GROWTH MORPHOMETRIC AND YIELD OF *Amaranthus viridis* AND *Solanum macrocarpon* GROWN WITH AQUAPONIC SLUDGE-BLACKSOLDIER FLY FRASS-BASED ORGANIC FERTILISER IN HYDROPONIC SYSTEM

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CERTIFICATION

This is to certify that this research was carried out by AKINMOLA OPEMIPO ADERIYIKE with matriculation number 222130, under my supervision in the Department of Aquaculture and Fisheries Management, University of Ibadan, Ibadan, Nigeria.

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DEDICATION

I dedicate this project to God, the giver of life and the savior of my soul, who strengthened me and held me, through this phase and season. All Glory to God alone.

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ABSTRACT

A combination of aquaponic sludge and Black Soldier Fly (BSF) frass wastes in organic fertilizer production has circular agriculture waste valorisation potentials. However, there is a gap on the performance of the fertilizer on agronomic plants. Therefore, this study investigated the growth performance of *Amaranthus viridis* and *Solanum macrocarpon* cultivated using sludge–frass fertilizer derived from a circular aquaponic–BSF production system.

The experiment compared aquaponic sludge-BSF frass combination organic fertilizer with synthetic fertilizer and water as control. The fertilizer treatment and water were applied to three replicates for each of *Amaranthus viridis* and *Solanum macrocarpon* in a completely randomized design in a Dutch vase hydroponic system for a growth trial. Before growth trials, the solid waste formula containing sludge obtained from the aquaponic system, combined with BSF frass were mixed and soaked in 200 liters of water, homogenized, and monitored for changes in conductivity, total dissolved solutes (TDS), and temperature for 24 hours, to ensure solute mineralization and associated water quality changes. Equal volume of dissolved (liquid) fertilizer was applied to the Dutch vases hydroponic system, where *Amaranthus viridis* seedling was planted at 1 stand per bucket in triplicate at 8:00 and 16.00 hours daily and monitored for 6weeks. Weekly plant growth parameters: plant height, stem diameter, leaf height, leaf width, and number of leaves, were measured. Data were analyzed through ANOVA across treatments at $p<0.05$.

Conductivity was 458.26±42.66 (Organic) and 781.35±41.71(Synthetic), TDS 1062.89±175.82(Organic) and 1837.37±70.61(Synthetic). These were significantly different across treatments, while the mean daily temperatures of 26.80±1.49 (organic) and 26.83±1.42 (synthetic) were similar. In *Amaranthus viridis*, mean plant height 11.7±5.71 (water) to 30.83±7.53 (organic), stem diameter 1.27±0.95 (water) to 3.62±1.18 (organic), leaf height 7.16±3.35 (water) to 16.78±4.53 (organic), and leaf width 2.09±0.99 (water) to 5.24±1.76 (organic) for leaf width were similar (p>0.05) across organic and synthetic fertilizers but significantly lowest in water treatment. The number of leaves was significantly lowest 14.29±12.33 in water, and highest, 81.51±64.64 in organic. Total yield of leaves was 5.57±3.98g (water) to 14.22±10.21g (organic) for leaf weight and 1.6±1.46g (water) to 22.56±15.65g (organic) for root weight. In the *S. macrocarpon*, mean plant height 10.8±4.74 (water) to 28.59±9.27 (organic), stem diameter 1.09±0.71 (water) to 2.99±1.17 (organic), leaf height 7.79±3.89 (water) to 20.96±5.44 (organic), and leaf width 4.62±2.11 (water) to 12.21±3.85 (organic) were similar ($p>0.05$) across organic and synthetic fertilizers. Number of leaves, 5.22±3.04 (water) to 16.93±6.5 (organic) were significantly different across treatments. Yield was 5.39±5.26g (water) to 36.56±29.3g (organic) for leaf weight and 3±3.83g (water) to 22.78±18.75g (organic) for root weight.

The aquaponic sludge-frass combination fertilizer dissolved with lower solute content compared to synthetic fertilizer. However, both have similar growth morphometrics with the organic fertilizer inducing a greater number of leaves in both the *Amaranthus viridis* and *Solanum macrocarpon.*

Keywords: Aquaculture waste management, Aquaponic sludge, Liquid organic fertilizer, Black soldier fly frass, Circular agriculture.

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TABLE OF CONTENT

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

CHAPTER ONE

INTRODUCTION

1.1 Background

Global food production systems are under increasing pressure to meet the demands of a growing population while ensuring environmental sustainability (FAO, 2020). By 2050, the global population is expected to reach 9.7 billion, necessitating a 70% increase in food production compared to current levels (United Nations, 2019). Conventional agricultural practices, while having contributed significantly to global food security, are increasingly criticized for their environmental costs, including soil degradation, biodiversity loss, and high greenhouse gas emissions (Tilman et al., 2011). This has driven interest in integrated, resource-efficient production systems such as aquaponics, hydroponics and circular integration.

Aquaponics is an integrated food production system that combines aquaculture, the cultivation of aquatic organisms such as fish with hydroponics, the soilless cultivation of plants (Goddek et al., 2019). In aquaponics, nutrient-rich water from fish tanks serves as a natural fertilizer for plants, while the plants purify the water for recirculation back to the aquaculture unit. This symbiotic relationship allows efficient water use, typically reducing consumption by up to 90% compared to traditional soil farming (Somerville et al., 2014). It also reduces reliance on synthetic fertilizers, which are energy-intensive to produce and often cause nutrient pollution in aquatic ecosystems (Schmautz et al., 2017).

Aquaponic systems generate two main waste streams, including the liquid effluent and solid sludge. The liquid effluent contains dissolved nutrients such as nitrogen, phosphorus, and potassium in plant-available forms, while the solid sludge contains organic matter, undigested feed, and mineral-bound nutrients. Both waste streams have the potential to serve as organic fertilizers if properly processed. However, their chemical composition and nutrient release characteristics vary, influencing their suitability for different cropping systems.

Hydroponics, on the other hand, offers a controlled environment for plant growth without soil, using nutrient-enriched water solutions to deliver essential minerals directly to the roots (Resh, 2022). It enables high-density crop production and year-round harvesting, making it suitable for urban agriculture and regions with poor or degraded soils. In recent years, research has begun exploring the use of aquaponic waste products, both liquid effluent and processed sludge, as nutrient solutions in hydroponics (Goddek & Keesman, 2018). This creates a closed-loop production model that minimizes waste discharge, recycles nutrients, and enhances sustainability.

Amaranths (*Amaranthus spp.*) and leafy African egg-plant (*Solanum macrocarpon*) are two important vegetables which serves domestic food supply in Africa. Amaranths are nutrient-dense leafy vegetables rich in vitamins, minerals, and protein (Sarker & Oba, 2018). Both crops respond well to balanced nutrient supply, but the form and concentration of nutrients can significantly influence yield and quality. The use of aquaponic waste as a nutrient source could potentially reduce production costs, improve sustainability, and support circular economy practices in agriculture (Rupasinghe et al., 2023). Application of this to the production of Amaranthus and solanum species would be an advantage for urban agriculture where wastes management often constitute a major challenge. However, there is the need for knowledge on the relative performance of such wastes in single or composite compared to the synthetic fertilizers. Moreso, growth morphometry and yield are critical performance indicators of either solid or liquid fertilizers.

Circular farming operates multiple agriculture production unit in a circle production from wastes from the other in way to mop up wastes, turning then to a chain of input and output. However, solid and liquid waste leakages are also possible. For instance, in an earlier experiment, Oyebola et al., (2025) reported a circular aquaponic, Black Soldier Fly (BSF) and hydroponic production system yielded solid wastes sludge from aquaponic, and frass from the BSF production whose combination contained high nutrient content and can be dissolved to produce liquid fertilizer. Such fertilizer would need to be characterized for production potentials in crops. Performance of fertilizer in plant production can be measured using the leaf, stem, root morphometrics and the final yield. However, there is a knowledge gap to understand the production potential of crops grown with the sludge-frass combination fertilizer.

Given the growing interest in sustainable farming systems, the evaluation of aquaponic solid waste-derived liquid fertilizers in hydroponic production of amaranths and Solanum species is both timely and essential. Such research not only contributes to the efficient utilization of aquaponic by-products but also addresses the broader challenges of nutrient recycling and waste minimization in agriculture.

1.2 Problem Statement

Conventional hydroponic systems rely heavily on synthetic nutrient solutions formulated from chemical fertilizers such as ammonium nitrate, potassium phosphate, and calcium nitrate (Resh, 2022). While these fertilizers deliver precise nutrient concentrations for optimal crop growth, their production is energy-intensive, dependent on non-renewable resources, and contributes significantly to greenhouse gas emissions. Additionally, runoff and leaching from excessive fertilizer-use lead to nutrient pollution, causing eutrophication in freshwater and marine ecosystems, which disrupts aquatic biodiversity and degrades water quality.

In aquaculture and aquaponics, nutrient-rich wastewater is a valuable resource that is often underutilized. Discharging aquaponic liquid effluent without treatment can contribute to environmental degradation, while the accumulation of solid sludge poses management challenges. Current waste handling practices in many aquaponic facilities focus on disposal rather than valorization, missing opportunities to recycle nutrients into productive agricultural systems (Liu et al., 2024).

There is limited research on the comparative efficiency of aquaponic solid waste-derived fertilizers in hydroponics, especially for different crop types such as leafy vegetables and fruiting plants. Solid sludge, when processed into a fertilizer, can provide a more balanced and slow-release nutrient profile. However, without detailed nutrient characterization and performance evaluation in hydroponic systems, it is unclear which source or what combination offers the best crop performance and environmental benefits.

Furthermore, nutrient composition in aquaponic waste can vary significantly depending on fish species, feed type, stocking density, and system design (Goddek et al., 2019). This variability complicates the development of standardized formulations for use in hydroponics. Without optimization, the use of aquaponic waste as a sole nutrient source may lead to nutrient deficiencies, excesses, or imbalances, affecting crop yield and quality (Hu et al., 2022).

Therefore, there is a critical need for studies that quantitatively assess the nutrient composition of insect frass and aquaponic solid waste-based fertilizers, and evaluate their agronomic efficiency in hydroponic production of economically important crops such as amaranths and African egg-plant.

This will inform best practices for integrating aquaponic by-products into hydroponic nutrient management, advancing sustainable agriculture goals.

1.3 Justification

The integration of aquaponic sludge waste and insect frass into hydroponic nutrient management aligns with global sustainability objectives, including the United Nations Sustainable Development Goals (SDGs) on zero hunger (SDG 2), responsible consumption and production (SDG 12), and life below water (SDG 14) (United Nations, 2015). By converting waste streams into valuable agricultural inputs, farmers can reduce environmental pollution, lower fertilizer costs, and improve resource use efficiency.

The proximate and mineral characterization of aquaponic solid sludge-derived liquid fertilizers is essential for determining their suitability in hydroponic systems. Nutrient profiling will identify whether they provide the macro- and micronutrients required for optimal growth of amaranths and tomatoes. Moreover, understanding the nutrient release dynamics can help in matching nutrient availability with crop demand, thereby maximizing yield and quality while minimizing nutrient losses.

Using aquaponic sludge and insect frass in hydroponics promotes a circular economy by closing nutrient loops, reducing the environmental footprint of aquaponics, and enhancing the economic viability of integrated food production systems (Rupasinghe et al., 2023). For smallholder farmers and urban growers, this approach offers a low-cost alternative to expensive commercial hydroponic nutrient formulations, improving profitability and resilience.

Additionally, amaranths and African egg-plant are strategic crops for nutritional security and income generation. Amaranths are rich in iron, calcium, and vitamin C, making them important for addressing micronutrient deficiencies, particularly in developing countries (Sarker & Oba, 2018). Demonstrating that aquaponic waste-derived fertilizers can sustain high yields of these crops will strengthen the case for adopting integrated waste recycling in urban and peri-urban agriculture.

Ultimately, this study will contribute to developing evidence-based recommendations for the use of aquaponic solid waste-derived fertilizers in hydroponics. By addressing agronomic performance, it supports the transition toward more sustainable, and resource-efficient agricultural systems.

1.4 Objectives

1.4.1 Main Objective

The main objective of the study is to evaluate the crop growth, and yield performance of aquaponic solid waste-frass combination derived liquid fertilizer in hydroponic cultivation of amaranths (*Amaranthus viridis*) and African egg-plant (*Solanum macrocarpon*).

1.4.2 Specific Objectives

The specific objectives are:

1. To assess the nutrient dissolution of the synthetic and solid frass-sludge combination solid fertilizers in aqueous solution over time of soaking.
2. To evaluate the leaf, stem and root growth morphometrics of *Amaranthus viridis* and *Solanum macrocarpon* grown with the solid synthetic and frass-sludge combination solid fertilizers in aqueous solution in hydroponic system.
3. To investigate the yield of *Amaranthus viridis* and *Solanum macrocarpon* grown with the solid synthetic and frass-sludge combination solid fertilizers in aqueous solution in hydroponic system.

CHAPTER TWO

LITERATURE REVIEW

2.1 IMPORTANCE OF FISH TO HUMAN

The main marine food source that gives the human body enough nourishment is fish. Since fish are a major source of food and revenue, their production is growing yearly, supporting a sustainable economy. Fish have a variety of bioactive components that make them a more palatable food source globally. Different fish species contain a wide range of bioactive chemicals, primary macronutrients, micronutrients, vitamins, and minerals that are crucial in preventing a variety of human diseases. Fish's nutritious richness contributes to its remarkable health advantages against a variety of human illnesses. Protein, peptides, and polyunsaturated fatty acids, especially eicosapentaenoic acid (EPA), alpha linolenic acid (ALA), omega fatty acids, and docosahexaenoic acid (DHA), are abundant in fish and have a good impact on human health. Fish and their byproducts are also great sources for creating different functional meals and nutraceuticals to combat a variety of human illnesses. Its byproducts have a substantial impact on immunological systems, cardiovascular illnesses, oxidative stress, inflammation, neurological disorders, infection, viral attacks, and other physiological issues. Furthermore, by controlling dietary concerns including food security, protein deficit, and other nutritionally linked difficulties, the therapeutic use of fish and their byproducts reveal the potential nutritional benefits to lessen the burden on public health. (Noreen, *et al,* 2025)

Like many other forms of life, fish are extremely valuable to humans. They have long been a staple food for many peoples, which has unfortunately led to the extinction of many species. Fishes now play a significant role in the economies of many countries and provide incalculable recreational and psychological value to naturalists, sports enthusiasts, and home aquarists. Behavior, ecology, evolution, genetics, and physiology research can benefit from examining specific features of different species. They serve as broad markers of pollution, in part for human benefit and in part to preserve what people view as an essential and priceless component of their culture, as well as life. (Joseph *et al,* 2016)

The Food and Agriculture Organization (FAO, 2020) reports that China alone accounted for 35% of the world's 179 million tonnes of fish produced in 2018. Asia (not including China) made up

34% of the continental total, followed by the Americas (14%), Europe (10%), Africa (7%), and Oceania (1%). By 2030, it is anticipated that the world's fish production would have increased by 15% to 204 million tonnes. While both capture fisheries and aquaculture are anticipated to contribute to this rise, aquaculture will be the main force behind this expansion. Between 1961 and 2017, the amount of edible fish consumed worldwide increased at an average yearly rate of 1.5%, between 1961 and 2017 [5], from 9.0 kg to 20.3 kg. Global consumption had risen to 20.5 kg per person by 2018. (Rebecca, *et al*, 2025)

2.2 SOURCES AND PRODUCTION OF FISH

Around the world, fish can be found in lakes, streams, estuaries, and oceans. Every individual in the majority of fish species lives exclusively in freshwater or marine environments. More than 225 species are diadromous, meaning they frequently spend some time in rivers and lakes and some time in the ocean. The majority of species are anadromous, meaning they spend most of their time in the sea but reproduce in freshwater. Some are catadromous, meaning they reproduce in the seas but then return to fresh water. Where a certain species will predominate is influenced by a variety of environmental conditions. In addition to physicochemical variables, competition and other biological interactions may have a significant impact. Certain species may exhibit a preference for lakes or streams in freshwater habitats. There may be differences in a species' preferences throughout its range. (Joseph et al, 2016)

Fish production can be broadly divided into two categories: aquaculture (fish farmed or cultivated on farms) and captured fish (wild-caught). Inland or marine capture and inland or marine aquaculture are supplementary classifications for both groups. Aquaculture provided 82.1 million tonnes of the 179 million tonnes of fish produced in 2018, with 96.4 million tonnes coming from capture (wild-caught) fish. 52% of fish for human consumption and 46% of fish produced worldwide came from aquaculture. (Rebecca, *et al*, 2025)

2.2.1. CAPTURE FISH PRODUCTION

Capture fisheries encompass the harvest of wild aquatic organisms from marine, coastal, and inland waters, critical for nutrition and economies in regions like Nigeria. Expanding on the initial review, this section delves deeper into historical evolution, management paradigms, regional contexts, and emerging challenges. Shwe Sin et al. (2024) . Capture fisheries date to prehistoric times but industrialized post-World War II, with production surging from 19 million tonnes in 1950 to peaks near 96 million tonnes by 2015 before stabilizing. The 1990s shift to precautionary approaches addressed overfishing crises, as in North Atlantic cod collapses. FAO's Code of Conduct for Responsible Fisheries (1995) formalized sustainability principles. (FAO, 2024)

Nigeria's capture fisheries yield ~1 million tonnes annually, with 80% artisanal from rivers (Niger-Benue), lakes (Kainji), and lagoons. Challenges include illegal unreported fishing (IUU), post-harvest losses (30-50%), and pollution from agriculture. Integration with aquaculture offers synergies, like rice-fish systems, but competition for water resources persists. (Umar et al., 2024)

Overfishing depletes 35% of stocks, per FAO assessments. Bycatch threatens non-target species, including seabirds and turtles, while destructive gear damages benthic habitats. Climate impacts—ocean acidification and warming—shift distributions, reducing catches in tropical zones like West Africa by 10-30% projected by 2050. (Blasco et al., 2020). Supporting 60 million livelihoods globally, capture fisheries provide 17% of animal protein but face inequities in benefit distribution. In Nigeria, women dominate processing, yet gender gaps limit access to credit and markets. Economic analyses show high multipliers (1:4 jobs), underscoring poverty alleviation potential. (Blasco et al., 2020)

2.2.2 AQUACULTURE PRODUCTION

One of the industries with the quickest rates of growth for protein supplies is aquaculture, which combines farming methods and natural resources to boost yields while protecting the environment. Aquatic organism farming, which includes raising fish, shellfish, and algae, has become essential to meeting the world's food supply needs. The need to identify alternate sources of protein is a direct result of the growing demand for foods high in protein brought on by the world's population expansion. (Vladimir et al, 2025). Concerns about food security have been raised by the world's population growth and rising life expectancy. In order to achieve the net balance of food demand and consumption, it is crucial to provide a sustainable food supply chain. Meanwhile, one of the key industries that contributes fisheries products as a major source of protein for human consumption is aquaculture (FAO, 2020). Given the detrimental effects on the ecology caused by the wild-caught fisheries, it is clear from the fisheries sector that aquaculture operations will become the main force behind meeting the demand worldwide. An additional benefit for this industry has been the rise in aquaculture practices for modifying culturally appropriate dietary intake and nutrient fortification. (Arshad et al, 2022)

Commercial and industrial aquaculture's contribution to world production has steadily and significantly increased during the past 20 to 30 years. The expansion of the aquaculture sector also helped small and medium-sized aquaculture businesses. The sector's contribution to commerce, revenue, and food security increased as it expanded and became more commercialized. Asia has seen the most growth, with other continents falling behind in recognizing aquaculture's potential to support food production and security. But there are indications of change. Over the past ten years, output growth rates have been higher in Africa and Latin America than in Asia, indicating a growing interest in aquaculture as a means of producing food outside of Asia. (Verdegem et al, 2023)

Adewumi, (2023) provided a brief description of Nigeria's aquaculture revealing that fish is in high demand since it is a comparatively inexpensive source of food protein that is crucial to many Nigerians' diets. Harvests from capture and culture make up the vast resource base that defines the Nigerian fishing industry. The growth of aquaculture is the hope for Nigerian fisheries because of the overexploitation of capture fisheries. Between 2000 and 2007, aquaculture production increased and accounted for 5–22% of all domestic fish production. Production systems must concentrate on how culture methods and the environment interact if aquaculture is to be sustainable. Importantly, aquaculture's development and growth as an industry coincided with an increase in awareness of its effects on the environment. The government can increase agricultural productivity by promoting environmentally friendly policies, extension technology, and suitable, responsible production.

In Nigeria, aquaculture plays a major role in national growth, job creation, income production, and the provision of essential nutrients. Ten million Nigerians are actively involved in various types of fishing operations, according to the Federal Ministry of Agriculture Nigeria. According to the National Bureau of Statistics (NBS), the fishing industry made up 3.24% of the nation's GDP in the first quarter of 2021. Nigeria consumes more fish than any other country in Africa and is among the world's top fish consumers. Nigeria consumes over 3.6 million tons of fish each year. With 1.4 million tons, this is more than twice as much as in 2004. Population growth and shifting dietary habits have been blamed for the rise in demand for fish. Ironically, Nigeria produces 1.04 million tons of fish (fisheries 75%, aquaculture 25%), meaning that imports must make up the remaining 2.5 million tons. This demonstrates that, contrary to the National Aquaculture Strategy's (NAS) goal, Nigeria is far from being self-sufficient. (Ogunji & Wuertz, 2023).

2.2.2.1 AQUACULTURE PRODUCTION SYSTEMS

The cultivation of aquatic organisms, including fish, crustaceans, mollusks, and aquatic plants, in water under regulated conditions is referred to as aquaculture or aquafarming. To put it another way, it may just be called "Underwater Agriculture." As commercial harvests of wild fish and shellfish supplies have decreased throughout time, aquaculture's growth rate has increased dramatically. (Khan et al, 2011). Fish are produced in aquaculture using a variety of systems and methods described below.

PONDS

Since many of the resources required to cultivate the crop are found in nature, pond aquaculture is typically the most lucrative method of raising aquatic creatures. When pond aquaculture is done correctly, the aquaculturist maintains the pond in balance with natural processes, allowing for surprisingly large food production with minimal technological assistance. Actually, mechanical aeration is the only water quality management technique frequently employed in pond aquaculture to augment naturally occurring dissolved oxygen supply. Pond aquaculture's economic sustainability is based on the low degree of technical intervention required to achieve high levels of food production. (Boyd & Tucker, 1998).

CAGE CULTURE

As a sustainable substitute for conventional open-water fish farming techniques, cage culture, also referred to as net pen aquaculture, is a fish farming technique that involves keeping fish in cages or net pens set up in natural water bodies like lakes, rivers, or coastal areas.

Cages are devices that keep the species being cultivated in a small space, typically at a high density, while keeping undesirable animals out of the wider water body.
Water circulation through cages (from the water body) is necessary to remove harmful metabolic wastes and provide the culture organisms with water of a high enough quality for long-term growth. (Tidwell, 2012).

RACEWAY AQUACULTURE

A raceway is essentially a water-carrying runway. A tank (raising unit) or a group of rectangular tanks with water flow along the long axis make up the standard raceway production system. A perfect raceway will have uniform water velocity throughout the tank cross section and water flow that is close to plug flow. Water velocities will, however, differ throughout the raceway's width and depth due to friction losses at the tankwater and air-water boundary layers. Mid-depth has the highest water velocity, while the air-water interface has somewhat lower speeds and the raceway bottom has significantly lower velocities. A defining feature of linear-pass raceways is a gradient in water quality from the rearing unit's inflow to outflow during production, with the best environmental conditions at the inflow and declining water quality as the water flows towards the outlet. The environmental conditions in circular raising units are comparatively consistent throughout the tank and are more fully mixed. (Tucker & Hargreaves, 2008)

Plate 2.1: A pond

Plate 2.2: Cage Culture

Plate 2.3: Raceway

RECIRCULATING AQUACULTURE SYSTEM (RAS)

The Recirculatory Aquaculture System (RAS) gives environmental sustainability a major boost while using fewer resources for increased productivity. In indoor tank-based systems where water exchange is restricted and biofiltration is necessary to lower the levels of ionized and unionized ammonia, RAS is utilized for fish production. RAS are made to use as little water as possible, regulate culture conditions, and provide complete waste stream management. By separating the animals from the outside world, they can also offer a certain level of biosecurity. This system cleans the water for recycling back through fish culture tanks by passing it through a number of mechanical and biological filtration systems; over 90% of the water is recycled back through the culture units. (Aich et al, 2020)

In order to overcome obstacles related to climate change, biosecurity, and other environmental factors that affect fish productivity, RAS has become a popular adaptation method. Additionally, over the past ten years, this technology and its developments have been incorporated into conventional land-based aquaculture methods to increase the aquaculture industry's sustainability and profitability. Today, pioneers in fish farming are setting the standard by constructing regulated indoor fish production facilities all over the world. The number of aquaculture facilities based on RAS has increased during the last few decades. The main reasons for this are that it has less of an impact on the environment than traditional fish farming systems, offers better water management, eco-friendly farming, environmental biosecurity, lower labor and cost needs, and higher feed conversion rates. By lowering water consumption and enhancing water recycling, RAS improves the production environment and, consequently, the growth, hygiene, and disease control of farmed fish. (Gupta et al, 2024).

Plate 2.4: Recirculatory system

2.3 AQUAPONICS

Aquaponics is a hybrid of hydroponics (plant growing without soil) and aquaculture (fish farming). Fish and plants share a closed-loop freshwater recycling system. After the nitrification process, the waste products produced by the fish are converted into nutrients for the plants. The procedure purifies the water before returning it to the fish tank, serving as biofilters. Aquaponics can help with sustainability and food security, but it can be difficult to operate because facilities must be continuously monitored to ensure that fish and plants are growing healthily. (Adric et al, 2017). In organic farming, aquaponics is a sustainable food supply. Any system that blends hydroponics and traditional aquaculture in a complementary setting is referred to as aquaponics. Fresh fish is a safe, healthful source of protein, and aquaponics farming is a very popular method of growing organic fruits, vegetables, greens, and herbs without the need of pesticides. (Shafeena, 2016). Because water is recycled and reused within the system, aquaponics systems can use up to 90% less water than conventional soil-based agriculture. This water efficiency helps to make aquaponics more sustainable overall and lessens the strain on freshwater resources. (Racoky et al, 2024).

Aquaponics can be set up in urban areas, providing locally grown produce and reducing the carbon emissions associated with transportation in the global food system. When combined with the potential for high yields and adaptability to a variety of settings, these systems maximize resource efficiency and promote a more sustainable and diversified farming approach. Aquaponics facilitates efficient nutrient recycling by turning fish waste into plant nutrients, minimizing waste discharge and the pollution of surrounding ecosystems. (Mudashiru et al, 2025).

There are different design techniques that are practical and effective are used in aquaponics systems. These designs include the Nutrient Film Technique (NFT) system, the drip system, the wick system, the Deep-Water Culture (DWC) or floating rafts configuration, and others. However, the Media-Bed system, the Nutrient NFT, and the DWC systems are the most widely used aquaponics approaches. (Mudashiru et al, 2025). Aquaponics is a viable method of producing food sustainably, with major advantages for urban agriculture, environmental sustainability, and resource efficiency. However, the technique has issues with scalability, technical complexity, and economic feasibility. To get over these obstacles and realize aquaponics' full potential, ongoing research and innovation are essential.

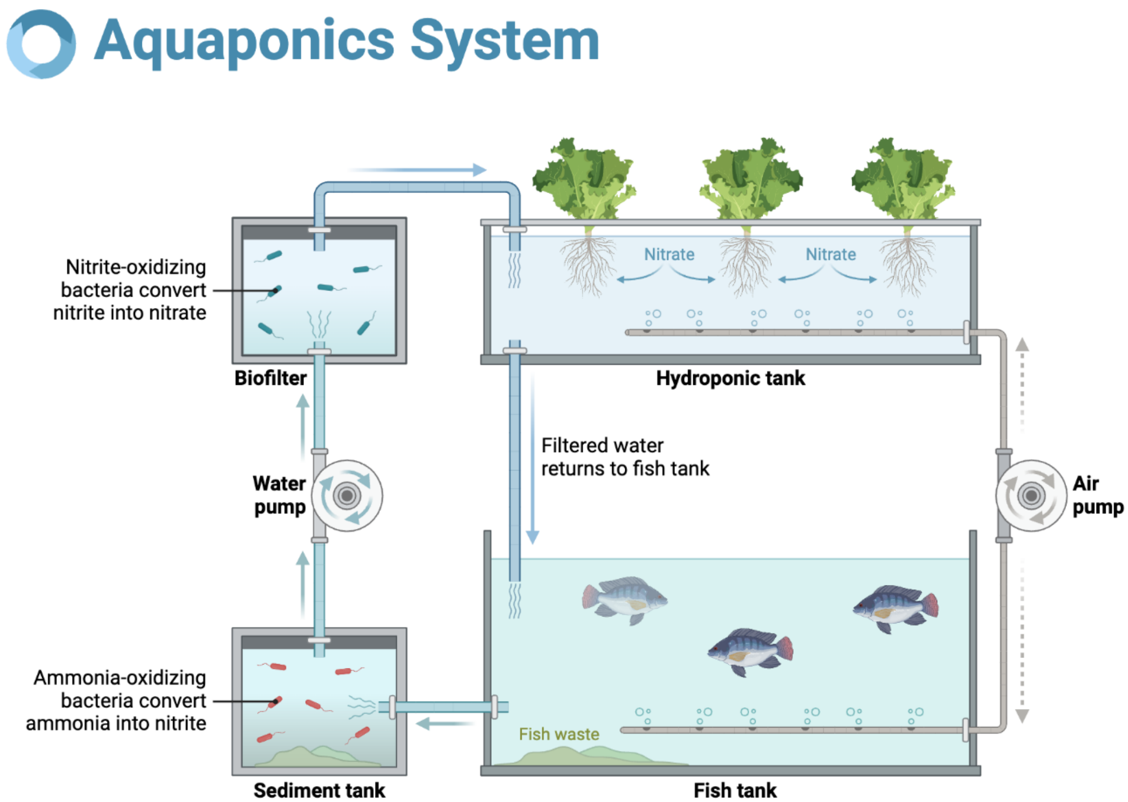

Figure 2.1: A typical aquaponic system

Plate 2.5: An Aquaponic system

Status of Aquaponics in Nigeria

The unique combination of hydroponic plant cultivation and fish farming makes aquaponics systems one of the most efficient and sustainable forms of aquaculture. These systems have several advantages over traditional farming methods, such as efficient nutrient cycling, reduced water usage, and lower environmental impacts. However, despite their importance and value in improving the aquacultural system, there are challenges that make it undesirable for everyone. (Abbatti et al, 2024)

As a sub-Saharan nation, Nigeria has had many difficulties with regard to the availability of food and water. The development of an intensive aquaponics system is therefore necessary in order to simultaneously address the issues of water scarcity in aquaculture and once more offer an additional source of food from plant materials cultivated through hydroponics, which forms the foundation of the contemporary aquacultural farming system known as aquaponics. The primary obstacles to the growth of aquaponics in Nigeria include high investment costs, a lack of technical expertise, and governmental regulations. Because aquaponic foods are more easily marketed and healthier than most other foods, including those from field crops, an intervention model that makes the aquaponic system's production simpler is needed in order to help more people. (Abubakar et al, 2022). In Nigeria, the acceptance of aquaponics systems will be partially due to the high startup costs and lack of technical know-how among our rural community members (Abbatti et al, 2024).

The University of Ibadan INtegrated and Circular Technologies for Sustainable city region FOOD systems in Africa (INCiTiS-FOOD) living laboratory reported in 2024 the successful growth of Solanum macrocarpon (Efo Igbagba), Solanum lycopersicum (tomatoes), and Capsicum annuum (bell pepper) with stable and good yields in their aquaponic unit. The results of the harvest demonstrated how well three distinct systems—the nutrient film technique, deep water culture, and gravel bed—supported the growth of the plants. Aquaponics integrates aquaculture and hydroponics to recycle nutrients and water, delivering measurable environmental, economic, and food-security benefits while offering high water-use efficiency and reduced waste. Adoption faces barriers in capital, energy, nutrient management, and policy support.

Aquaponics couples recirculating aquaculture and soilless plant production in a single, closed-loop system that uses fish-derived nutrients to grow crops and plants to filter water for fish (Danish et al, 2021). Its significance lies in the potential to produce protein and vegetables together with reduced external inputs, making it relevant to sustainability, urban agriculture, and resource-constrained regions (Danish et al, 2021). Aquaponics is described as a systems-based solution that can contribute to Sustainable Development Goals and food-sovereignty objectives by intensifying production per unit of water and land while minimizing waste streams (Ibrahim et al, 2023).

2.3.1 Environmental benefits and water efficiency of Aquaponics

Aquaponics reduces water consumption, nutrient discharge, and environmental emissions by recirculating water and converting dissolved fish wastes into plant-available nutrients (Greenfield et al, 2022). Systems design influences outcomes, with decoupled or multi-loop designs enabling independent optimization of fish and plant subsystems to improve nutrient balance and reduce discharges (Keesman, 2020).

a. **Water saving** Aquaponics systems report substantial water-use reductions compared with conventional soil-based production, with reviews citing efficiencies up to ~90% in some designs and contexts (Ibrahim et al, 2023), (Lora et al, 2024).
b. **Nutrient recycling** Fish effluent supplies nitrogen and phosphorus to plants, reducing the need for synthetic fertilizers and lowering the risk of eutrophication from aquaculture effluents (Greenfield et al, 2022).
c. **Ecosystem services** By retaining and reusing nutrients and water onsite, aquaponics can reduce wastewater discharge, lessen pressure on freshwater sources, and enable productive use of non-arable or urban spaces (Greenfeld et al, 2022), (Kotzen, 2019).
d. **Environmental impact nuance** Life-cycle and environmental assessments indicate aquaponics often delivers clear water- and nutrient-related benefits, but results vary with energy use, system boundaries, and design choices, highlighting the need for standardized LCA methods for policy guidance (Greenfeld et al, 2022).

2.3.2 Economic benefits and nutritional quality of Aquaponics

Aquaponics can generate multiple revenue streams (fish and high-value crops), reduce fertilizer costs, shorten supply chains, and enable production in high-rent or non-arable locations, improving market access and potentially raising profitability (Okomoda et al, 2022). Nutrient inputs derived from fish effluent reduce chemical fertilizer purchases and can support production of leafy greens, herbs, and specialty crops that command premium prices (Ibrahim et al, 2023), (Okomoda et al, 2022).

a. Cost-effectiveness Studies note potential cost savings from on-site nutrient recycling and reduced water usage, but emphasize that economic performance depends on scale, system efficiency, energy costs, and selected species (Okomoda et al, 2022).

b. **Profitability drivers'** Key factors improving commercial viability include higher crop value (e.g., herbs, medicinal plants), optimized system design (decoupled loops or DRAPS), and reduced post-harvest and transport costs when located near markets (Okomoda et al, 2022).

c. **Market opportunities** Urban agriculture, niche organic or medicinal-plant markets, and integrated value chains can raise returns; integration with automation and IoT can increase yields and decrease labor costs over time (Nair et, 2024).

d. **Nutritional and food quality** Plants grown with aquaponic nutrient regimes show good nutritional profiles and the system enables year-round, pesticide-reduced production; aquaponics has also been proposed to cultivate medicinal plants and other high-value botanicals while relieving pressure on wild stocks (Stoyanova et al, 2024).

Economic assessments consistently recommend attention to energy use, startup capital, and species selection when projecting returns (Okomoda et al, 2022).

2.3.3 Food security implications and ecosystem services

Aquaponics offers localized, high-intensity production of protein and vegetables that can strengthen food availability and diversity in urban, peri-urban, and water-limited regions (Danish et al, 2019). By producing both fish and vegetables with reduced water and land footprints, aquaponics contributes to resilience against supply-chain disruptions and can support household- and community-level food self-reliance (Ibrahim et al, 2023).

A. **Local provisioning** Systems sited within cities or marginal lands reduce transport emissions and enable fresher produce for nearby consumers (Kotzen, 2019).

B. **Resilience and sovereignty** The technology supports smallholder and family farming adaptations and can be aligned with food-sovereignty goals when accessible designs and training are available (Danish et al, 2019), (Okomoda et al, 2022).

C. **Ecosystem services** On-site nutrient retention, lower wastewater discharge, and reduced synthetic fertilizer demand mitigate risks to aquatic ecosystems and contribute to water-quality goals when systems are properly managed (Greenfeld et al, 2022).

Evidence indicates aquaponics can be a meaningful component of diversified food systems, especially where water scarcity or land constraints limit conventional agriculture (Ibrahim et al, 2023), but outcomes depend on appropriate technology matching and capacity building (Danish et al, 2019.

2.3.4 Challenges in Aquaponics

Aquaponics faces barriers that limit wider adoption: relatively high start-up costs, energy demands for pumps and climate control (especially for indoor systems), the technical complexity of balancing fish and plant requirements, and regulatory or certification gaps for products (okomoda et al, 2022). Life-cycle studies highlight that energy and material inputs can erode environmental benefits if systems are poorly designed or powered by fossil energy, motivating innovations in decoupled designs, renewable energy integration, and standard LCA methodologies (Greenfeld et al, 2022), (Keesman, 2020).

a. **Technical constraints** Nutrient insufficiencies for certain high-demand crops and the need for robust nitrification and water-quality control are recurrent operational challenges.

b. **Economic and policy constraints** Access to affordable capital, market development, organic certification ambiguity, and lack of supportive regulations hinder scaling.

c. **Research and development priorities** Standardized environmental accounting, optimized species and feed formulations, modular affordable designs, and smart monitoring to reduce labor and energy footprints are key directions for improving impacts Nair et al, 2024.

Aquaponics provides evidence-based environmental and water-efficiency advantages, economic opportunities for niche and localized markets, and meaningful contributions to food security and ecosystem service goals when designed and managed appropriately. Realizing those benefits at scale will require continued technical refinement, context-appropriate system selection, renewable-energy integration, and stronger policy and market support.

2.3.5 Components of aquaponic system

- Rearing tank: this is the tank in which the cultured fish are kept.
- A settling basin is a device used to collect food scraps and separated biofilms in order to filter out tiny particles.
- A biofilter is a space where nitrifying bacteria can proliferate and transform ammonia into nitrates that plants can use.
- The hydroponics subsystem is the part of the system that uses the water's extra nutrients to grow plants.
- Sump: the system's lowest point, where water enters and exits and is pushed back to the raising tanks

2.4 Waste management in Aquaponics

Fish waste is recycled into useful goods and used as a natural fertilizer and source of nutrients for plant growth, which is what makes aquaponics unique. All parts of the system benefit from the cooperation of the fish, plants, and microorganisms in the soil and fish waste, which also encourages a circular economy (Manan et al, 2025). Via their gills, fish release ammonia, which bacteria transform into nitrite and subsequently nitrate, the form of nitrogen that plants prefer (Rakocy & Masser, 2016). Through this technique, plants can recover dissolved nutrients that build up in recirculating systems instead of releasing them as waste (Rakocy & Masser, 2016).

A significant amount of fish sludge is filtered out as waste in aquaponic, indicating lost nutrient resources, while current commercial aquaponics only recycles liquid effluent (Zhang et al., 2021). Through efficient treatment phases, recirculating aquaculture systems, which are a component of aquaponic units, are successful in producing aquatic animals with a low water consumption. However, the concentrated sludge that is left over after the solid filtration stage, which contains rich nutrients and organic matter, is typically thrown away. By treating the sludge on-site, one of the most recent advancements in aquaponic technology seeks to maximize nutrient recycling and lessen any potential adverse environmental effects. (Delaide et al 2019). According to research, the length of hydraulic retention time affects fish development performance and nutrient dynamics, with longer retention times leading to increased ammonia excretion (Dediu et al., 2012).

Optimizing nutrient usage in aquaponic systems by recovering nutrients from fish sludge through anaerobic or aerobic digestion and returning them as liquid fertilizer has emerged as a desirable strategy to improve sustainability (Zhang et al., 2021).

By purifying the water to eliminate harmful waste materials and then reusing it, recirculating systems are made to rear a lot of fish in comparatively tiny amounts of water. Organic matter and non-toxic nutrients build up as a result of repeatedly using the water. If these metabolic by-products are used to produce secondary crops that are profitable or that somehow enhance the main fish production system, they don't have to be wasted. Integrated systems are those that use byproducts from the production of the primary species to cultivate additional crops. (Racokcy et al, 2017).

Aquaponics represents a paradigm shift from waste disposal to waste utilization, integrating fish production with plant cultivation in closed-loop systems (Rakocy et al, 2006). The fundamental principle involves converting fish wastes into plant nutrients through a series of biological processes including mechanical separation, microbial nitrification, and plant uptake (Estim & Mustafa 2017)

The nutrient cycling process begins with fish metabolism converting feed into dissolved ammonia and particulate organic matter. Mechanical filtration removes solids to prevent biofilter clogging, while nitrifying bacteria oxidize ammonia to nitrite and subsequently to nitrate, the primary plant-available nitrogen form (Concepion & Dadios, 2020). Plants absorb these nutrients along with phosphorus and micronutrients, with well-balanced systems achieving nitrogen utilization rates of approximately 70% of feed inputs (Yoshiaki et al 2025)

System design considerations include hydraulic retention time, biofilter sizing, and plant-to-fish ratios that must be optimized for specific species combinations and production goals (Pamintuan & Dima, 2019). The integration of multiple biological processes requires careful balancing to maintain water quality parameters suitable for both fish and plants while maximizing nutrient utilization efficiency (Tetreault et al, 2023).

Aquaponics systems generate various waste streams that pose environmental risks if not properly managed. Brazilian aquaponics producers commonly generate sludge, packaging waste, dead fish, and unusable plant fractions, yet many lack comprehensive waste management practices, often relying on inadequate disposal methods (Bizon & Castro, 2023). Aquaculture systems, which form the foundation of aquaponics, typically convert only 30% of supplied nutrients into product, with the remaining 70% potentially discharged into the environment, altering water quality and accumulating residual nutrients in surrounding areas (Chiquito-Contreras et al., 2022).

Proper waste management techniques can mitigate these risks. Solid fish waste can be filtered and processed through nitrification using bio-filters, while automated monitoring systems can maintain optimal water quality parameters (Nithya & P. T., 2023). Risk analysis models emphasize that monitoring and controlling essential environmental parameters is crucial for maintaining healthy, stable aquaponic systems and minimizing associated risks (Galati & Romania, 2020).

2.4.1 Composition of waste

Fish feed, the primary source of nutrients in aquaponics, is partially absorbed into fish biomass and transformed into soluble excreta and solid feces together with different amounts of uneaten or residual feed. Plants may receive macronutrients and micronutrients from the soluble components. Solid waste and leftover feed make up fish sludge, which is made up of suspended and precipitated solids. Zhang et al, 2020. Strauch et al. (2018) shows that, In the sediments, 7.1–9.9% of the feed accumulated as dry matter, which included 3.7–5.2% nitrogen and 5.5–8.7% total organic carbon.

Aquaponics is considered a sustainable production system because it fertilizes plants with recirculating aquaculture system (RAS) wastewater that is enriched in macronutrients (like nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S)) and micronutrients (like iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo)). Delaide et al., 2019

In RAS and aquaponic systems, the water must be continuously filtered to remove solids in order to maintain high water quality. The two primary methods for solid filtering are letting the particles decant in clarifiers and keeping them in a mesh (also known as mesh filtration as drum filters). Sludge is recovered from these mechanical filtration systems and released as sewage in the majority of conventional plants. The sludge is often dried and used as fertilizer on farm crops. Delaide et al, 2019

Interestingly, fish excrete up to 50% (in dry matter) of the feed they consume as solids, and the majority of the nutrients that enter aquaponic systems through fish feed end up in these solids and, consequently, in the sludge. For instance, more than 80% of the valuable P that may be utilized for plant production is eliminated by efficient solid filtration. Consequently, it is crucial to recycle these priceless nutrients for aquaponic uses. To help close the nutrient loop to a greater extent and lessen the environmental impact of aquaponic systems, it appears that a suitable sludge treatment that may mineralize the nutrients in sludge for reuse in the hydroponic unit is required. Delaide et al, 2019

Aquaculture sludge shouldn't be thought of as trash because it contains significant amounts of water, nutrients, and energy. Protein, fat, and carbs (based on dry matter) make up 17%, 3%, and 62% of leftover feed and fish excrement, respectively. Aquaculture solid waste is a good source of the majority of macronutrients and micronutrients that plants need. Between 7 and 32% of the wastewater's total nitrogen and 30 and 84% of its total phosphorus are found in the sludge solids. For macronutrients, the sludge contains 6% of nitrogen, 18% of phosphorus, 6% of potassium, 16% of calcium, and 89% of magnesium; for micronutrients, it contains 24% of iron, 86% of manganese, 47% of zinc, and 22% of copper. (Jeng et al, 2021).

2.4.2 Use of Sludge as fertilizer

Aquaculture operations produce substantial organic waste, primarily as sludge, comprising uneaten feed, fish excreta, and various particulate matter. Historically viewed as a disposal issue, sludge is progressively acknowledged as a resource with potential agricultural uses. When properly processed, it contains essential nutrients such as nitrogen, phosphorus, and organic carbon that can improve soil fertility and promote plant growth. Recent studies and reports, such as the FAO’s State of World Fisheries and Aquaculture (2022), underscore the significance of transforming aquaculture by-products into valuable inputs, thereby mitigating environmental impacts and promoting circular economy practices. The utilization of sludge as fertilizer not only mitigates waste management challenges in aquaculture but also fosters sustainable agricultural advancement.

RAS waste often takes the form of sludge made up of bacteria growth, a tiny proportion of uneaten feed particles, and stabilized fish excreta like feces. This trash is nutrient-rich and organic in nature. Fish (processing) waste, which comprises items left behind after fish processing, such as dead or damaged fish, fish trims, and tissues (such as heads, guts, tails, fins, skins, scales, and bones), is not the same as fish sludge. In comparison to other animal production or industrial effluent, fish sludge typically has a low total solids (TS) percentage (1.5–3%) and includes between 50 and 92% volatile (organic) proportion. The qualities of the sludge can also differ significantly depending on the type of fish (Basnet, 2022).

Every commercial aquaponics system needs to separate solids (fish waste and feed remnants), which build up at the bottom of sedimentation tanks using gravity, in addition to supplementing nutrients. To prevent clogging the biological filters and harming the plant roots, which hinders nutrient absorption, gas exchange, and the movement of molecules in touch with the roots, sludge must be eliminated from the aquaponics system. In order to prevent environmental contamination, the coarse materials that have been deposited at the sedimentation tank's bottom must also be collected and disposed of appropriately (Lenz et al., 2021). The sludge contains amounts of both macro and micronutrients, which means it may be able to meet the nutritional needs of plant production (Lez et al., 2021).

Sixty to ninety percent of the nitrogen (N) that fish excrete is dissolved in process water, depending on the species. Aquaponic systems, as opposed to traditional RAS, use these soluble nutrients from the fish unit to grow plants in a single hydroponic unit. Therefore, in a well-balanced aquaponics system, extra nitrogen fertilization is not necessary. (Monsees et al., 2017). As a nitrogen fertilizer, fish sludge can be effective. If applied to agricultural land where there is a strong demand for nutrient inputs, the nitrogen content of fish sludge can be effectively recycled as nitrogen fertilizer. (Brod et al., 2017)

In RAS process water, phosphorus (P) is less prevalent than nitrogen (N). Nevertheless, P is necessary for plant development. Only dissolved inorganic phosphate (PO_4^{3-}), also known as soluble reactive phosphorus (SRP), can be assimilated by plants. Fish excrete dietary P rather than retain it in large quantities. The main sources of P, either in organic or inorganic form as PO_4^{3-}, are fish feces and feed remnants because the dissolved P firmly adsorbs onto particles. As a result, a large portion of P is lost during the mechanical removal of suspended materials and can only be recovered through fertilizer recycling. Modern plant-based diets that replace fishmeal increase the amount of organic phosphorus obtained from plants that is deposited in the sludge, but they also lower Soluble Reactive Phosphorus (Basnet, 2022).

According to certain research, sludge can be mineralized to release nutrients that are attached to the particles into the water, allowing plants to absorb them and boosting plant yields while reusing the sludge. On the other hand, not much is known about using aquaponics sewage directly in soil to boost vegetable yields.

2.5 HYDROPONICS

The cultivation of plants without soil is known as hydroponics. The term "hydroponics," which comes from the Greek words "hydro" (water) and "ponos" (labor), refers to the process of growing plants without the use of soil by using various substrates (chemically inert), such as sand, gravel, or liquid (water), to which nutrients are added as well as a nutrient solution submerged in the roots. (Jan et al., 2020).

Rapid industrialization and urbanization are reducing the amount of arable land as well as traditional farming methods, which has a variety of detrimental effects on the environment. Techniques for producing enough food must change in order to feed the world's expanding population in a sustainable manner. An alternate strategy for sustainable production and the preservation of rapidly dwindling land and water resources is growth medium modification. Soil-less cultivation may be successfully started in the current situation and is being considered as a substitute for growing nutritious food plants, crops, or vegetables. (Sharma et al., 2018). Among these, hydroponics is becoming more and more well-liked because to its effective resource management and food production. Hydroponics can be used to cultivate a wide range of commercial and specialized crops, such as strawberries, peppers, tomatoes, cucumbers, green vegetables, and many more. This page discusses the global hydroponic market, various aspects of hydroponics, and crops grown in hydroponic systems. (Sharma et al., 2018).

Growers claim that hydroponic systems are the only way to achieve continuous production, which means that plants may be produced anywhere—in small areas with a controlled growth environment—all year long and in a short growing season. Growers frequently respond that hydroponics always enables them to have greater yields and productivity without being constrained by weather and environment. ("Hydroponics – a Review," 2020). Furthermore, because hydroponics uses a highly controlled environment and allows for more homogenous production without sacrificing water or nutrients, gardeners frequently assert that the quality of hydroponic produce is greater. Additionally, because hydroponics is not reliant on seasonality, its yields are consistently higher all year long. (Okemwa, 2015). With this method, it is essentially possible to grow any type of crop, fruit, vegetable, or fodder. When flowers are cultivated hydroponically, they produce more bloom and color. A hydroponics system may be automated, which makes it better for collecting final products and more controlled. Many plants, such as fruits, vegetables, flowers, and medicinal crops, can be cultivated hydroponically or without soil. (Jan et al., 2020).

2.5.1 TYPES OF HYDROPONICS

Unlike conventional farming, hydroponics grows food without the need for soil. This method involves growing plants on either natural or artificial substrates, from which the roots can readily draw nutrients from a prepared nutrition solution. There are various hydroponic food-growing techniques, and how they are used varies depending on the plant, the climate where you live, and your budget, among other things. (Velazquez-Gonzalez et al., 2022).

Wick System

This is the simplest hydroponic system requiring no electricity, pump and aerators. Plants are placed in an absorbent medium like coco coir, vermiculite, perlite with a nylon wick running from plant roots into a reservoir of nutrient solution. Water or nutrient solution supplied to plants through capillary action. This system works well for small plants, herbs and spice and doesn’t work effectively that needs lot of water. (Sharma et al., 2018b)

Deep Water Culture

Plant roots are suspended in nutrient-rich water in deep water culture, and an air stone delivers air straight to the roots. The traditional example of this technology is the hydroponic bucket system. The roots of the plants are suspended in a nutritional solution in net pots, where they rapidly grow into a sizable mass. Because algae and molds can grow quickly in the reservoir, it is imperative to monitor the oxygen and nutrient concentrations, pH, and salinity. This method works well for larger fruit-producing plants, particularly tomatoes and cucumbers, which thrive in it. (Jan et al., 2020). The plant's root is submerged in the nutrient solution in this method, and the remainder of the plant is held above water level by a variety of materials, including wood, cork bark, and polystyrene. (Velazquez-Gonzalez et al., 2022).

Drip Hydroponic System

Both commercial and home growers frequently employ the drip hydroponic technique. With the aid of a pump, each plant root receives the proper amount of water or fertilizer solution from the reservoir. Typically, plants are grown in growing media that is somewhat absorbent so that the fertilizer solution drips gradually. More water conservation allows for the methodical growth of a variety of crops. (Sharma et al., 2018b). This technique works best with crops that resemble tomatoes and peppers. In this instance, a controlled flow of the nutrient solution is sent straight to the plant roots. At specified times, the solution is supplied, and in closed systems, any remaining solution is put back into the storage tank. (Velazquez-Gonzalez et al., 2022).

Nutrient Film Technique

This technique, sometimes referred to as NFT, is similar to the floating root system, with the exception that the plant roots are submerged in a liquid stream that passes through a pipe system rather than entirely in the nourishing solution. Despite requiring less nutritional solution than the floating root system, NFT needs more components and energy to function. The nutrient solution can flow continuously or intermittently, and the excess solution gravitationally returns to the storage tank. (Velazquez-Gonzalez et al., 2022).

Ebb and Flow

This is the first commercial hydroponic system that uses the flood-drain concept. A grow tray and a reservoir with a nutritional solution within are used in this setup. The grow tray is periodically flooded with nutrient solution by a pump, which gradually drains away. Although a variety of crops can be grown, root rot, algae, and mold are prevalent problems that call for a customized system with a filtering unit. (Jan et al., 2020).

Dutch bucket hydroponic system

The Dutch bucket hydroponic system, also known as the bato bucket system, is widely used for producing large fruiting crops such as tomatoes, cucumbers, and peppers (Resh, 2013; Dorais et al., 2017). A critical factor influencing plant performance in this system is the choice of substrate, which must provide mechanical support, sufficient water retention, adequate aeration, and appropriate drainage (Savvas & Gruda, 2018). Among the various substrate options, **cocopeat** and **rice husk** have gained attention due to their availability, renewability, and relatively low cost in many tropical and subtropical regions (Abad et al., 2002; Suryanto et al., 2019).

Properties of Cocopeat and Rice Husk

1. **Cocopeat (Coir):** Derived from the fibrous mesocarp of coconut husks, cocopeat is characterized by high water-holding capacity (up to 8–9 times its dry weight) and excellent porosity, which promotes good root aeration (Abad et al., 2002; Awang et al., 2009). It also possesses moderate cation exchange capacity, which helps buffer nutrients in the root zone. However, unwashed cocopeat may contain high levels of soluble salts, requiring pretreatment before use (Raviv & Lieth, 2008).
2. **Rice Husk (RH):** Rice husk, an abundant by-product of rice milling, is lightweight and provides good drainage and aeration when used as a substrate (Suryanto et al., 2019). Unlike cocopeat, it has lower water-retention capacity and decomposes more rapidly under continuous use, which may affect long-term stability (Raviv & Lieth, 2008). Carbonised rice husk (husk charcoal) is often preferred because it improves structural stability and reduces microbial decomposition (Yahya et al., 2017)

2.6 BLACK SOLDIER FLY

The black soldier fly, Hermetia illucens (Diptera: Stratiomyidae), is found across the world, but it is most prevalent in the equatorial tropics. Asia, Europe, the southeast United States, and other regions make up its native range. Decomposing fruits, vegetable waste, animal manure, and municipal organic waste are among the many organic wastes that the black soldier fly larvae (BSFL) eat in large quantities. (Liu et al, 2017).

The black soldier fly (Hermetia illucens) is a species of fly distinguished by its black body with some translucent abdominal segments, measuring about 15-20 mm long. Adults have a wasp-like appearance with club-shaped antennae, blue-green metallic wings, and characteristic non-biting behavior. The adult flies do not feed but rely on energy stored during the larval stage. The larvae are cream to light brown, flattened, segmented, and about 27 mm long. They have strong chewing mouthparts and are highly efficient at converting organic waste into nutrient-rich biomass. This efficiency has made the species a focus of sustainable waste management and animal feed production research (Cai et al., 2022).

Morphologically, the species exhibits sexual dimorphism, with females generally larger than males. Studies comparing wild and domesticated populations reveal variations in morphology and reproductive behaviors, highlighting domestication effects on size and reproductive output—wild populations typically have larger body size and higher egg production (Masse et al., 2023). The larval stage undergoes rapid development through six instars, followed by a prepupal stage that migrates away from the original feed substrate to pupate. This migration facilitates easier harvesting of larvae for industrial use.

Ecologically, black soldier fly larvae contribute significantly to biodegradation, feeding on a variety of organic waste materials including animal manure, food scraps, and agricultural by-products. Through this process, they reduce waste volume and produce biomass rich in protein and fat, which is highly suitable as an alternative, sustainable feed ingredient in aquaculture and livestock industries. The use of BSF larvae in fish feed has shown promise in partially or fully replacing conventional fishmeal, providing economic and environmental advantages (Cai et al., 2022; Masse et al., 2023).

Adult black soldier flies are non-pestilent, do not bite or transmit diseases, and tend to stay near the larval feeding sites for reproductive purposes. Their short adult lifespan, typically around 5 to 8 days, revolves around reproduction and egg laying near waste substrates where larvae will thrive (Oliveira et al, 2016).

2.6.1 BLACK SOLDIER FLY FRASS

Black soldier fly (*Hermetia illucens*) frass, the residual waste from larvae processing organic materials, has emerged as a promising organic fertilizer supporting sustainable agriculture and aquaculture systems. It enables nutrient recycling, enhances soil health, and supports crop productivity, aligning with circular economy principles critical for resource-limited settings such as Nigeria (Abd Manan et al., 2024).

Composition and Nutrient Profile of BSF Frass

BSF frass consists primarily of insect excreta, undigested food residues, exuviae, and microorganisms. Its nutrient profile typically presents an approximate balanced ratio of nitrogen, phosphorus, and potassium, reported as $N:P_2O_5:K_2O \approx 1:0.9:1.1$, making it a well-rounded organic fertilizer (Gärttling & Schulz, 2021). The frass also contains bioactive compounds such as chitin, a polysaccharide known to stimulate plant defenses, improve immune response, and enhance microbial soil diversity (Anedo et al., 2025).

Chitin content (10–30%) found in BSF frass is particularly important for its nematicidal effects and fostering beneficial soil microbes, reducing reliance on synthetic nematicides that pose environmental hazards (Anedo et al., 2025). Additionally, the low carbon-to-nitrogen (C:N) ratio promotes quick mineralization and nutrient release into the soil, accelerating plant growth (Anedo et al., 2025). This contrasts with traditional organic fertilizers which tend to release nutrients more slowly and have a higher environmental footprint.

Efficacy in Plant Growth and Soil Health

Multiple studies reported significant improvements in crop yield and soil health from BSF frass application. For instance, on-farm trials demonstrated that BSF frass, especially when combined with 5% chitin supplementation, increased potato tuber yield by 20–72% compared to unfertilized controls and outperformed chemical nematicides in reducing nematode infestation (Anedo et al., 2025). Similarly, Beesigamukama (2020) found BSF frass more effective than commercial organic fertilizer (SAFI) in enhancing maize yield in tropical soils, asserting its economic and ecological advantages.

Research also indicates BSF frass application improves soil microbial biomass and enzymatic activity, fostering beneficial microbial communities vital for nutrient cycling and plant health (Abd Manan et al., 2024). These microbial dynamics are critical in aquaponics and fisheries systems where soil or substrate health underpins the productivity of both plants and aquatic organisms.

Role of BSF Frass in Aquaculture and Integrated Systems

In aquaculture, BSF frass can be utilized as a biostimulant for plant components of integrated systems such as aquaponics. Preliminary studies suggest that frass addition promotes phytoplankton and microbial growth, which indirectly supports fish health by improving water quality and nutrient availability (Herliwati, 2025). This highlights BSF frass's potential as a sustainable input reducing dependency on chemical fertilizers and antibiotics in aquaculture.

Environmental and Socioeconomic Benefits

BSF frass production contributes to waste valorization by converting organic waste into valuable biofertilizer, thus reducing landfill use and greenhouse gas emissions (Abd Manan et al., 2024). Economically, its use can lower fertilizer costs for smallholder farmers and enhance livelihoods by promoting sustainable farming practices (Tambeayuk et al., 2025). The local production potential aligns well with Nigeria's agricultural sustainability goals.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study location is the living laboratory of the INtegrated and Circular Technologies for Sustainable City Region FOOD systems in Africa (INCiTiS-FOOD) project's aquaponic and insectary laboratories, located in the Department of Aquaculture and Fisheries Management at the University of Ibadan, Ibadan, Nigeria. The project was sponsored by the European Union, INCiTiS-FOOD brings together 23 partners with a variety of backgrounds and diverse skills from Europe and Africa in fields such as academia, industry, research, and communication. Eight (8) living laboratories are part of the project throughout Africa, including two in Nigeria at the University of Ibadan and Lagos State in Nigeria. The initiative creates agricultural and food technology that can be used in both rural farming communities and metropolitan areas.

3.2 Experimental Design

The experiment utilised completely randomised design involving three treatments. Treatment 1 is the Organic Fertilizer (Sludge + Frass), Treatment 2 – Inorganic/synthetic Fertilizer Mixture and Treatment 3– Control (Water Only). All treatments were in triplicate in each dutch vase for each crop.

A Dutch bucket hydroponic system was used for growing *Amaranthus viridis and Solanum macrocarpon.* The setup included several plastic buckets, each with a drainage outlet at the bottom to prevent waterlogging. These outlets were linked to a central drainage line that carried the excess solution into a collection reservoir, ensuring proper drainage across the system.

Each bucket was filled with a growing medium made up of cocopeat and rice husk. Cocopeat was chosen because it holds water well, provides aeration, and supports root development, while rice husk was added as a cheap, locally available material that improves porosity and drainage. Together, they created a stable medium that allowed good root anchorage and nutrient uptake.

Unlike typical Dutch bucket systems that rely on pumps to circulate nutrient solutions, this experiment involved manual application. The assigned nutrient solutions (organic (Sludge and frass), Inorganic, or control (water) treatment) were measured and applied directly into each bucket at regular intervals (once daily).

Plate 3.1: The Dutch Vase Hydroponic system for the experiment.

3.2.1 Plant Material

Two indigenous leafy vegetable species were used in this study: *Amaranthus spp.* (amaranth) and *Solanum macrocarpon* (African eggplant). These crops were chosen because they are widely consumed in Nigeria, have high nutritional value, and relatively short growth cycles, making them suitable for hydroponic research.

Amaranthus (*Amaranthus spp.*): Seeds of amaranth were obtained from a certified seed supplier/experimental farm. Amaranth is a fast-growing vegetable mainly cultivated for its tender leaves, which are rich in protein, vitamins A and C, folate, and minerals such as iron and calcium. It adapts well to hydroponic systems because of its shallow roots, rapid biomass production, and tolerance to different media. Seeds were sown in germination trays containing sterilized nursery medium and watered daily until germination. Healthy and uniform seedlings at the two-leaf stage were transplanted into the Dutch bucket system filled with cocopeat and rice husk.

African Eggplant (*Solanum macrocarpon*): Seeds of African eggplant were also sourced from a reliable supplier (specify source). This crop is an indigenous solanaceous vegetable grown mainly for its edible leaves and, in some cases, its fruits. The leaves are commonly used in traditional dishes and are valued for their fiber, vitamins, and mineral content. Seeds were raised in germination trays containing sterilized nursery substrate, watered regularly, and allowed to establish. Seedlings with four true leaves were selected and transplanted into the Dutch bucket system. For both crops, transplanting was done early in the morning to reduce transplant shock. Seedlings were handled carefully to avoid root damage, and once placed in the hydroponic buckets, they were stabilized in the cocopeat–rice husk medium. All plants were grown under the same conditions of temperature, light, and ventilation to ensure uniform growth and reliable treatment comparisons.

Plate 3.2: *Solanum macrocarpon* grown in Dutch bucket system

3.3 Experimental Procedure

3.3.1 Sample Collection and Preparation for Liquid Organic fertilizer

3.3.1.1 Sample Collection of Organic fertiliser

Liquid fertilizer solution of the treatment 1 which is the Organic Fertilizer (Sludge + Frass) was produced by dissolution in water. Prior to dissolution, aquaponic sludge samples from digester tank of the described aquaponic setup for the INCITIS-FOOD project was gathered and dried. The aquaponic sludge employed in this study is made from these solid wastes collected on daily basis, dried and stored in polyethylene bag. Similarly, frass obtained from the brewery waste based BSF production were collected, dried and bagged in polyethylene bags. These were stored in room temperature till use. The collected sludge were from the radial flow tank and digester, first spread evenly on clean, plastic-lined concrete drying platforms to prevent contamination from soil or foreign particles. Sun drying was adopted as the primary method, taking advantage of natural heat and aeration. The sludge was regularly turned at 4-hour intervals using a wooden spatula to facilitate even drying and to prevent caking. Drying continued until the material attained a friable texture, indicating a significant reduction in moisture content (typically over 48–72 hours depending on weather conditions). For improved handling, the dried sludge was gently ground with a wooden pestle and passed through a 2 mm mesh sieve to obtain fine particles. This step ensured homogeneity and reduced the risk of uneven nutrient release during later application. To preserve its nutrient content, particularly nitrogen and phosphorus, the sludge was immediately transferred into airtight polyethylene bags, properly labeled, and stored under shade until mixing.

The frass obtained from black soldier fly larvae rearing chambers was similarly processed but under shaded drying conditions. This method was deliberately chosen to minimize nutrient losses, particularly nitrogen volatilization, which occurs rapidly under direct exposure to sunlight. The frass was spread thinly on plastic trays in a well-ventilated screen house, allowing slow air drying over 3–5 days. The material was stirred gently twice daily to avoid mold formation and encourage uniform drying. Once sufficiently dried, the frass was pulverized manually to break down clumps and sieved to obtain fine granules. The finer particle size facilitated better blending with sludge and enhanced nutrient availability during fertilizer application. The processed frass was then packaged in moisture-proof containers and stored in a cool, dry environment until required for mixture preparation.

3.3.1.2 Preparation of Liquid organic fertilizer

The dried sludge and frass were weighed and combined in a 30:70 ratio by weight, respectively. The mixing was carried out on a clean, hard plastic bowl to avoid contamination, using manual tools to achieve a uniform consistency. Homogeneity was critical, as it ensured that nutrient concentrations remained consistent throughout the mixture. To improve stability and shelf life, the blended organic fertilizer was allowed to cure for 24 hours in a closed container. This step helped stabilize microbial activity and reduce potential heating effects from organic interactions. The mixture was then packaged in double-layered polyethylene bags, tightly sealed, and labeled accordingly before storage.

3.3.2.1 Sample Collection of inorganic fertilizer

This treatment involved a mix of commonly used inorganic fertilizers for hydroponic production. The mixture included:

1. **Foliar Plus** – a general-purpose foliar nutrient solution
2. **NPK 20-20-20 + TE** – a balanced fertilizer with added trace elements for overall growth
3. **Potasse** – a potassium-rich fertilizer for leaf expansion and photosynthesis
4. **YaraLiva Tropicote (Calcium Nitrate/Nitrabor)** – a source of calcium and nitrogen to support strong cell walls and vegetative growth
5. **Magnesium Sulfate (Epsom salt)** – to provide magnesium for chlorophyll formation and sulfur for amino acid synthesis

The inorganic fertilizers were purchased from an accredited agrochemical supplier to guarantee quality and authenticity. The mixture was composed of the following components, weighed precisely with a digital balance:

- Foliar Plus – 0.155 g
- NPK 20-20-20-TE – 125.7 g
- Potasse – 25.06 g
- YaraLiva Nitrabor – 63.24 g

- Magnesium sulfate – 25.28 g

All inorganic inputs were handled under standard fertilizer preparation protocols to avoid contamination and nutrient loss.

3.3.2.2 Preparation of Liquid inorganic fertilizer

The weighed inorganic fertilizer components (Foliar Plus, NPK 20-20-20-TE, Potasse, YaraLiva Nitrabor, and Magnesium sulfate) were placed in a large, dry plastic bowl. Mixing was carried out manually with a clean spatula in a clockwise motion to ensure uniform blending of granules and powders. Special care was taken to avoid clumping or segregation of lighter materials during mixing.

To further guarantee uniformity, the mixture was sieved lightly through a mesh screen, after which it was immediately stored in airtight containers to protect it from atmospheric moisture. The prepared inorganic fertilizer blend was kept in a dry storage chamber under ambient temperature until dilution and application.

3.3.3 Determination of the Dissolution Time for Organic and inorganic fertiliser

The Total Dissolved Solutes (TDS) of the soaked organic and inorganic fertlisers were measured of their TDS, conductivity and Temperature and mean daily values determined. These parameters were measured using an electronic probe (). The values were taken daily throughout until the fertilizer was exhausted.

3.3.4 Application of the organic and inorganic Fertiliser

The application of the fertilizer was designed to test comparative growth and yield performance of the fertilizers on two plant species in a completely randomized experimental design.

Prior to application, both the organic and inorganic fertilizer preparations were diluted to ensure safe and uniform delivery of nutrients. Specifically, 200 g of either the organic mixture or the inorganic blend was measured using a digital balance and dissolved in 200 L of clean, chlorinefree water. Dilution was performed in large plastic drums reserved exclusively for fertilizer solutions, ensuring no cross-contamination with other agrochemicals. Each 200 L batch of fertilizer solution was applied gradually over a period, serving as the daily fertigation input for the experimental crops.

3.3.4.1 Data Collection

Growth Parameters:

Growth performance of *Amaranthus spp.* and *Solanum macrocarpon* under the different fertilizer treatments was evaluated using standard morphological indicators. The following parameters were measured at regular intervals during the experimental period:

1. **Plant Height (cm):** Plant height was measured from the base of the stem at the substrate level to the tip of the highest fully expanded leaf using a ruler or measuring tape.
2. **Number of Leaves:** The total number of fully expanded leaves per plant was counted manually. Only leaves that were green and physiologically active were considered.
3. **Leaf Area (cm^2):** Leaf area was determined using the non-destructive method, where the maximum length and width of selected leaves were measured and multiplied by a correction factor (species-specific constant).
4. **Plant Diameter (cm):** The stem or canopy diameter was measured at the widest point across the plant base using a digital caliper or measuring tape, depending on plant size.

These parameters were collected at intervals of 7 days to monitor growth progression across treatments. Data obtained provided a basis for comparing the effects of organic, inorganic, and control treatments on vegetative development.

Plate 3.3: Sampling process

3.4 Statistical Analysis

Data collected on growth and yield parameters of *Amaranthus spp.* and *Solanum macrocarpon* were subjected to statistical analysis to determine the effect of the different fertilizer treatments. Analysis of Variance (**ANOVA**) was employed to test for significant differences among treatments. Where significant differences were observed, mean separation was carried out using **Tukey's Honest Significant Difference (HSD) post hoc test** to identify specific treatment effects.

All statistical analyses were conducted using **R statistical software**. The level of significance was set at $\mathbf{p < 0.05}$, meaning that treatment effects were considered statistically significant at a 95% confidence interval.

Data Presentation:
Results were expressed as **mean ± standard error (SE)** for each treatment. Processed data were presented in **tables, charts, and graphs** to aid comparison and visualization of treatment effects on plant growth and yield performance.

CHAPTER FOUR

RESULTS

4.1 Nutrient dissolution of the synthetic and solid frass-sludge combination solid fertilizers in aqueous solution

Table 4.1 shows the mean values of nutrient dissolution, indicating parameters of the synthetic and solid frass-sludge combination solid fertilizers in aqueous solution. From the table, Total Dissolved Solids (TDS) and conductivity were significantly different for synthetic and organic fertilizers. The values range from 1062.89±175.82 (Organic) to 1837.37±70.61 (Synthetic) for TDS and 458.26±42.66 (Organic) to 781.35±41.71 (Synthetic) for conductivity. Temperature was statistically similar ($P>0.05$) across organic and synthetic fertilizers; the values range from 26.8±1.49 (organic) to 26.83±1.42 (synthetic). Figure 4.1 shows the pattern of nutrient dissolution, indicating parameters of the synthetic and solid frass-sludge combination fertilizers in aqueous solution.

4.2 Growth performance and yield of *Amaranthus viridis* and *Solanum macrocarpon* cultivated hydroponically using aquaponic solid waste-derived fertilizer, and conventional nutrient solutions.

Table 4.2 showed the mean values of growth parameters of Amaranthus viridis plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial. From the table, mean plant height, stem diameter, leaf height, and leaf width were statistically similar ($p>0.05$) across organic and synthetic fertilizers while water treatment had significantly lowest values. The values ranged from 11.7±5.71 (water) to 30.83±7.53 (organic) for plant height, 1.27±0.95 (water) to 3.62±1.18 (organic) for stem diameter, 7.16±3.35 (water) to 16.78±4.53 (organic) for leaf height and 2.09±0.99 (water) to 5.24±1.76 (organic) for leaf width. Number of leaf varied significantly across the three treatments. The values ranged from 14.29±12.33 (water) to 81.51±64.64 (organic).

The mean values of the growth parameters for the Solanum macrocarpon plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial (Table 4.3) showed that mean plant height, stem diameter, leaf height, and leaf width were statistically similar ($p>0.05$) across organic and synthetic fertilizers while water treatment had significantly lowest values. The values ranged from 10.8±4.74 (water) to 28.59±9.27 (organic) for plant height, 1.09±0.71 (water) to 2.99±1.17 (organic) for stem diameter, 7.79±3.89 (water) to 20.96±5.44 (organic) for leaf height and 4.62±2.11 (water) to 12.21±3.85 (organic) for leaf width. Number of leaves varied significantly across the three treatments. The values ranged from 5.22±3.04 (water) to 16.93±6.5 (organic).

Table 4.4 showed the relationship between the mean values of the growth parameter for the Solanum macrocarpon plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial. From the table, mean plant height, stem diameter, leaf height, and leaf width were statistically similar ($p>0.05$) across organic and synthetic fertilizers while water treatment had significantly lowest values.

The values ranged from 10.8 ± 0.71 (Solanum_water) to 30.83 ± 1.12 (Amaranthus_organic) for plant height, 1.09 ± 0.11 (Solanum_water) to 3.62 ± 0.18 (Solanum_organic) for stem diameter, 7.16 ± 0.5 (Amaranthus_water) to 20.96 ± 0.81 (Solanum_organic) for leaf height, 2.09 ± 0.15 (Amaranthus_water) to 12.21 ± 0.57 (Solanum_organic) for leaf width and 5.22 ± 0.45 (Solanum_water) to 81.51 ± 9.64 (Amaranthus_organic).

Figure 4.2 shows the pattern of Mean growth parameters of Amaranthus viridis grown with with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial. In organic fertilizer, number of leaves was significantily higher than other parameters while stem diameter was the lowest. Similarly, in the synthetic and water treatment, number of leaves was significantly higher than other parameters while stem diameter was the lowest.

In Solanum macrocarpon, the pattern of mean growth parameters of Solanum macrocarpon grown with with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial (Figure 4.3) show that in the three treatments, plant height was significantly higher that other parameters while stem diameter was the lowest.

4.3 Harvest of *Amaranthus viridis* and *Solanum macrocarpon* grown with the solid synthetic and frass-sludge combination solid fertilizers in aqueous solution in hydroponic system.

Figure 4.7 shows the harvest trend in 30 days of Amaranthus viridis plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial. From the figure, the peak harvest was at the second harvest for both organic and synthetic fertilizers while for the water (control), harvest is its peak at the third harvest. The harvest trend for solanum macrocarpon plant (figure 4.8) grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial shows that the peak harvest was at the second harvest for both organic and synthetic fertilizers while for the water (control), harvest is its peak at the third harvest.

4.4 Yield of *Amaranthus viridis* and *Solanum macrocarpon* grown with the solid synthetic and frass-sludge combination solid fertilizers in aqueous solution in hydroponic system.

Table 4.5 showed the mean values of harvest yield of Amaranthus viridis plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial. From the table, total weight, leaf weight, and root weight varied significantly ($p>0.05$) across the three treatments, organic fertilizers, synthetic fertilizers and water treatment which had significantly lowest values. The values ranged from 7.17±5.29 (water) to 36.78±24.13 (organic) for Total weight, 5.57±3.98 (water) to 14.22±10.21 (organic) for leaf weight and 1.6±1.46 (water) to 22.56±15.65 (organic) for root weight.

The mean values of harvest yield of Solanum macrocarpon plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial (Table 4.6) showed that, the total weight of yield, leaf weight and root weight varied significantly ($p<0.05$) across the three treatments, organic fertilizers, synthetic fertilizers and water treatment which had significantly lowest values. The values ranged from 8.39±8.54 (water) to 59.33±45.92 (organic) for total weight, 5.39±5.26 (water) to 36.56±29.3 (organic) for leaf weight and 3±3.83 (water) to 22.78±18.75 (organic) for root weight. Figure 4.9 shows the pattern of harvest yield of Amaranthus viridis grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial. In organic and synthetic fertilizers root weight was significant higher that leaf weight, while in water (control) treatment, it was significantly lowest. In Solanum macrocarpon, the pattern of harvest yield (Figure 4.10) shows that in the three treatments leaf weight is significantly higher than root weight.

Table 4.1: Mean values of Nutrient dissolution rate of the synthetic and solid frass-sludge combination solid fertilizers in aqueous solution in 24hours

Parameter	Synthetic	Organic
Conductivity	1837.37 ± 70.61^{a}	1062.89 ± 175.82^{b}
TDS	781.35 ± 41.71^{a}	458.26 ± 42.66^{b}
Temperature	26.83 ± 1.42^{a}	26.8 ± 1.49^{a}

Means with different superscripts along the same row are significantly different ($p<0.05$)

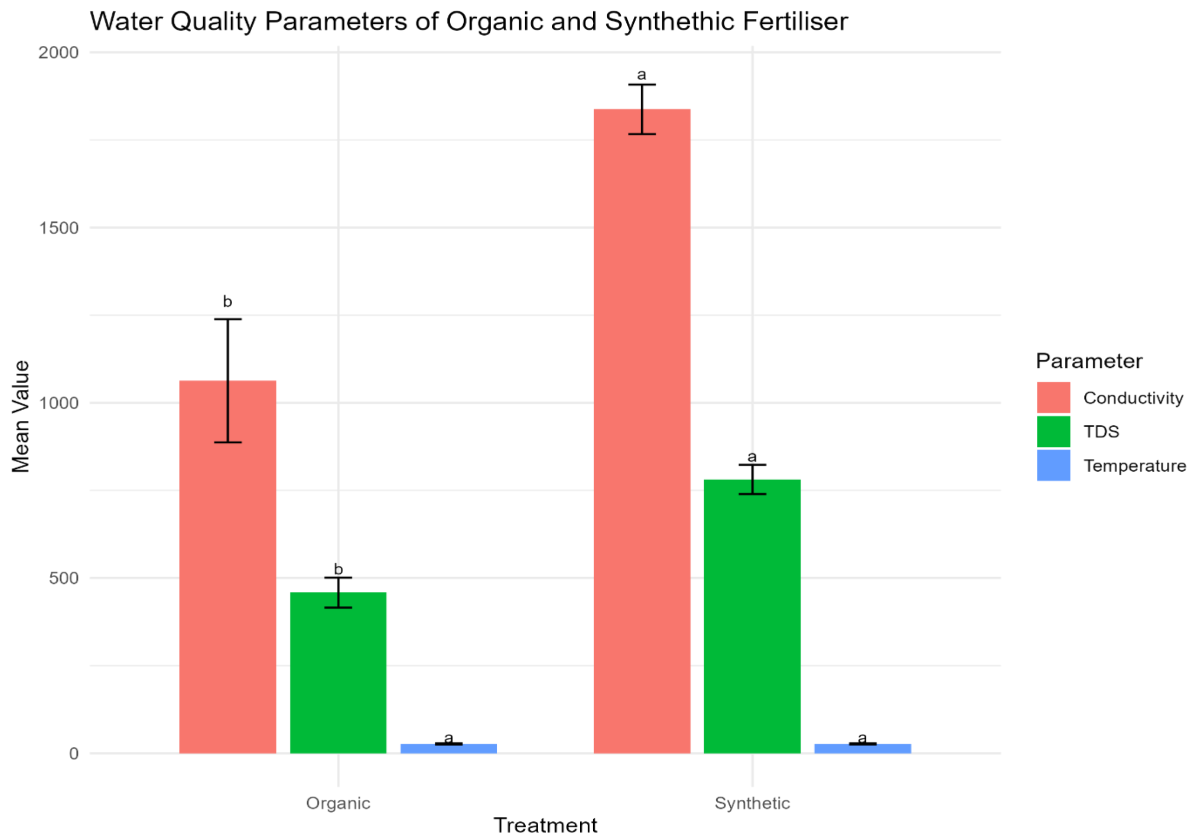

Figure 4.1: Pattern of Nutrient dissolution of the synthetic and solid frass-sludge combination solid fertilizers in aqueous solution

Table 4.2: Mean values of growth Parameters of *Amaranthus viridis* plant grown with frass-sludge organic fertilizer, Synthetic Fertiliser and Water (Control) in a 30days Growth Trial

Parameter	ORGANIC	SYNTHETIC	WATER
PLANT HEIGHT (cm)	30.83 ± 7.53^{a}	30.18 ± 10.09^{a}	11.7 ± 5.71^{b}
STEM DIAMETER (cm)	3.62 ± 1.18^{a}	3.35 ± 1.39^{a}	1.27 ± 0.95^{b}
LEAF HEIGHT (cm)	16.78 ± 4.53^{a}	17.13 ± 5.92^{a}	7.16 ± 3.35^{b}
LEAF WIDTH (cm)	5.24 ± 1.76^{a}	5.22 ± 2.63^{a}	2.09 ± 0.99^{b}
NO OF LEAF	81.51 ± 64.64^{a}	45.73 ± 23.55^{b}	14.29 ± 12.33^{c}

Mean with the same superscript along the same row are significantly different ($p<0.05$)

Table 4.3: Mean values of growth Parameters of *Solanum macrocarpon* plant grown with frass-sludge organic fertilizer, Synthetic Fertiliser and Water (Control) in a 30days Growth Trial

Parameter	ORGANIC	SYNTHETIC	WATER
PLANT HEIGHT (cm)	28.59±9.27^{a}	26.42±11.56^{a}	10.8±4.74^{b}
STEM DIAMETER (cm)	2.99±1.17^{a}	2.69±1.59^{a}	1.09±0.71^{b}
LEAF HEIGHT (cm)	20.96±5.44^{a}	18.76±8.48^{a}	7.79±3.89^{b}
LEAF WIDTH (cm)	12.21±3.85^{a}	10.53±5.12^{a}	4.62±2.11^{b}
No. OF LEAF	16.93±6.5^{a}	15.85±7.21^{a}	5.22±3.04^{b}

Mean with the same superscript along the same row are significantly different ($p<0.05$)

Table 4.4: Relationship of Mean values of growth Parameters of Amaranthus Viridis and Solanum macrocarpon plant grown with frass-sludge organic fertilizer, Synthetic Fertiliser and Water (Control) in a 30days Growth Trial

Parameter	Amaranthus Organic	Amaranthus Synthetic	Amaranthus Water	Solanum Organic	Solanum Synthetic	Solanum Water
Plant height (cm)	30.83 ± 1.12 a	30.18 ± 1.5 a	11.7 ± 0.85 b	28.59 ± 1.38 a	26.42 ± 1.72 a	10.8 ± 0.71 b
Stem diameter (cm)	3.62 ± 0.18 a	3.35 ± 0.21 ab	1.27 ± 0.14 c	2.99 ± 0.17 ab	2.69 ± 0.24 b	1.09 ± 0.11 c
Leaf height (cm)	16.78 ± 0.67 a	17.13 ± 0.88 a	7.16 ± 0.5 c	20.96 ± 0.81 b	18.76 ± 1.26 ab	7.79 ± 0.58 c
Leaf width (cm)	5.24 ± 0.26 a	5.22 ± 0.39 a	2.09 ± 0.15 c	12.21 ± 0.57 b	10.53 ± 0.76 b	4.62 ± 0.31 a
Number of leaves	81.51 ± 9.64 a	45.73 ± 3.51 c	14.29 ± 1.84 b	16.93 ± 0.97 b	15.85 ± 1.07 b	5.22 ± 0.45 b

Means with different superscripts along the same row are significantly different ($p < 0.05$).

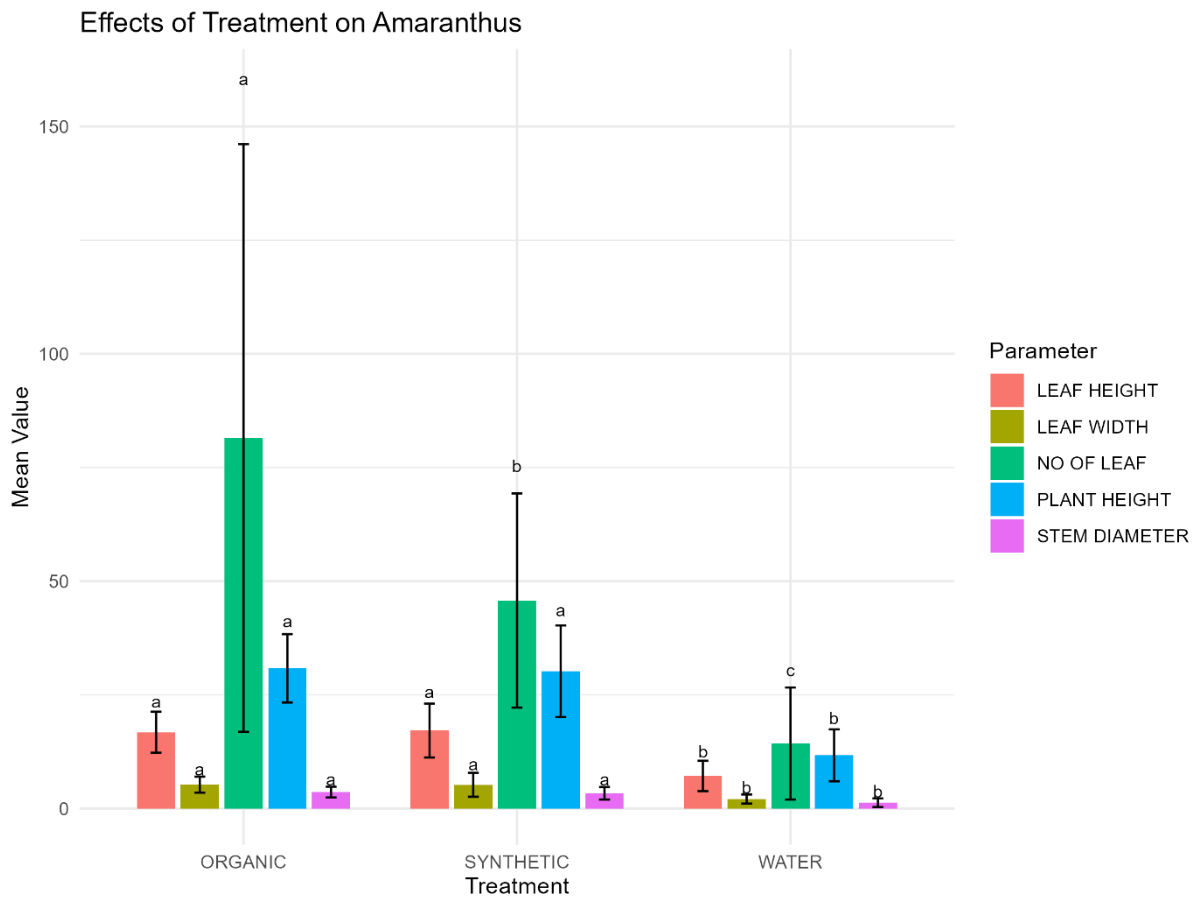

Figure 4.2: Pattern of Mean growth parameters of Amaranthus viridis grown with frass-sludge organic fertilizer, Synthetic fertilizer and Water (Control) in a 30days Growth Trial

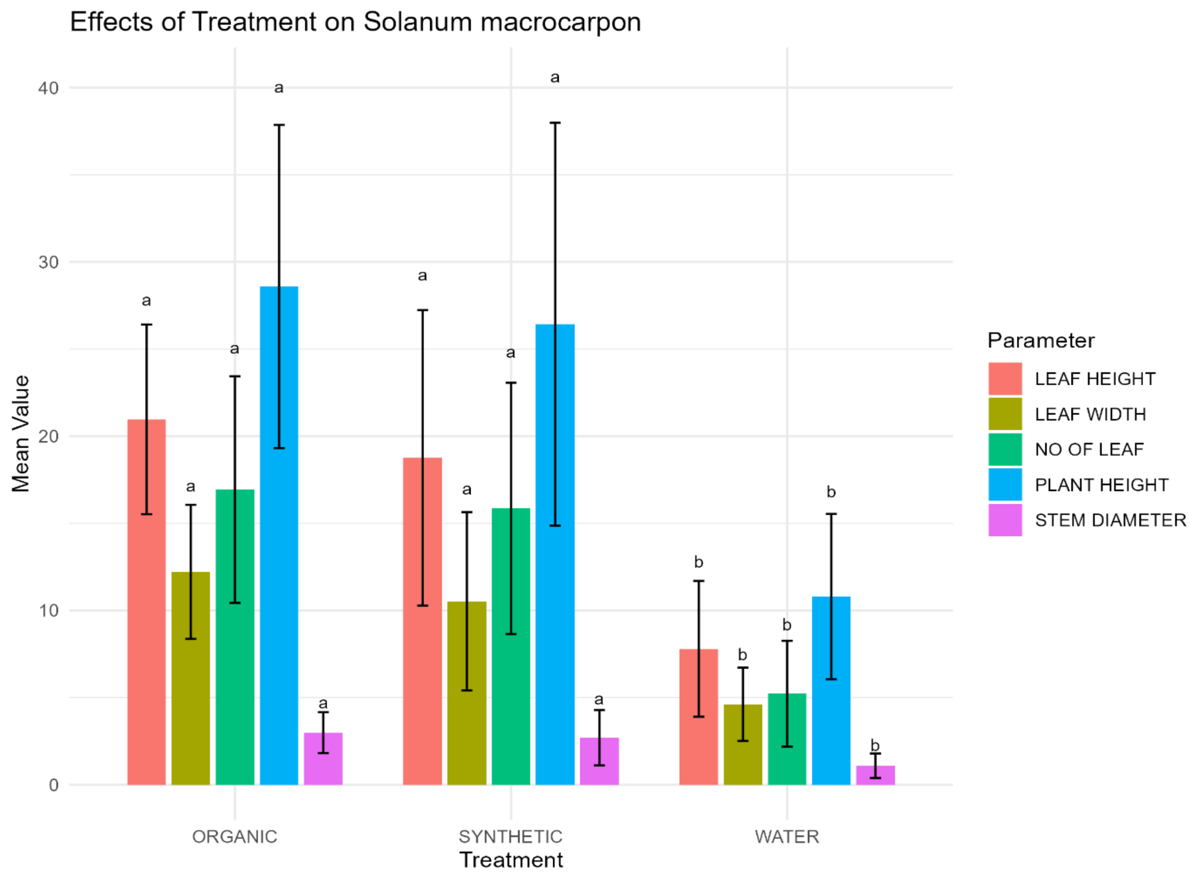

Figure 4.3: Pattern of Mean growth parameters of Solanum macrocarpon grown with frass-sludge organic fertilizer, Synthetic fertilizer and Water (Control) in a 30days Growth Trial

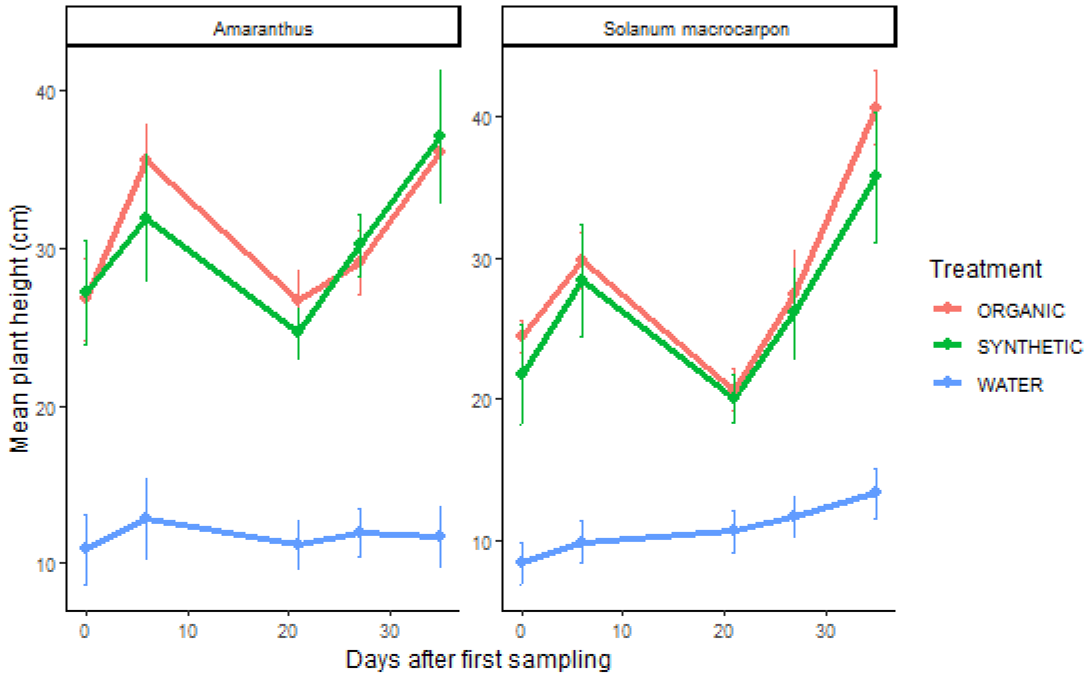

Figure 4.4: Pattern of plant height in Amaranthus viridis and Solanum macrocarpon plant grown with frass/sludge organic fertilizer, synthetic fertilizer and water treatments in a 30 days growth Trial

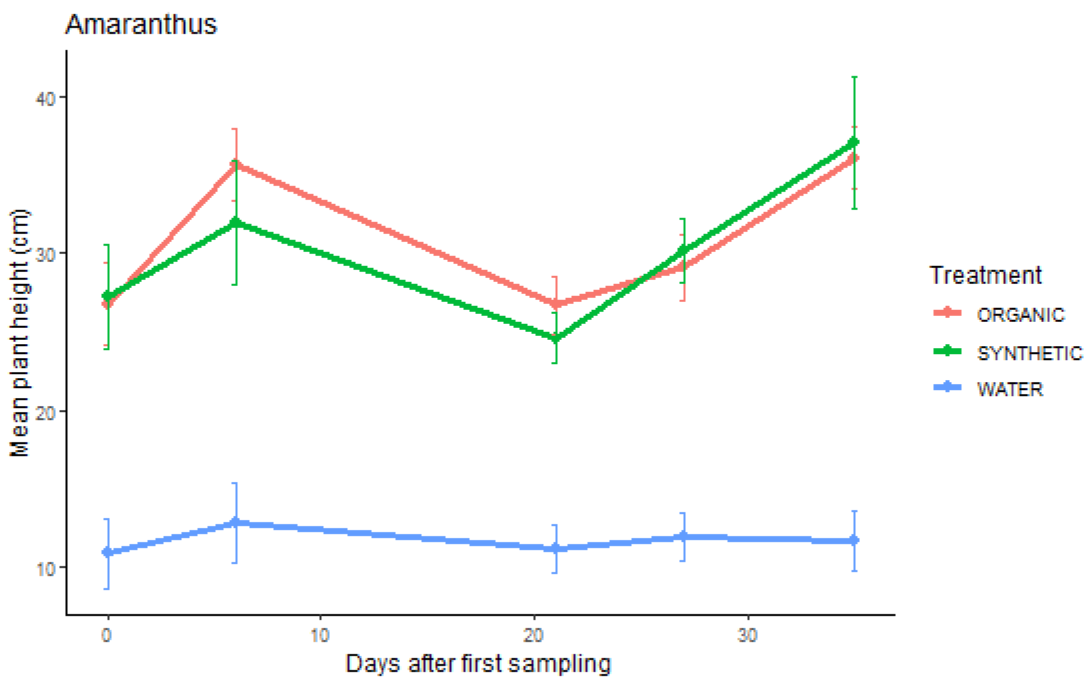

Figure 4.5: Pattern of plant height in Amaranthus viridis plant grown with frass/sludge organic fertilizer, synthetic fertilizer and water treatments in a 30 days growth Trial.

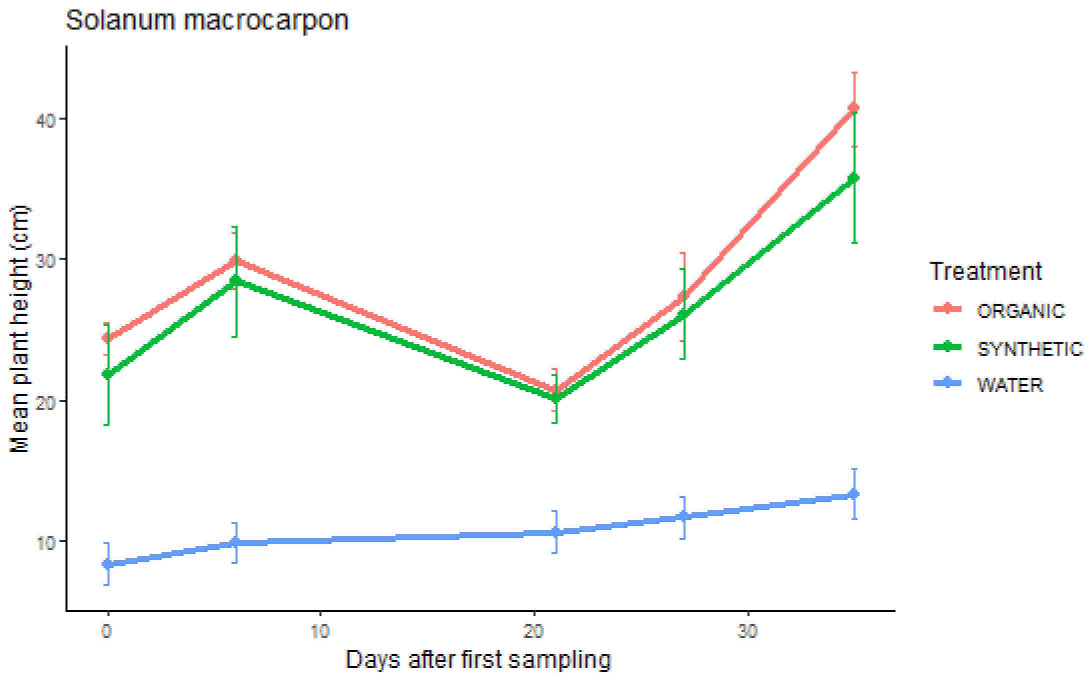

Figure 4.6: Pattern of plant height in Solanum macrocarpon plant grown with frass/sludge organic fertilizer, synthetic fertilizer and water treatments in a 30 days growth Trial

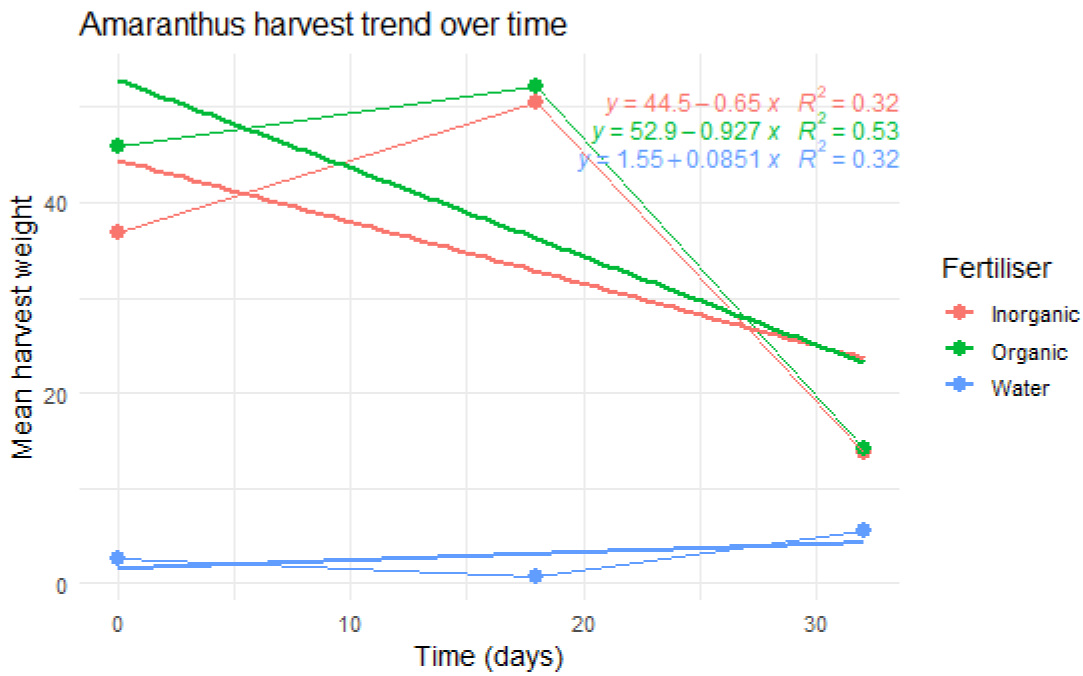

Figure 4.7: Harvest trend of Amaranthus viridis plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial.

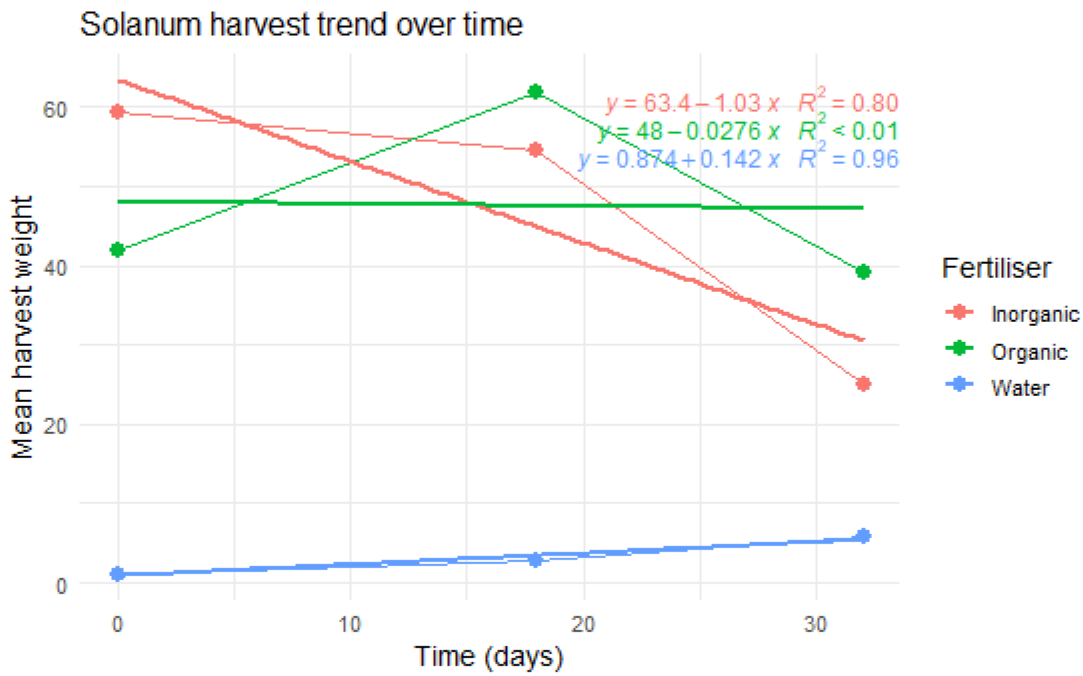

Figure 4.8: Harvest trend of Solanum macrocarpon plant grown with frass-sludge organic fertilizer, synthetic fertilizer and water (control) in a 30 days growth trial.

Table 4.5: Mean Harvest Yield (Weight) of Amaranthus viridis plant grown with frass-sludge organic fertilizer, Synthetic Fertiliser and Water (Control) in a 30days Growth Trial

Parameter (g)	Organic	Inorganic	Water
Total weight	36.78 ± 24.13^{a}	30 ± 13.49^{a}	7.17 ± 5.29^{b}
Leaf weight	14.22 ± 10.21^{a}	13.78 ± 5.74^{ab}	5.57 ± 3.98^{b}
Root weight	22.56 ± 15.65^{a}	16.22 ± 9.71^{a}	1.6 ± 1.46^{b}

Means with different superscripts along the same row are significantly different ($p < 0.05$).

Table 4.6: Mean Harvest Yield (Weight) of Solanum macrocarpon plant grown with frass-sludge organic fertilizer, Synthetic Fertiliser and Water (Control) in a 30days Growth Trial

Parameter	Organic	Inorganic	Water
Total weight	59.33 ± 45.92^{a}	46 ± 23.55^{a}	8.39 ± 8.54^{b}
Leaf weight	36.56 ± 29.3^{a}	25.11 ± 12.97^{ab}	5.39 ± 5.26^{b}
Root weight	22.78 ± 18.75^{a}	20.89 ± 15.2^{a}	3 ± 3.83^{b}

Means with different superscripts along the same row are significantly different ($p < 0.05$).

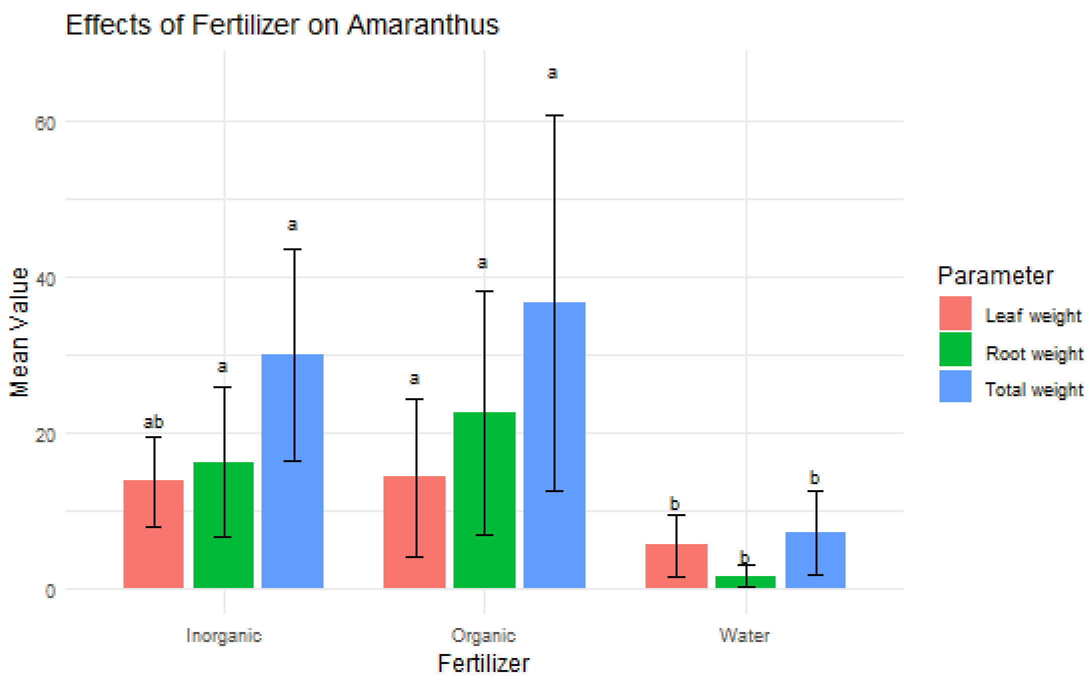

Figure 4.9: Pattern of Harvest Yield of Amaranthus viridis grown with frass-sludge organic fertilizer, Synthetic fertilizer and Water (Control) in a 30days Growth Trial

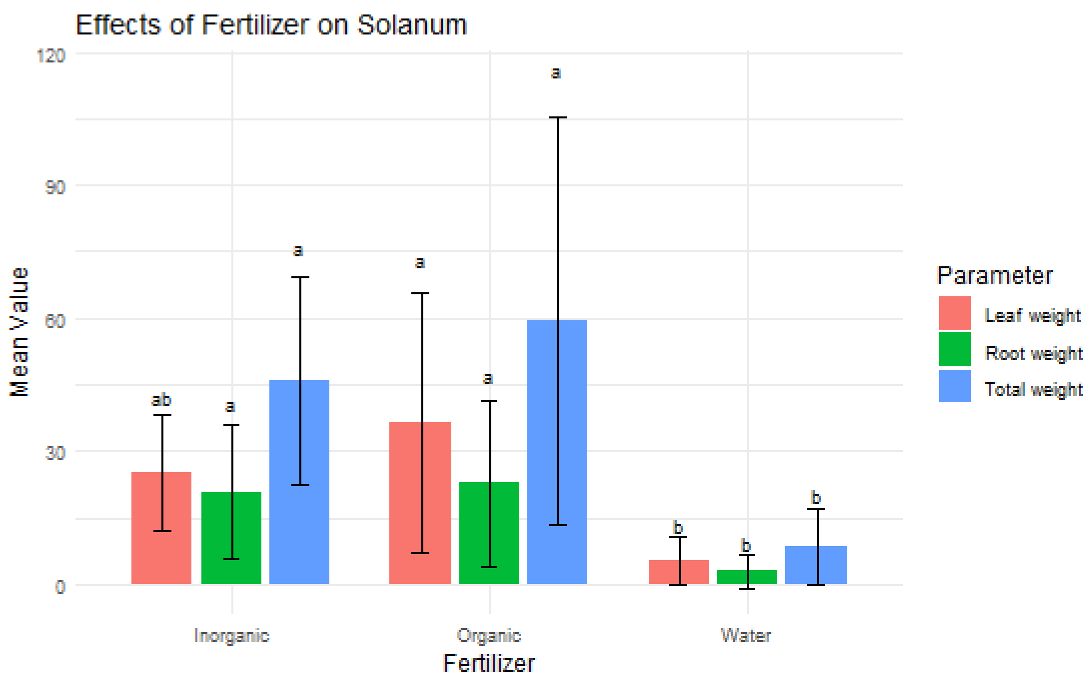

Figure 4.10: Pattern of Harvest Yield of Solanum macrocarpon grown with frass-sludge organic fertilizer, Synthetic fertilizer and Water (Control) in a 30days Growth Trial

CHAPTER FIVE

DISCUSSION

5.1 Nutrient dissolution of the synthetic and solid frass-sludge combination solid fertilizers in aqueous solution

The nutrient dissolution behavior of the synthetic fertilizer and the solid frass–sludge combination fertilizer in aqueous solution revealed clear and consistent differences between the two nutrient sources throughout the soaking period. Results from this study demonstrated that the synthetic fertilizer produced significantly higher values of total dissolved solids (TDS) and electrical conductivity (EC) than the frass–sludge fertilizer, indicating a greater extent of nutrient release into solution.

The significantly higher TDS values recorded for the synthetic fertilizer reflect a larger quantity of soluble nutrients released during soaking, while the elevated conductivity values further confirm the presence of higher concentrations of dissolved ionic species. These findings indicate that nutrients from the synthetic fertilizer were more readily and rapidly dissolved in water compared to those from the frass–sludge fertilizer. In contrast, the lower but appreciable TDS and EC values observed in the frass–sludge fertilizer solution suggest a slower and more controlled nutrient release pattern, which is characteristic of organic-based fertilizers.

The similarity in temperature values between both fertilizer treatments throughout the soaking period indicates that the differences observed in nutrient dissolution were due primarily to fertilizer composition rather than thermal effects. This strengthens the reliability of the observed dissolution trends.

The pattern illustrated in Figure 4.1, where conductivity emerged as the most dominant parameter and was highest in the synthetic fertilizer, further confirms the greater solubility and faster nutrient availability associated with synthetic fertilizer formulations. Meanwhile, the gradual dissolution observed in the frass–sludge fertilizer highlights its potential as a slow-release nutrient source, which may enhance nutrient use efficiency and reduce nutrient losses during crop production.

Overall, these findings demonstrate that both fertilizer types were capable of releasing nutrients into aqueous solution; however, the synthetic fertilizer exhibited significantly faster and greater nutrient dissolution, while the frass–sludge combination fertilizer provided a more sustained release of nutrients. These results satisfy the first objective of the study by confirming distinct nutrient dissolution behaviors of the synthetic and frass–sludge fertilizers over the soaking period.

5.2 Growth Performance of *Amaranthus viridis* and *Solanum macrocarpon* under Different Nutrient Treatments

The growth performance of *Amaranthus viridis* and *Solanum macrocarpon* under sludge-frass fertilizer (organic), synthetic fertilizer, and water (control) revealed clear and consistent trends throughout the experimental period. Results from this study demonstrated that plants supplied with organic and synthetic nutrient solutions exhibited significantly superior growth performance compared to those grown with water alone. This pattern was consistently observed across major vegetative growth parameters, including plant height, stem diameter, leaf height, leaf width, and number of leaves.

The similarity observed between the organic and synthetic nutrient treatments indicates that nutrients recovered from aquaponic sludge and Black Soldier Fly frass were adequately mineralized and made available for plant uptake. This suggests that sludge-frass fertilizer can effectively meet the nutritional requirements of leafy vegetables cultivated hydroponically. In contrast, the consistently poor performance recorded under the water treatment highlights the importance of nutrient supplementation in hydroponic systems, where plants rely entirely on externally supplied nutrients for growth and development.

In *Amaranthus viridis*, plants grown with organic fertilizer recorded the highest number of leaves, which is a critical growth attribute for leafy vegetables harvested primarily for foliage. Increased leaf production under organic nutrient treatment suggests enhanced nitrogen availability, which is known to promote vegetative growth, leaf initiation, and chlorophyll formation. Similarly, plants grown under synthetic fertilizer also performed comparably, further confirming that the organic nutrient source was nutritionally sufficient.

For *Solanum macrocarpon*, organic and synthetic nutrient treatments supported significantly greater plant height, leaf height, and leaf width compared to the control. The enhanced vegetative growth observed reflects favorable physiological conditions resulting from adequate nutrient availability, particularly macronutrients such as nitrogen, phosphorus, and potassium. These findings satisfy the first objective of the study.

5.3 Physiological Responses and Nutrient Uptake Patterns of *Amaranthus viridis* and *Solanum macrocarpon*

Although direct laboratory analysis of nutrient uptake was not conducted, physiological responses inferred from growth indicators provided valuable insight into nutrient utilization by the crops. Parameters such as leaf number, leaf size, stem diameter, and biomass accumulation serve as reliable indicators of nutrient uptake efficiency in plant studies.

The significantly higher leaf number observed in *Amaranthus viridis* under organic fertilizer treatment suggests efficient nitrogen assimilation and utilization. Nitrogen is a major component of amino acids, proteins, and chlorophyll, and its availability directly influences photosynthetic capacity and vegetative development. The comparable physiological performance recorded under synthetic fertilizer further supports the adequacy of the organic nutrient solution derived from aquaponic waste.

In *Solanum macrocarpon*, increased plant height and expanded leaf dimensions under organic and synthetic nutrient treatments indicate enhanced cell division and elongation. Thicker stems recorded under these treatments also suggest improved structural development, which may be associated with sufficient potassium and calcium availability. Conversely, plants grown under water treatment exhibited reduced growth, reflecting nutrient stress and limited physiological efficiency.

The observed differences between the two crops indicate species-specific nutrient uptake and allocation patterns. While *Amaranthus viridis* exhibited a growth strategy focused on leaf proliferation, *Solanum macrocarpon* showed greater emphasis on vertical growth and leaf expansion. These variations emphasize the need for crop-specific nutrient management in hydroponic and aquaponic-integrated systems, thereby addressing the second objective of the study.

5.3 Harvest Trend and Yield Performance under Different Nutrient Regimes

Harvest trends recorded over the 30-day growth period showed that both *Amaranthus viridis* and *Solanum macrocarpon* grown with organic and synthetic fertilizers attained peak harvest earlier than those grown under the water treatment. In both crops, peak harvest occurred during the second harvest under organic and synthetic treatments, while the control plants reached peak harvest at a later stage. This delay observed in the control treatment can be attributed to slower growth rates resulting from nutrient deficiency.

Yield analysis further revealed that organic fertilizer produced the highest total biomass in both crops, followed closely by synthetic fertilizer, while water treatment consistently resulted in the lowest yield. In *Amaranthus viridis*, root weight was higher under organic and synthetic treatments, suggesting improved root development and enhanced nutrient absorption capacity. Improved root systems are essential for nutrient and water uptake, particularly in hydroponic environments.

In contrast, *Solanum macrocarpon* recorded higher leaf weight relative to root weight across treatments, reflecting its growth habit and economic value as a leafy vegetable. The superior yield performance observed under organic fertilizer highlights the effectiveness of sludge-frass fertilizer nutrients in supporting biomass accumulation and early harvest. These findings reinforce the feasibility of using recycled aquaponic waste as a nutrient source in hydroponic crop production, thereby addressing the first and third objectives of the study.

5.4 Sustainability Implications of Integrating Aquaponic Waste Recycling into Hydroponic Systems

The integration of aquaponic solid waste recycling into hydroponic systems offers significant sustainability benefits. By converting fish waste into plant-available nutrients, the system reduces environmental pollution associated with aquaculture effluents while simultaneously minimizing dependence on synthetic fertilizers. This approach aligns with the principles of sustainable agriculture and circular economy, where waste materials are reused as valuable inputs.

The comparable growth and yield performance observed between organic and synthetic nutrient treatments in this study demonstrates that aquaponic waste–derived fertilizer can serve as an effective alternative nutrient source. This has important implications for small-scale farmers, urban agriculture practitioners, and regions where access to synthetic fertilizers is limited or costly.

Additionally, the adoption of integrated aquaponic-hydroponic systems can contribute to food security by promoting efficient use of water and nutrients. The dual benefits of waste reduction and enhanced crop productivity underscore the relevance of this approach for sustainable vegetable production.

5.5 Conclusion

This study established that aquaponic sludge and Black soldier fly frass derived fertilizer is an effective nutrient source for hydroponic cultivation of *Amaranthus viridis* and *Solanum macrocarpon*. Growth performance and yield parameters recorded under organic fertilizer treatment were comparable to those obtained using synthetic nutrient solutions and significantly superior to the control treatment. The findings indicate that nutrients recovered from aquaponic waste can adequately support plant physiological development, yield formation, and early harvest.

Overall, the integration of aquaponic waste recycling into hydroponic systems presents a sustainable and environmentally friendly approach to vegetable production, with potential benefits for waste management, resource efficiency, and food security.

5.6 Recommendations

Based on the findings of this study, the following recommendations are made:

1. Aquaponic sludge and Black Soldier Fly frass derived fertilizer should be adopted as a sustainable alternative to synthetic nutrient solutions in hydroponic cultivation of leafy vegetables.
2. Long-term experiments covering extended growth periods and multiple harvest cycles are recommended to assess system stability and productivity.
3. Future research should evaluate the economic viability and scalability of integrating aquaponic waste recycling into commercial hydroponic operations.

4. Policymakers and agricultural stakeholders should encourage the adoption of integrated aquaponic-hydroponic systems to promote sustainable food production and environmental conservation.

CHAPTER 6

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APPENDIX

Two-Way ANOVA for Amaranthus

Parameter	Term	df	statistic	p.value
PLANT HEIGHT	TREATMENT	2	93.81	< 0.001
PLANT HEIGHT	DATE	4	4.96	< 0.001
PLANT HEIGHT	TREATMENT:DATE	8	1.09	3.73e-01
PLANT HEIGHT	Residuals	120		
STEM DIAMETER	TREATMENT	2	116.63	< 0.001
STEM DIAMETER	DATE	4	36.34	< 0.001
STEM DIAMETER	TREATMENT:DATE	8	3.25	2.21e-03
STEM DIAMETER	Residuals	120		
LEAF HEIGHT	TREATMENT	2	80.43	< 0.001
LEAF HEIGHT	DATE	4	7.19	< 0.001
LEAF HEIGHT	TREATMENT:DATE	8	1.93	6.16e-02
LEAF HEIGHT	Residuals	120		
LEAF WIDTH	TREATMENT	2	46.97	< 0.001
LEAF WIDTH	DATE	4	5.82	< 0.001
LEAF WIDTH	TREATMENT:DATE	8	1.21	2.98e-01
LEAF WIDTH	Residuals	120		
NO OF LEAF	TREATMENT	2	52.16	< 0.001
NO OF LEAF	DATE	4	15.13	< 0.001

Parameter	Term	df	statistic	p.value
NO OF LEAF	TREATMENT:DATE	8	4.97	< 0.001
NO OF LEAF	Residuals	120		

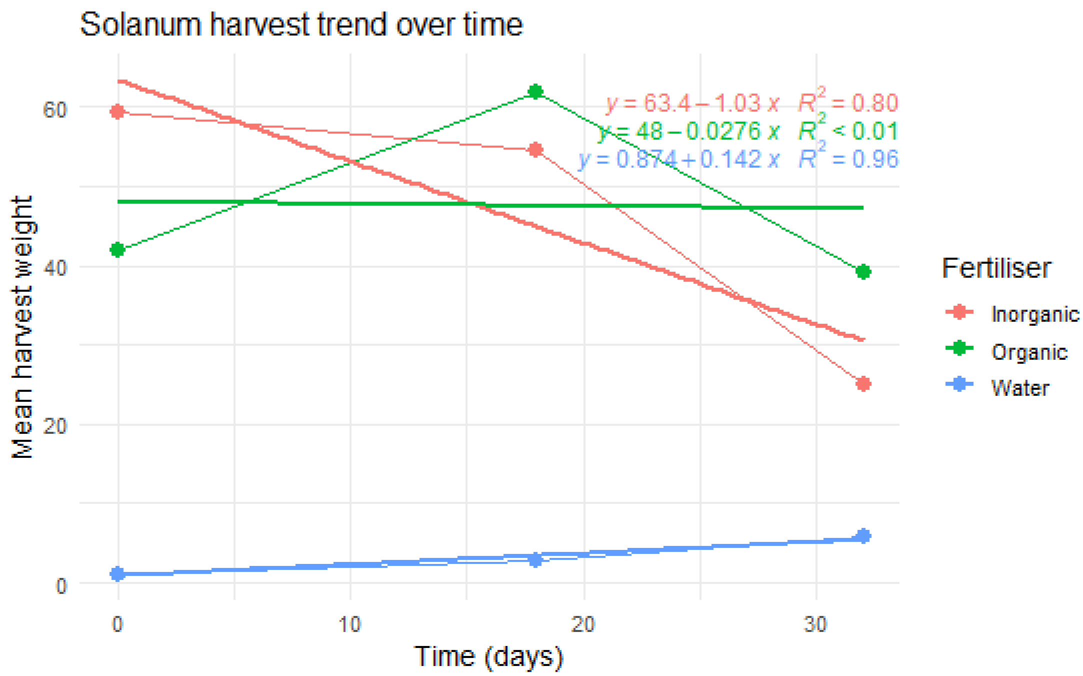
Two-Way ANOVA for Solanum macrocarpon

Parameter	Term	df	statistic	p.value
PLANT HEIGHT	TREATMENT	2	71.72	< 0.001
PLANT HEIGHT	DATE	4	11.55	< 0.001
PLANT HEIGHT	TREATMENT:DATE	8	1.73	9.77e-02
PLANT HEIGHT	Residuals	120		
STEM DIAMETER	TREATMENT	2	49.97	< 0.001
STEM DIAMETER	DATE	4	18.30	< 0.001
STEM DIAMETER	TREATMENT:DATE	8	1.60	1.31e-01
STEM DIAMETER	Residuals	120		
LEAF HEIGHT	TREATMENT	2	68.62	< 0.001
LEAF HEIGHT	DATE	4	6.70	< 0.001
LEAF HEIGHT	TREATMENT:DATE	8	1.32	2.42e-01
LEAF HEIGHT	Residuals	120		
LEAF WIDTH	TREATMENT	2	59.19	< 0.001
LEAF WIDTH	DATE	4	7.54	< 0.001
LEAF WIDTH	TREATMENT:DATE	8	1.88	6.90e-02
LEAF WIDTH	Residuals	120		
NO OF LEAF	TREATMENT	2	104.91	< 0.001
NO OF LEAF	DATE	4	26.63	< 0.001
NO OF LEAF	TREATMENT:DATE	8	3.36	1.66e-03

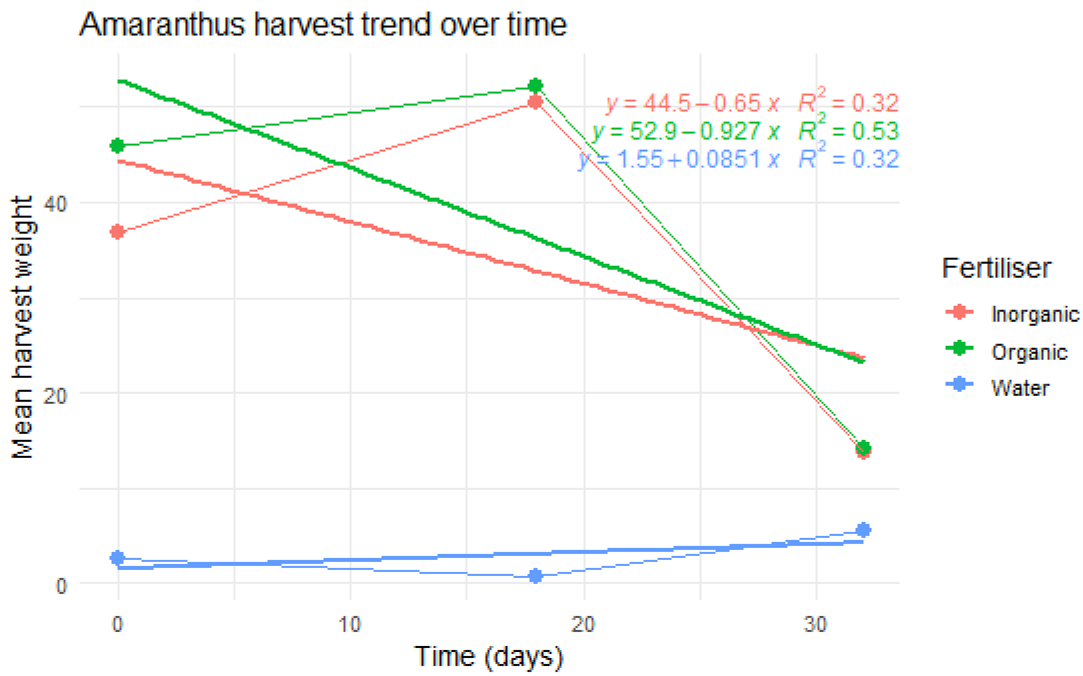
Parameter	Term	df	statistic	p.value
NO OF LEAF	Residuals	120		

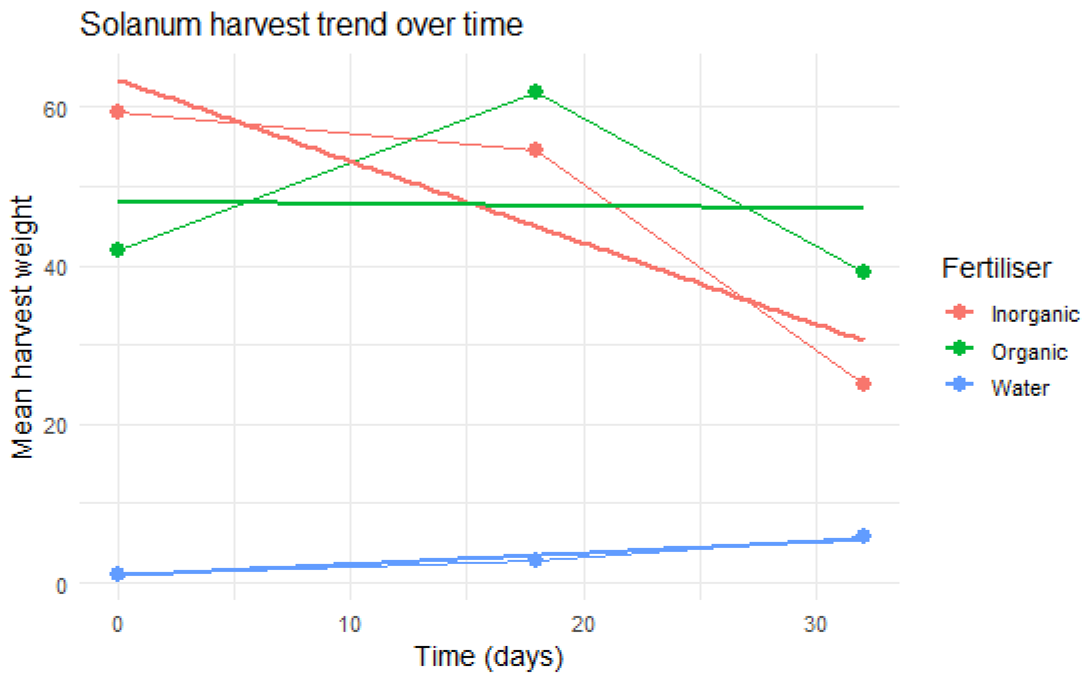
Regression Table

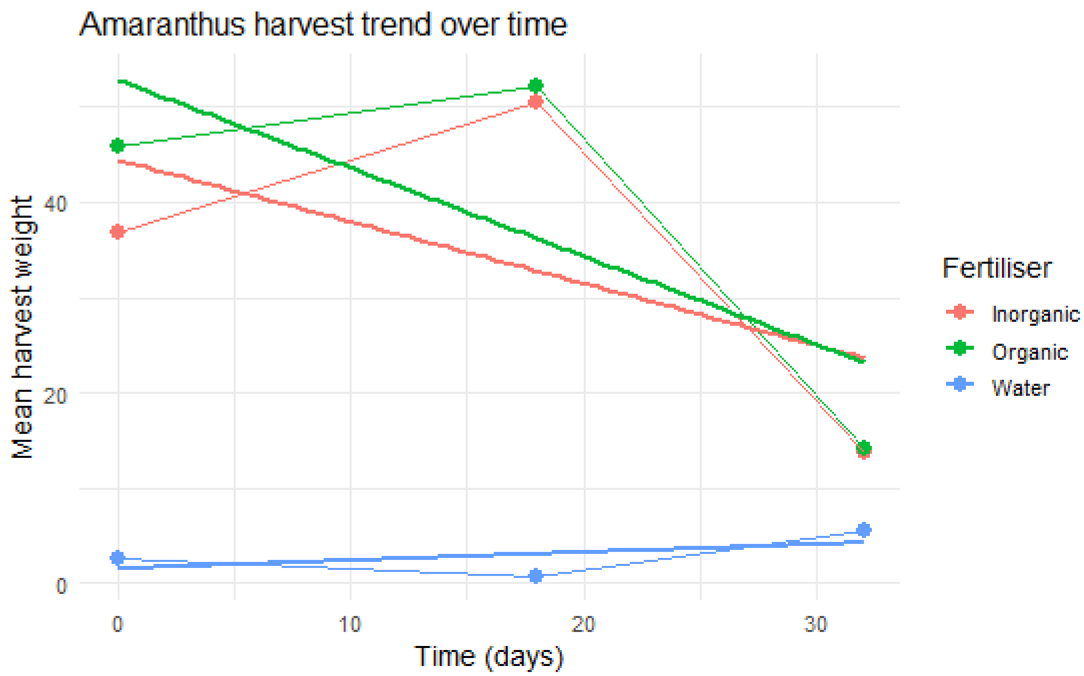
Plant	Fertiliser	a	b	R2	b_SE	b_Statistics	b_p_value	b_CI_low	b_CI_high
Amaranthus	Inorganic	44.4971215	-0.64982729	0.316467502	0.9550211	-0.68043238	0.6196373	-12.784521	11.4848664
Amaranthus	Organic	52.8949338	-0.92702936	0.533553401	0.8667733	-1.06951771	0.4786232	-11.940428	10.0863692
Amaranthus	Water	1.5482729	0.08510363	0.318042690	0.1246189	0.68291101	0.6185600	-1.498330	1.6685370
Solanum	Inorganic	63.4355210	-1.02835348	0.795585495	0.5212605	-1.97282050	0.2986658	-7.651597	5.5948897
Solanum	Organic	48.0161197	-0.02763385	0.001280333	0.7717947	-0.03580467	0.9772158	-9.834215	9.7789471
Solanum	Water	0.8743523	0.14198330	0.959177302	0.0292913	4.84728545	0.1295183	-0.230198	0.5141646



Solanum harvest trend over time
y = 63.4 − 1.03 x R2 = 0.80
y = 48 − 0.0276 x R2 < 0.01
y = 0.874 + 0.142 x R2 = 0.96
Mean harvest weight
Time (days)
0
20
40
60
0
10
20
30
Fertiliser
Inorganic
Organic
Water


Amaranthus harvest trend over time
y = 44.5 − 0.65 x R² = 0.32
y = 52.9 − 0.927 x R² = 0.53
y = 1.55 + 0.0851 x R² = 0.32
Mean harvest weight
0
20
40
0
10
20
30
Time (days)
Fertiliser
Inorganic
Organic
Water


Solanum harvest trend over time
Mean harvest weight
60
40
20
0
0
10
20
30
Time (days)
Fertiliser
Inorganic
Organic
Water


Amaranthus harvest trend over time
Mean harvest weight
40
20
0
0
10
20
30
Time (days)
Fertiliser
Inorganic
Organic
Water

ANOVA Table for Amaranthus

term	Df	Sumsq	meansq	statistic	p.value
Fertiliser	2	19,309.309	9,654.6544	29.89	< 0.001
Date	2	7,883.250	3,941.6248	12.20	< 0.001
Fertiliser:Date	4	5,863.566	1,465.8915	4.54	2.52e-03
Residuals	72	23,255.871	322.9982		

Fertiliser Post Hoc

Fertiliser	Mean	SD	Mean ± SD	Letters
Inorganic	33.666667	28.46050	33.67±28.46	a
Organic	37.444444	24.41994	37.44±24.42	a
Water	2.966667	4.10450	2.97±4.1	b

Fertiliser * Date Post Hoc

Fertiliser	Date	Mean ± SE	df	lower.CL	upper.CL
Water	2025-08-19	2.56 ± 5.99 [a]	72	-9.386720	14.49783
Inorganic	2025-08-19	36.78 ± 5.99 [b]	72	24.835502	48.72005
Organic	2025-08-19	45.89 ± 5.99 [b]	72	33.946613	57.83116
Water	2025-09-06	0.78 ± 5.99 [a]	72	-11.164498	12.72005
Inorganic	2025-09-06	50.44 ± 5.99 [b]	72	38.502168	62.38672
Organic	2025-09-06	52.22 ± 5.99 [b]	72	40.279946	64.16450
Water	2025-09-20	5.57 ± 5.99 [a]	72	-6.375609	17.50894
Inorganic	2025-09-20	13.78 ± 5.99 [a]	72	1.835502	25.72005
Organic	2025-09-20	14.22 ± 5.99 [a]	72	2.279946	26.16450

ANOVA Table for Solanum

term	df	sumsq	meansq	statistic	p.value
Fertiliser	2	34,372.525	17,186.2623	32.65	< 0.001
Date	2	3,755.784	1,877.8920	3.57	3.33e-02
Fertiliser:Date	4	5,261.198	1,315.2994	2.50	5.00e-02
Residuals	72	37,893.500	526.2986		

Fertiliser Post Hoc

Fertiliser	Mean	SD	Mean ± SD	Letters
Inorganic	46.296296	36.447871	46.3±36.45	a
Organic	47.555556	21.343948	47.56±21.34	a
Water	3.240741	4.498654	3.24±4.5	b

Fertiliser * Date Post Hoc

Fertiliser	Date	Mean ± SE	df	lower.CL	upper.CL
Water	2025-08-19	1.11 ± 7.65 [a]	72	-14.133037	16.35526
Organic	2025-08-19	41.78 ± 7.65 [b]	72	26.533630	57.02193
Inorganic	2025-08-19	59.22 ± 7.65 [b]	72	43.978074	74.46637
Water	2025-09-06	2.89 ± 7.65 [a]	72	-12.355259	18.13304
Inorganic	2025-09-06	54.56 ± 7.65 [b]	72	39.311407	69.79970
Organic	2025-09-06	61.78 ± 7.65 [b]	72	46.533630	77.02193
Water	2025-09-20	5.72 ± 7.65 [a]	72	-9.521926	20.96637
Inorganic	2025-09-20	25.11 ± 7.65 [ab]	72	9.866963	40.35526
Organic	2025-09-20	39.11 ± 7.65 [b]	72	23.866963	54.35526

Plate 3.1 INCiTIS Aquaponic Laboratory.

Plate 3.3 Radial flow tank