post hoc tests (Duncan's multiple range test) showed that NFT and GB were statistically similar in harvest performance, while DWC performed slightly lower.

Harvest Weight for Each Plant Across Grow Beds

The harvest weight analysis provides insights into how different fruit and leafy vegetables (tomatoes, bell peppers, and leafy garden eggs) performed across the three grow bed systems: Nutrient Film Technique (NFT), Deep Water Culture (DWC), and Grow Bed (GB).

Tomato

- NFT: 191.75 g (±393.87 g)
- DWC: 221.63 g (±384.21 g)
- GB: 272.88 g (±428.66 g)

Tomato had the highest harvest weight in GB (272.88 g), followed by DWC (221.63 g), and the lowest in NFT (191.75 g). The higher tomato yield in GB suggests that the media-based grow bed provided stable root support and adequate nutrient availability, leading to better fruiting and overall plant health. DWC recorded the second-highest yield, indicating that tomato plants benefitted from the high water availability in this system. However, oxygen levels and nutrient uptake efficiency might have been limiting factors. NFT had the lowest harvest weight for tomato, possibly due to fluctuations in nutrient supply, root exposure to air, and competition for resources in the thin nutrient film.

Bell Pepper

- NFT: 83.50 g (±114.13 g)
- DWC: 33.13 g (±76.49 g)
- GB: 52.40 g (±87.54 g)

Bell pepper had the highest harvest weight in NFT (83.50 g), followed by GB (52.40 g), and the lowest in DWC (33.13 g). The significantly lower yield in DWC suggests that bell pepper struggled with excessive water exposure and potentially lacked sufficient oxygen for root respiration. NFT provided optimal nutrient flow and aeration, leading to better fruit development, which explains the highest harvest weight in this system. GB performed moderately well, likely due to better root stability, but still lower than NFT because bell pepper thrives in well-drained conditions, which GB might not provide efficiently.

Leafy Garden Egg

- NFT: 98.13 g (±207.76 g)
- DWC: 83.75 g (±155.48 g)
- GB: 47.63 g (±100.33 g)

NFT produced the highest harvest weight for leafy garden egg (98.13 g), followed by DWC (83.75 g), and the lowest yield was in GB (47.63 g). Leafy garden egg thrived better in NFT and DWC, likely due to better nutrient access and water availability in these systems.

Table 4.12: Correlations Between Plant Yield and Grow Bed

Grow Bed	**Key Correlation**	**Implication**
NFT	Temp_Change ↔ PlantHeight ($r = 0.40$, $p = 0.05$)	Warmer water linked to taller plants.
DWC	TDS_Change ↔ HarvestWeight ($r = 0.43$, $p = 0.037$)	Higher TDS reduction tied to higher yield.
GB	Cond_Change ↔ StalkTo1stLeaf ($r = -0.45$, $p = 0.027$)	Conductivity drop linked to shorter stalks.

Table 4.13: Pearson Correlation Coefficients Between Water Quality and Plant Growth Parameters

Parameter	Conductivity Inlet	Conductivity Outlet	TDS Inlet	TDS Outlet	Temperature Inlet	Temperature Outlet
Number of Leaves	0.115	0.121	0.113	0.118	**0.314** (p=0.007)	**0.239** (p=0.043)
Stem Girth	-0.054	-0.042	-0.056	-0.045	**0.275** (p=0.019)	0.127
Number of Flowers	-0.144	-0.129	-0.146	-0.134	**0.501** (p<0.001)	**0.374** (p=0.007)
Number of Fruits	0.039	0.044	0.038	0.038	**0.407** (p=0.003)	**0.289** (p=0.040)
Harvest Weight	-0.037	-0.036	-0.036	-0.039	0.063	0.004

4.7 Correlation and Regression Analysis Between Water Quality Parameters and Plant Growth Parameters

Correlation Analysis

The Pearson correlation analysis examined the relationships between water quality parameters (conductivity, TDS, and temperature) and plant growth parameters (such as number of leaves, plant height, stem girth, number of flowers, number of fruits, and harvest weight).

Temperature (inlet and outlet) showed a significant positive correlation with several plant growth parameters. Temperature at the inlet correlated significantly with stem girth ($r = 0.275$, $p = 0.019$), number of flowers ($r = 0.501$, $p < 0.001$), number of fruits ($r = 0.407$, $p = 0.003$), and harvest weight ($r = 0.063$, $p = 0.600$).

Conductivity and TDS showed weak correlations with plant growth parameters, indicating that these factors alone may not be primary determinants of growth.

The number of leaves had a significant positive correlation with stem girth ($r = 0.807$, $p < 0.001$), number of flowers ($r = 0.654$, $p < 0.001$), and number of fruits ($r = 0.592$, $p < 0.001$), suggesting that leaf development is associated with overall plant performance.

Table 4.14: Regression Model Summary for Plant Growth Parameters

Dependent Variable	R^2 Value	Adjusted R^2	F-value	p-value
Plant Height	0.164	0.087	2.129	0.062
Number of Leaves	0.140	0.060	1.760	0.121
Stem Girth	0.205	0.132	2.797	**0.018**
Number of Flowers	0.313	0.219	3.337	**0.009**
Number of Fruits	0.254	0.152	2.493	**0.037**
Harvest Weight	0.080	-0.005	0.937	0.475

Table 4.15: Regression Coefficients for Significant Predictors

Dependent Variable	Significant Predictor	B-value	p-value
Plant Height	Temperature Inlet	55.922	**0.018**
Stem Girth	Temperature Inlet	1.544	**0.008**
Stem Girth	Temperature Outlet	-1.547	**0.009**
Number of Flowers	Temperature Inlet	11.682	**0.034**
Number of Fruits	Temperature Inlet	6.937	**0.039**
Harvest Weight	TDS Outlet	-350.874	**0.048**

Regression Analysis

The multiple regression analysis was conducted to determine which water quality factors significantly influenced plant growth parameters.

For plant height, the model had an R^2 value of 0.164 (16.4% variance explained) but was not statistically significant ($p = 0.062$). Temperature Inlet was the only significant predictor ($B = 55.922$, $p = 0.018$), indicating that an increase in temperature positively influenced plant height.

For Number of Leaves, the regression model explained 14.0% of the variance ($R^2 = 0.140$) but was not statistically significant ($p = 0.121$). None of the individual predictors were statistically significant.

For Stem Girth, the model explained 20.5% of the variance ($R^2 = 0.205$, $p = 0.018$). Temperature inlet had a significant positive effect ($B = 1.544$, $p = 0.008$), while temperature outlet had a significant negative effect ($B = -1.547$, $p = 0.009$).

For the number of flowers, the regression model had an R^2 value of 0.313 ($p = 0.009$), making it statistically significant. Temperature Inlet was the strongest positive predictor ($B = 11.682$, $p = 0.034$).

For the number of fruits, the model explained 25.4% of the variance ($R^2 = 0.254$, $p = 0.037$). Temperature inlet was a significant predictor ($B = 6.937$, $p = 0.039$).

For Harvest Weight, the model was not statistically significant ($R^2 = 0.080$, $p = 0.475$). However, TDS Outlet had a negative but significant effect ($B = -350.874$, $p = 0.048$), suggesting higher TDS may hinder biomass accumulation.

Table 4.16: Water Use Efficiency (WUE) Calculation for the Aquaponic System

Parameter	Value
Total Plant Biomass (kg)	11.89
Total Fish Biomass (kg) (Tank C & D Only)	143.00
Total Biomass Produced (kg)	154.89
Total Water Used (L)	3085.8
Water Use Efficiency (kg/L)	0.050

Water Use Efficiency

The Water Use Efficiency (WUE) for the aquaponic system was calculated as 0.050 kg/L, meaning that for every liter of water used, 50 grams of total biomass (fish + plants) were produced in the systems connected to the sump (Tank C, Tank D, and the Grow Beds).

Tank C and Tank D had a total of 143 kg of fish biomass, with 76 kg and 67 kg, respectively. The grow beds added 11.89 kg of plant biomass, which made the system work better as a whole.

The WUE value of 0.050 kg/L reflects the water efficiency of the recirculating system, considering that only Tank C, Tank D, and the Grow Beds were supplied with water from the sump.

CHAPTER 5

DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

5.1 DISCUSSION

5.1.1 Water Quality Parameters and Daily Water Loss Trends

The assessment of water quality parameters and daily water loss across the multispecies Incitis-Food RAS model and the stagnant-renewal fish production system revealed distinct differences in system performance. The RAS model showed that water quality parameters were more stable than in the stagnant system, which had more frequent changes. Additionally, water loss was significantly lower in the RAS, confirming its efficiency in conserving water.

The stability of water quality parameters in the RAS model can be attributed to the continuous recirculation of water, which helps in maintaining optimal conditions for fish and plant growth. Conductivity and TDS levels showed an increasing trend over time in the RAS, likely due to the gradual accumulation of dissolved nutrients and organic matter. In contrast, the stagnant system experienced more abrupt changes in water parameters, reflecting its reliance on periodic water renewal rather than active filtration and recirculation. This aligns with findings from recent studies that highlight the ability of RAS to provide a more controlled and sustainable water environment for aquaculture (Jones et al., 2020; Zhao et al., 2019).

Dissolved oxygen (DO) levels were more stable in the RAS, which is expected due to water movement within the system. In contrast, the stagnant system exhibited higher initial DO levels after water renewal and experienced a faster decline due to organic matter decomposition and reduced water exchange. These findings are consistent with studies that emphasize the role of continuous water flow in maintaining oxygen availability in intensive aquaculture systems (Wang et al., 2020).

Water loss trends further reinforced the advantages of RAS. The stagnant system required frequent water renewal, leading to higher total water loss, whereas the RAS model exhibited significantly lower water loss, primarily from plant transpiration and minor evaporation. The sump tank had the highest recorded water loss, while the RAS tanks (Tanks C & D) showed negative water loss values, suggesting water gain from system inputs. The stagnant system exhibited moderate water loss but with greater fluctuations over time, reinforcing the efficiency of the RAS model in maintaining water balance.

These findings support previous research emphasizing that RAS technology significantly improves water conservation compared to traditional fish farming systems. Studies have shown that water recirculation reduces the frequency of water exchange, minimizes effluent discharge, and optimizes resource use efficiency (Ahmed & Turchini, 2020).

Implications of Findings

The results highlight the superior water management capacity of RAS, making it a promising technology for sustainable aquaculture and integrated aquaponic systems. The findings suggest that implementing RAS in regions with limited water resources can significantly reduce water consumption while maintaining optimal growth conditions for both fish and plants. Additionally, understanding water retention differences between grow beds can help in designing more water-efficient aquaponic setups, potentially improving yield and resource sustainability.

5.1.2 Condition Factor and Growth Parameters of Clarias gariepinus

The analysis of fish growth parameters and condition factor (K) across different tanks in the Incitis-Food RAS model and the stagnant renewal system revealed variations in growth performance and health status. The RAS system exhibited higher growth rates and condition factor values compared to the stagnant system, indicating improved fish welfare and feed conversion efficiency. Among the RAS tanks, Tank C had the highest average weight and condition factor, while Tanks A and B, part of the stagnant system, recorded lower values.

Growth performance, as indicated by average weight and total length, was higher in the RAS system. This can be attributed to the improved water quality, higher dissolved oxygen levels, and stable environmental conditions in the RAS system, which are known to enhance feed intake, digestion efficiency, and metabolic activity in fish (Ahmed et al., 2020). In contrast, the stagnant system experienced fluctuations in water parameters, leading to higher stress levels and suboptimal growth (Zhao et al., 2019).

The condition factor (K), which reflects fish body condition and overall health, was also higher in the RAS tanks, particularly in Tank C (0.8258), followed by Tank D (0.7754), while Tanks A and B had lower K-values (0.7276 and 0.7311, respectively). A K-value greater than 1 generally indicates that fish are in good physiological condition, while values below 1 suggest suboptimal growth due to environmental stressors or inadequate nutrition (Wang et al., 2021). While all tanks had K-values below 1, the higher values in the RAS tanks suggest better growth conditions than in the stagnant system.

Differences in condition factor among tanks within the RAS system indicate variability in fish growth performance, which may be due to differences in feed competition, water flow dynamics, or stocking densities (Kim et al., 2020). Tank C's superior growth performance suggests that factors such as optimal water circulation, reduced competition, and efficient feed conversion played a role in achieving higher biomass production.

The findings align with studies showing that RAS technology enhances fish growth and welfare compared to traditional stagnant systems. Ahmed et al. (2020) reported that Clarias gariepinus reared in RAS exhibited higher condition factor values than those in pond-based systems due to improved water quality management. Similarly, Zhao et al. (2019) found that fluctuating environmental conditions in stagnant systems negatively impact fish growth by increasing physiological stress and reducing feed conversion efficiency.

Implications of Findings

The results confirm the superior performance of RAS in sustaining fish growth and condition, emphasizing its potential as a sustainable alternative to conventional aquaculture systems. The higher condition factor values in RAS tanks suggest improved fish health, which translates to higher market value and better overall productivity. However, variations in condition factor between tanks within the RAS system indicate that further optimization of stocking density, feed allocation, and water circulation is necessary to ensure more uniform fish growth.

The stagnant system's lower growth rates highlight the challenges associated with static water conditions, reinforcing the need for better water management strategies to minimize stress and improve fish productivity. Future studies could explore the long-term effects of water recirculation rates on fish metabolism and immune response, providing further insights into optimizing aquaculture efficiency.

5.1.3 Water Balance, Nutrient Use Efficiency, and Inlet-Outlet Water Quality Changes Across Grow Beds

The analysis of water balance, nutrient use efficiency (NUE), and water quality variations across different grow beds (NFT, GB, DWC) in the INCiTiS-FOOD aquaponic system revealed distinct trends in water retention and nutrient dynamics. The NFT system exhibited the highest nutrient use efficiency, followed by the GB system, while the DWC system recorded the lowest efficiency. Additionally, water quality changes were observed between the inlet and outlet of each system, indicating active nutrient absorption by plants.

The superior nutrient use efficiency (NUE) in the NFT system aligns with findings from previous studies indicating that NFT systems optimize nutrient delivery by maintaining a thin film of nutrient-rich water, allowing for rapid plant uptake (Li et al., 2020). The lower NUE in DWC suggests that nutrients may become diluted due to the larger water volume, reducing the concentration available for plant absorption (Kim et al., 2020).

The moderate NUE observed in GB suggests that while gravel-based systems facilitate nutrient retention through biofilm activity and microbial interactions, they may not be as effective as NFT in delivering nutrients directly to plant roots (Wang et al., 2021). The findings confirm earlier research indicating that NFT systems support higher nutrient absorption due to increased aeration and faster nutrient cycling (Schmautz et al., 2019).

Water quality analysis showed a notable decrease in total dissolved solids (TDS) and conductivity from inlet to outlet in all systems, reinforcing the evidence of nutrient uptake by plants. However, the degree of reduction varied, with NFT exhibiting the most significant drop, supporting its higher efficiency in nutrient utilization.

These results align with studies demonstrating that NFT systems are more effective in controlled aquaponic environments due to their enhanced nutrient absorption capacity (Ahmed & Turchini, 2020). Similar findings have highlighted that gravel beds enhance microbial-driven nutrient cycling, though they may have slightly lower direct plant uptake than NFT (Martins et al., 2020). Research also suggests that DWC systems, despite their stability, often require additional nutrient supplementation due to lower absorption rates (Zhao et al., 2019).

Implications of Findings

The study underscores the importance of system design in optimizing nutrient use efficiency. The superior NUE in NFT suggests that it may be the best choice for maximizing plant growth efficiency, while GB systems offer a balanced approach between microbial activity and plant uptake. The lower efficiency in DWC highlights the need for careful nutrient management in deep water culture systems to prevent excessive dilution.

Additionally, the variations in water quality changes at the inlet and outlet emphasize the need for continuous monitoring to optimize nutrient delivery and minimize waste. Future aquaponic designs could incorporate automated nutrient dosing strategies to adjust for variations in nutrient absorption across different grow beds.

5.1.4 Plant Growth Morphometry and Harvest Weight Across Grow Beds

The evaluation of plant growth morphometry (height, leaf number, stem diameter, fruit/flower production) and harvest weight across NFT, GB, and DWC grow beds revealed variations in growth performance among different plant species. Tomato plants showed the highest growth rate and fruit yield in the GB system, while bell pepper performed best in NFT, and leafy garden egg exhibited better performance in GB compared to DWC. The DWC system recorded the lowest overall plant growth and harvest weight across all crops.

The superior growth and yield of tomatoes in the GB system suggest that the substrate-based environment provided better root support and microbial activity, enhancing nutrient availability and water retention. Previous studies have shown that gravel beds improve plant growth by facilitating microbial nitrification and stable root zone conditions (Martins et al., 2020).

The higher performance of bell pepper in NFT indicates that nutrient availability and oxygenation in the system supported its growth requirements more effectively. Research has reported that NFT systems enhance growth by ensuring a steady flow of nutrients, which is particularly beneficial for crops with moderate nutrient demands and smaller root systems (Schmautz et al., 2019).

The better performance of leafy garden egg in GB suggests that the substrate provided stable moisture retention and improved nutrient cycling, which supports the needs of leafy vegetables. In contrast, the lower performance of plants in DWC may be attributed to excess water retention reducing oxygen availability to roots, leading to suboptimal nutrient absorption. Studies indicate that oxygen deprivation in DWC systems can limit root respiration, negatively affecting plant metabolism and growth (Kim et al., 2020).

These findings align with prior research demonstrating that gravel-based systems enhance root health and microbial activity, benefiting nutrient-demanding crops like tomatoes (Ahmed et al., 2020). The lower yields in DWC support findings that hydroponic deep water culture requires additional aeration to optimize plant growth (Wang et al., 2021). The improved performance of bell pepper in NFT is consistent with studies suggesting that NFT systems work well for crops with relatively shallow roots that require consistent nutrient flow (Li et al., 2020).

Implications of Findings

The results highlight the importance of matching crop types with appropriate grow bed systems to optimize aquaponic productivity. The higher tomato yield in GB suggests that substrate-based systems may be more effective for fruit-bearing crops, while leafy vegetables like leafy garden egg performed well in GB, likely due to better nutrient retention. The success of bell pepper in NFT suggests that crops with moderate nutrient needs and shallow root structures may thrive in flowing water systems.

The poor performance in DWC underscores the need for improved aeration strategies to enhance root oxygenation. Future studies could explore oxygen enrichment techniques in DWC to improve plant productivity.

5.1.5 Relationship Between Water Quality Changes and Plant Growth Parameters Across Grow Beds

Correlation and Regression Analysis of Water Quality and Plant Growth

The correlation and regression analysis revealed significant relationships between water quality parameters (conductivity, total dissolved solids (TDS), and temperature) and plant growth metrics (leaf number, stem girth, and harvest weight). The results showed that conductivity and TDS had strong positive correlations with plant growth parameters, while temperature exhibited weaker or negative relationships. The NFT system demonstrated the strongest associations between water quality and plant performance, followed by GB and DWC.

The positive correlations between conductivity, TDS, and plant growth indicate that higher dissolved nutrient availability improves plant biomass accumulation. This supports previous findings that conductivity serves as an indicator of nutrient richness in aquaponic systems (Ahmed & Turchini, 2020). The weaker relationship observed for temperature suggests that elevated temperatures may have negatively influenced plant metabolism, leading to reduced growth efficiency (Wang et al., 2021).

Regression analysis further confirmed that conductivity was the strongest predictor of plant growth, particularly for leaf number and stem girth. The low predictive value of temperature suggests that other environmental factors, such as light intensity and oxygen availability, may have played a more significant role in plant development (Li et al., 2020). The NFT system displayed the highest regression coefficients, reinforcing its effectiveness in delivering stable nutrient levels, whereas DWC showed the weakest predictive relationships, likely due to nutrient dilution effects (Schmautz et al., 2019).

These findings align with research demonstrating that conductivity and TDS are critical drivers of plant growth in aquaponic systems (Martins et al., 2020). The observed strong correlation in NFT aligns with studies emphasizing its ability to optimize nutrient uptake, while the weaker associations in DWC reflect challenges related to oxygen availability and nutrient dilution (Zhao et al., 2019).

Implications of Findings

The results underscore the importance of monitoring conductivity and TDS levels to optimize nutrient availability for plant growth. The strong predictive power of conductivity suggests that maintaining stable nutrient levels is essential for maximizing crop yield. The higher correlation observed in NFT highlights its suitability for high-efficiency nutrient delivery, making it an ideal choice for water-efficient and high-yield aquaponic farming.

5.1.6 Water Use Efficiency (WUE) and System Performance

The calculated Water Use Efficiency (WUE) for the system was 0.050 kg/L, meaning that for every liter of water used, 50 grams of biomass (fish + plants) were produced. The breakdown of fish biomass showed a higher yield in tanks C and D, which were part of the recirculating system.

The WUE value indicates efficient water utilization, aligning with established benchmarks for sustainable aquaponic production. Higher WUE values suggest better resource conservation and minimal water wastage, which is a key advantage of recirculating aquaponic systems (RAS) (Ahmed et al., 2020).

The distribution of fish biomass across tanks highlights the impact of water management on growth outcomes. Tanks C and D, which were directly connected to the sump, produced more biomass, which supports the idea that stable water quality makes fish more productive (Kim et al., 2020).

The WUE value aligns with research indicating that 0.040–0.060 kg/L represents the standard efficiency range for effectively managed aquaponic systems (Li et al., 2020). The correlation between water conservation strategies and fish biomass yield aligns with research indicating that controlled water exchange improves fish health and feed conversion rates (Martins et al., 2020).

Implications of Findings

The results highlight the importance of efficient water management in achieving sustainability in aquaponics. The WUE of 0.050 kg/L suggests that further optimization of nutrient cycling and water retention strategies could enhance system productivity. Future improvements could focus on reducing water loss from the sump and increasing nutrient retention through optimized grow bed design.

5.2 CONCLUSION

This study evaluated the water use efficiency, plant growth performance, and fish growth in a model urban food production system under the INCiTiS-FOOD project utilizing recirculating aquaponics (RAS) and stagnant renewal systems. The findings provided valuable insights into water quality management, nutrient utilization, and system optimization for sustainable food production.

The results demonstrated that fish growth performance was significantly enhanced in the RAS system, as indicated by higher condition factor values in Tanks C and D. This highlights the importance of stable water conditions in improving fish health and feed conversion efficiency. Furthermore, plant growth varied across the different grow bed types, with tomatoes performing best in GB, bell peppers in NFT, and leafy garden egg in GB. The Deep Water Culture (DWC) system exhibited the lowest overall plant growth performance, likely due to oxygen limitations and nutrient dilution effects.

The results also showed that the RAS model maintained more stable water quality parameters than the stagnant system, with lower water loss and improved nutrient retention. The correlation and regression analyses confirmed that conductivity and total dissolved solids (TDS) were key drivers of plant growth, particularly in the Nutrient Film Technique (NFT) and Gravel Bed (GB) systems.

The calculated Water Use Efficiency (WUE) of 0.050 kg/L confirmed the system's ability to convert water input into biomass efficiently, aligning with industry benchmarks for sustainable aquaponics. These findings highlight the potential of integrated aquaponic systems for resource-efficient urban food production, while also emphasizing areas requiring further optimization, such as nutrient management in DWC and water conservation strategies for improved WUE.

5.3 RECOMMENDATIONS

System Optimization

To optimize the efficiency and sustainability of the Incitis-Food aquaponic system, several improvements are recommended. Nutrient monitoring and dosing strategies should be enhanced to ensure optimal plant uptake and minimize nutrient loss, particularly in NFT and DWC systems. Additionally, oxygenation in DWC should be improved to enhance root aeration and nutrient absorption, which could be achieved through the introduction of aeration pumps or adjusted water flow rates. For fish production, stocking density and feeding strategies should be optimized in the RAS system to further improve growth performance and condition factor values.

Water Conservation Strategies

Water conservation is also crucial for maintaining system sustainability. The implementation of water-saving techniques such as automated flow regulation can help reduce unnecessary water loss from the sump. Furthermore, evaporation-reducing covers should be introduced for open water reservoirs to minimize water loss in hot climates. Exploring alternative water sources, such as rainwater harvesting, to supplement system needs will further enhance sustainability and reduce dependence on external water sources.

Crop-Specific System Adjustments

In terms of crop-specific adjustments, tomatoes should continue to be cultivated in GB systems, given their demonstrated high yield and nutrient uptake efficiency. Bell peppers perform best in NFT and should be prioritized in this system, while modifications in nutrient delivery may be necessary to optimize the growth of leafy garden egg. DWC systems should be reserved for crops with lower oxygen demands, or aeration enhancements should be implemented to improve their overall performance.

Future Research Directions

Future research should focus on long-term nutrient cycling patterns in aquaponic systems to optimize fertilization strategies. Additionally, the assessment of microbial communities in different grow beds could provide insights into their impact on nutrient breakdown and plant growth. Exploring alternative substrates for GB systems may further enhance water retention and nutrient efficiency, improving overall system productivity.

Adopting these recommendations will help improve the efficiency and sustainability of aquaponic food production, ensuring that the INCiTiS-FOOD model can serve as a viable solution for urban agriculture and resource-efficient farming.

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