A SMART CIRCULAR ECONOMY FOR INTEGRATED ORGANIC HYDROPONIC-AQUAPONIC FARMING

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DEDICATION

With heartfelt gratitude, I dedicate this thesis to my parents, family members, and educators whose encouragement and guidance have been indispensable throughout my academic pursuit.

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LIST OF ABBREVIATIONS

Abbreviation	Description
WHO	World Health Organization
CAGR	compound annual growth rate
VF	vertical farming
CE	circular economy
CPS	cyber-physical system
ACT	aerated composting tea
RPD	Rapid Product and Process Development
BSFL	black soldier fly larvae

ABSTRACT

With the global problem of population growth and climate change, current challenges to traditional agriculture include a long-term decline in the available arable land, soil depletion, water scarcity, and food security. To mitigate these challenges, agricultural methods must undergo a significant transformation to become more efficient and environmentally sustainable. Soilless agriculture particularly, vertical farming provides the best possible solution to these growing problems. With the growth of vertical farming, it has been evident that many investors have gone out of business because of high investment costs, high maintenance costs, high energy costs and high labor costs, and high waste generation. This research expanded the integrated organic hydroponic-aquaponic farming system and investigated the feasibility of a zero-waste circular economy to find parameters for the profitability of the system through zero waste and reduced operational costs, byproduct utilization, balancing the capacities, and product selection. The research utilized technology, technical knowledge, and the proposed integrated hydroponic-aquaponic circular model to convert the traditional vertical farming method to a zero-waste circular economy opportunity by using hydroponic plant waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost on the growth of halophyte plants. This study proposes a circular economy model for vertical farming that can contribute to the development of a sustainable agricultural system. The simulation study justified the research objectives and demonstrated the feasibility of the proposed model. The model has the potential to revolutionize the agricultural sector by providing a more efficient and sustainable approach to food production, resource conservation, and economic growth through minimizing waste and maximizing the use of resources. Overall, the results of this study provide valuable insights into the development of a more environmentally friendly and economically viable vertical farming process.

1. INTRODUCTION

1.1 Statement of the Problem

1.1.1 Population Growth

The world's population is projected to reach around 11 billion by the year 2100, making food safety and sustainable agriculture significant problems [1]. Based on the report of the UN, the present global population will continue to grow. To meet the growing worldwide need for food, traditional agriculture is now insufficient. Moreover, the living circumstances and demands for meat, fruit, and vegetable are also expanding [2]. In terms of land usage, cultivation, and food production to fulfill this rising demand of the global population has resulted in food scarcity that is becoming difficult to alleviate [3].

1.1.2 Climate Change

It is important to note that the rapid increase in global temperature will have a substantial impact on agricultural productivity in the next years since 10% of arable land will be abandoned for every degree of temperature increase [4]. Currently, climate change has become a significant concern since it is anticipated that agriculture would be profoundly affected in the next 50 years. Since carbon dioxide is a key impact factor on agricultural productivity, the considerable worldwide rise in carbon dioxide emissions can affect the world economy via the impacts on agriculture's overall output rate. In particular, research by Mulatu et al. for Ethiopia suggests that the effect of CO_2 emissions will reduce the world agricultural GDP since it will diminish agricultural production leading to a decreasing number of trade and non-traded products. It should also be taken into consideration the fact that food travels every day hundreds of miles to fulfill consumer demand from manufacturing regions to metropolitan consumers, generating enormous volumes of CO_2 [5].

To complete the full picture of the climate change challenges, soil degradation caused by extreme floods and droughts is an additional evolutionary process that significantly reduces the rate of growth of plants. Traditional food production techniques have provided humans with food solutions since the dawn of humanity. Over time, new novel techniques were introduced to conventional farming to increase output, cut costs, and reduce the environmental impact of crops. Conventional agriculture appears to have an increasing demand for water since it consumes over seventy percent of the world's available freshwater [3]. Moreover, the restricted soil water-holding capability that emerges from the inadequate mulching of soil and the consistent application of similar fertilizers/soil preparation procedures is a very significant concern in terms of the sustainability of traditional farming's water usage efficiency. According to scientific findings, the continuation of these practices leads to poor moisture in the soil status and inadequate conservation levels in conventional agricultural systems [6].

1.1.3 Limited Arable Land

Agriculture is the primary driver of land use changes, with almost half of the world's habitable area currently dedicated to farming lands [3]. However, the global population continues to grow, putting additional pressure on arable land. Unfortunately, the amount of arable land is decreasing, mainly due to urbanization, soil degradation, deforestation, and climate change. Therefore, it is becoming increasingly challenging to sustainably produce food for the growing population, and traditional farming practices may not be sufficient to meet the demand [7, 8]

1.1.4 Limited Freshwater

Nearly half of the global population would be living in locations of significant water stress by the year 2030, as predicted by the World Health Organization (WHO) study in 2017. One of the crucial future challenges is the freshwater supply [9]. The potential rise in water scarcity and harsh weather may result in lower yields and greater yield variations. These drawbacks will be more prevalent in warmer areas [10]. Given that agriculture uses seventy percent of the total freshwater resources, the growing water scarcity is directly associated with food production [11].

1.1.5 Food Safety

With the effects of global climate change, less developed nations will have to deal with additional food safety issues. For instance, human feces used as fertilizer (estimated at 50 percent of world agriculture) can induce cholera, typhoid fever, and various parasite illnesses [4]. Considering the quick remedy of these types of contagious diseases, even the most industrialized nations confront food security and safety issues today. Notable is the pandemic of COVID-19, caused by the SARS-CoV-2 virus and first detected in China's Hubei and Wuhan provinces. The illness is believed to have started at a fish market in Wuhan where marmots, bats, snakes, and birds were sold. It is known that the coronavirus family may be transmitted between humans and animals. From the study of Zhou et al., 96% of COVID-19's genomic composition is identical to that of the coronavirus prevalent in bats [12]. Therefore, food security is a big concern, since there have been several instances of such occurrences globally in recent years, resulting in billion-dollar losses owing to food shortages caused by bacterial contagious diseases [3].

1.2 Solution Approaches

To accomplish the global problems, agriculture should restructure for solving the issues of growing food while also ensuring ecological safety. For both environmental and human health, the production of nutritious agricultural products has become crucial [20]. Some of the approaches include:

1.2.1 Organoponic Systems

Organoponic systems, or "organopónicos" in Spanish, are a widespread method of farming in Cuba [13]. The term refers to elevated beds containing a mixture of soil and biological waste. This farming approach is most prevalent when the soil fertility is low and there are insufficient chemical inputs. This makes the method suited for developing regions and countries lacking enough infrastructure or availability of fertilizers as well as other inputs. This specific method is highly sustainable since it functions without fertilizer and therefore is related to environmentally favorable practices [14].

1.2.2 Integrated Agriculture

Integrated agriculture might be yet another solution. Zero-acreage Farming, commonly known as ZFarming, was employed by Specht et al. This concept, however, refers to any growing techniques that produce food without using land or outdoor places, like green roofs. The idea of incorporating vegetable cultivation into existing structures is primarily motivated by the need to save resources and improve resource utilization. It is essential to incorporate effective management cycles to reach a high level of productivity. Energy usage, fertilizer distribution, waste management, as well as land utilization are all methods for achieving efficiency. Globally, a variety of greenhouse systems that are extremely effective are now in use [15]. In addition, it may be able to meet the greenhouses' water needs through the use of recycled or collected rainwater. Regarding nutrition and fertilization, organic waste use in the type of waste from animal waste, residues from plants, or food industry or house waste might be considered [16].

1.2.3 Soilless Agriculture

Soilless agriculture might provide a creative resolution for soil infertility and the conservation of water requirements [17]. This necessitates a considerable shift in agricultural practices in the direction of increased agrotechnical input effectiveness and greener agriculture. However, to achieve maximum benefits from soilless agriculture, it is crucial to incorporate sustainable methods including organic farming processes, precision agricultural methods, and agroecology [18]. Therefore, soilless agriculture is gaining appeal among farmers due to its efficiency, productivity, and environmental benefits. The global market for soilless agriculture is projected to reach $16.6 billion by 2025, expanding at an 11.9% compound annual growth rate (CAGR) over the next five years [1]. Especially it is important to ensure that soilless processes have minimal environmental and operational cost impacts. Concerning the issue of nutrient and water losses in soilless farming, closed systems give the highest performance, while open-loop methods are also much more effective than soil farming [7]. It is proven that it is possible to get high-quality soilless plants [19]. However, consumers continue to be skeptical of these goods, mostly because of the idea that soilless production techniques are artificial, originating from unnatural growth, and therefore characterized by inferior internal quality, for example in terms of flavor and nutritional content. In most instances, the presence/absence of soil is the only distinction in both soilless and traditional farming. It is not uncommon for soilless agriculture to be conducted organically.

1.2.3.1 Vertical Farming

Vertical farming (VF) is perhaps the most complicated and futuristic notion of soilless methods [8]. Vertical agricultural production would permit a greater area under cultivation on a comparatively small base area, hence reducing the requirement for vast tracts of arable land. The relative proximity of large-scale food production to customers and the regulated atmosphere throughout the building, which permits better yields, are major benefits [20].

The vertical farming idea of Skyfarming is designed for growing the essential crop which is rice. Germer et al. explored the opportunities and limitations associated with vertical rice growing. For minimal weight, and hence reduced statistical needs, an aeroponic system that supplies nutrient-rich mist to the rice roots is proposed [21]. Mok et al. state that the work by Germer et al. is the only study of its sort that rationalizes the technological restrictions and benefits of Vertical Farming principles [22]. The benefits of vertical farming encompass year-round crop production, control of food miles, the decrease of water usage for agricultural production and recycling process, the reuse of organic waste, reduced fertilizer requirement and pesticide residuals in food, increase in productivity, the mitigation against weather-related changes in agricultural production, the utilization of renewable source and decrease of fossil fuels, and the development of the high-tech 'Green Technology'. Vertical farming might solve a variety of current and pressing issues, including urban unemployment, the promotion, and growth of small to medium-sized businesses, as well as the direct availability of fresh food to city dwellers [2]. The need for new sustainable farming methods is being explored due to sustainability concerns in conventional agriculture, and vertical farming is identified as an underexplored aspect of sustainable food production. A quantitative model was presented in recent studies that evaluated the economic potential of vertical farming systems in a competitive market setting, identifying key factors and assessing the trade-offs between economic and risk aversion potential [23, 24].

The necessity for a large amount of nutritious food to satisfy the increasing demand of the global population underscores the need of adopting new and sophisticated technologies and practices in agriculture that coordinate water and nutrient requirements to achieve maximum production. The new contemporary agricultural system offers various advantages, including water efficiency, higher yield, and the ability to produce crops year-round in a regulated environment [25].

1.3 An Introduction to Vertical Farming

1.3.1 Background

Even though the idea of vertical farming was introduced decades ago, it is currently gaining interest as a solution to both environmental and overpopulation problems. It is the most advanced and technologically sound method of crop cultivation. The ability to precisely manage cultural and environmental parameters enables constant year-round food production via indoor vertical farming. Modern vertical farming utilizes glasshouse-like techniques in which natural sunlight is supplemented with an artificial lighting setup. The concept of vertical farming seems to be quickly growing across Asia, particularly in Japan and China [26].

From an entirely agronomic perspective, vertical farming methods (within such a broad range of options thoroughly detailed by the study of Beacham et al. [27]), primarily increase the number of plants and lessen stress toward the farmland, which is now in danger owing to the loss of usable land as a result of the growth in the urban areas [28]. Additionally, they permit the use of underutilized and unsuited soils for agricultural output within municipalities, abandoned structures, and rooftops. Fresh vegetable production in the urban and suburban areas under enclosed structures increases the food production system's resilience to climatic instability by ensuring local fresh food supply regardless of unanticipated climate fluctuations. Fruit crops, on the other hand, have limited promise since, although being theoretically appropriate for vertical farming, they are constrained by their huge size and their relatively lengthy development cycles.

The construction of buildings (for glasshouses or controlled environmental setups) and the costs of water and energy utilization (particularly for water pumping distribution and artificial lighting) are factors that contribute to the widespread perception that vertical farming systems are expensive and produce a lot of greenhouse gas emissions. However, it has been projected that the use of solar panels could meet the latter two energy needs [27]. To improve output, it is required to lower expenses associated with various technological variables and eliminate the weak areas of crop production, which will become increasingly important in urban agricultural systems. Further study is required on the economic and environmental impacts of vertical farming methods [18].

Regarding agriculture's unsustainable nature, vertical farming can add new food production capabilities to current conventional farming. However, it has its restrictions such as intensive energy needs, technological advancement, regional factors such as public demand for certain food items, information transfer, and agricultural conditions [26]. Nutritive medium is used in vertical farming, including hydroponic, aeroponic, and aquaponic culture techniques [29, 30].

1.3.2 Hydroponic

In hydroponic systems, plants grow without soil in a specific medium or nutrient solution with additional nutrients provided. Only water and fertilizer-containing nutrients are used in hydroponic plant cultivation. Hydroponic plant cultivation has a plethora of benefits, including the lack of soil requirement, better yields, stability, zero nutritional pollution emitted into the atmosphere, and greater water and nutrient usage efficiency owing to controls over nutrient concentration. The output of closed-loop soilless agriculture such as hydroponic farming increases by about 5% in comparison to the open systems, according to earlier research [31-33].

Growing plants without soil paves the way for an in-depth investigation into alternative agricultural methods and their promotion [34].

Simple settings to extremely complex ones are all possible with hydroponic systems, which are incredibly beneficial [35]. The plant roots are immersed in nutritional solution using this procedure, and the solution's chemical properties are constantly checked and maintained. Better yield capacity, fewer soil-related cultivating issues (both abiotic and biotic), less usage of pesticides and fertilizers, and improved water and nutrient efficiency are only a few of the key benefits of hydroponic systems [26, 35].

Hydroponically produced plants can include flowers, climbers, herbs, and vegetables. The use of inert material, including coconut fibers, rock fragments, etc., is necessary for hydroponically grown plants. All nutrients and minerals are present in the nutrition solution that is supplied to the plants. From basic settings to modern design, this strategy is quite helpful for the cultivation process [35]. Vegetables are cultivated in hydroponic systems in water containing the nutrients and minerals the plants require. This enables precise nutrition delivery and dose. It's interesting to note that urban agriculture and hydroponics specifically had their origins in times of crisis [36].

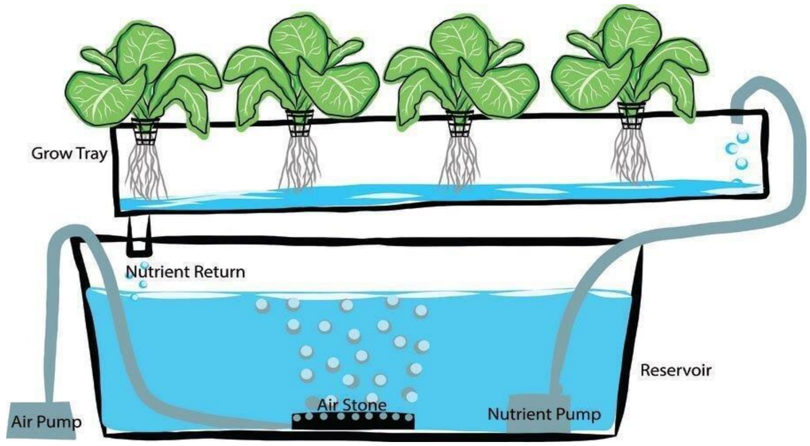


Figure 1. Hydroponic [37]

1.3.3 Aeroponic

A type of hydroponics known as aeroponics grows plants by spraying them using nutrient-rich water rather than employing any type of growing medium at all. In this technique, plant roots are put in a dimly lit container, and at regular intervals, a nutrient-rich solution is sprayed upon the roots. Fast plant growth, simplicity of maintenance, flexibility concerning area, and a reduced need for fertilizers and water are the key benefits of this system [35].

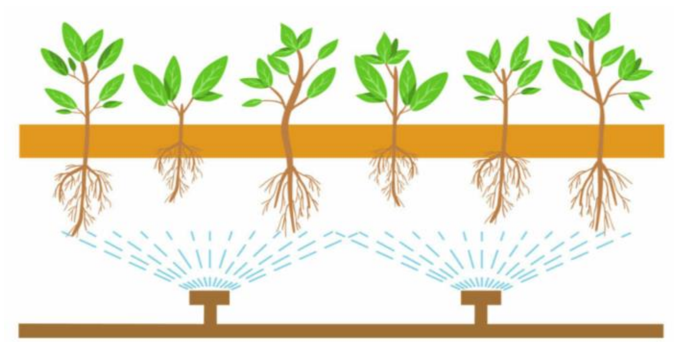


Figure 2. Aeroponic [38]

1.3.4 Aquaponic

A steady aquatic environment with little variation in ambient nutrients, as well as oxygen levels, is maintained by an aquaponic system, which depends on the integrated interaction between the plants and the animals. In other words, aquaponics is the union of hydroponics, or the soilless method of growing plants, and aquaculture, or the practice of producing fish. Excreta from fish raised in indoor reservoirs is used to create nutritionally rich water solutions, which are the source of nutrients for plants in vertical farming. In turn, the plants clean and filter the recycled water [26]. Plants that are developing are fed organically by fish excrement, and the plants themselves act as the natural filters for water that fish dwell in. The microorganisms (nitrifying bacteria) as well as compost of red worms that flourish in the growth medium constitute the third group of contributors. These microorganisms transform the ammonia inside fish waste into nitrites, then on to nitrates, and the sediments into compost, which the plants use as food [35]. Farmers can reduce the cost and labor associated with fertilizing plants in this way [39].

It has several advantages, including water conservation due to water recyclability via biological filtration as well as recirculation, reduction of the need for synthetic fertilizers, efficiency, and cost-effectiveness because waste products from one biological system act as nutrients for another, provision of organic liquid fertilizer application that assure healthy plant development and water cleaning for fish habitat [26].

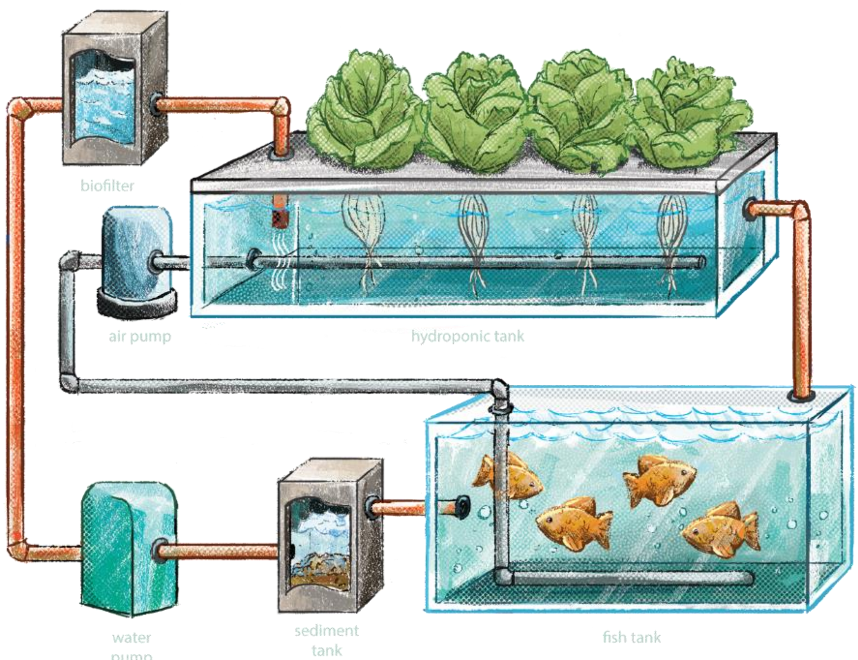


Figure 3. Aquaponic [40]

The key benefits of these contemporary farming methods are their increased productivity and water saving. Except for the fact that hydroponics and aeroponics both require the addition of fertilizer and that there are no fish in the nutrient solution, all three techniques may be used to grow plants in raised beds. Aquaponics is a method of growing plants and fish in a mutually beneficial relationship where the fish provide food for the plants as well as the plants clean and filter the fish's surroundings. All the technologies are built on hydroponic systems, which is also the simplest for the setup. It may subsequently be modified to make an aquaponics arrangement. But aeroponics demands additional upkeep and consideration when constructing a partially to completely controlled environment. In contrast to traditional agriculture, all three technologies boost water usage efficiency while reducing water loss [35].

1.4 Research Gap

Soilless agriculture particularly, vertical farming has not been fully successful so far in finding solutions to issues such as expensive land and construction costs [41], high operating costs owing to electricity consumption [42], high labor costs [43], site preferences, concerns around USDA organic products, and small variations in crop species [26]. With the growth of vertical farming, it has been evident that many investors have gone out of business because of high investment costs, high maintenance costs, high waste generation [44], and high energy costs [45].

1.5 Focus of the Research

The focus of this research was to evaluate different methods and add/modify the sequence of processes and alternatives of a circular economy to achieve zero waste and make the VF and its supplementary processes financially viable for the farmers. This research assessed all components of a circular economy model, evaluates byproducts, studied the balancing of resources and capacities in each stage, and select high value-added products to achieve the minimum cost/highest profitability. The study strives to find answers to the following research questions:

1. What is the full concept of a circular economy in vertical farming?

2. What are the various components, parameters, and alternatives involved in each stage of the

vertical farming circular economy?

3. How can the circular economy concept be implemented in vertical farming and what performance measures should be used to assess its effectiveness?

4. Is there a significant difference in the performance of aquaponic processes with and without the use of black soldier fly larvae (BSFL)?

5. Apart from BSFL, what other factors contribute to growth variation in aquaponic setups?

6. Is the location of the growth area a significant factor in the performance of the aquaponic setup?

7. What is the growth comparison among hydroponic, aquaponic (with BSFL), and aquaponic (without BSFL) setups?

8. What is the flow of value-adding components in the circular economy of vertical farming?

9. How can a circular economy model be developed for vertical farming?

10. What are the optimal settings and capacities required in each stage to achieve balance and minimize waste in the circular economy of vertical farming?

The research questions that frame this study are addressed in each respective chapter depending on their relevancy. Chapter 2 provides a detailed exploration of the circular economy concept in vertical farming, addressing questions 1 and 2. This chapter provides a comprehensive understanding of the circular economy concept in vertical farming. Chapter 3 focuses on the implementation of the circular economy concept in vertical farming and discusses the performance measures that should be used to evaluate its effectiveness, which corresponds to question 3. This chapter examines how the circular economy model can be applied to vertical farming systems and identifies key indicators that can be used to evaluate its performance. Chapter 4 investigates the impact of black soldier fly larvae (BSFL) on the performance of aquaponic processes and examines other factors that contribute to growth variation in aquaponic setups, which aligns with questions 4-6. In this chapter, the growth comparison among hydroponic, aquaponic (with BSFL), and aquaponic (without BSFL) setups is evaluated, corresponding to question 7. Chapter 5 analyzes the flow of value-adding components in the circular economy of vertical farming, answering question 8. Chapter 6 develops a circular economy model for vertical farming and identifies the optimal settings and capacities required in each stage to achieve balance and minimize waste, which corresponds to questions 9 and 10. This chapter explores how the circular economy model can be applied to different types of vertical farming systems and identifies key factors that need to be considered in developing an effective circular economy model.

2. CIRCULAR ECONOMY FOR VERTICAL FARMING

2.1 Research Questions

Circular economy (CE) is a concept based on sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products. This chapter is trying to address the research gap in vertical farming by proposing and validating a circular economy in vertical farming to address the following research questions:

1. What is the full concept of a circular economy in vertical farming?
2. What are the various components, parameters, and alternatives involved in each stage of the vertical farming circular economy?

2.2 What is Circular Economy Concept?

The circular economy concept refers to an economic framework that aims to produce the least amount of waste possible while maximizing the use of resources. The idea of a circular economy has been influenced by some interconnected concepts, including loop closing, ecological design, industrial environment, industrial symbiosis, analysis of life cycle, as well as economic performance [46]. The circular economy idea seems to be fundamentally a shift in the environment brought about by the requirement for the ecological economy that demands human commercial activities to be following 3R's principles of reducing, reusing, and recycling [47, 48]. When it comes to extending the product life that has achieved the end of the functional or physical usefulness and could otherwise be discarded, the concept of circular economy (CE) and its three R principles are completely consistent [49]. This enables economic development and ecological safety. The recycling process begins when a product has reached the end of its useful lifetime and would have otherwise been discarded. This idea implies that a circular business model based on the reuse, recycling, or repair of resources and goods should be employed instead of the traditional take-make-waste paradigm. Closed material loops, which imply that resources are utilized further as bulk material, goods, or components, are a requirement for the circular economy concept [50].

2.3 Methodology

The method to answer these two above questions in section 2.1 was the development of a cyber-physical system (CPS). In this chapter physical infrastructure and equipment (i.e., processes and resources), entities (i.e., material, energy, and value), and capacity (i.e., capacity, process speed, batch size) were designed, implemented, measured, and demonstrated. The Cyber (virtual) model part will be explained in Chapter 6.

This research utilized technology, technical knowledge, and a new integrated hydroponic-aquaponic circular model to expand the conventional vertical farming method to a circular economy ecosystem (proposed by Dr. Asiabanpour in BlueWater, USDA Grant Number 2020-38422-33097) [51]. All aquaponic and hydroponic system components (e.g., water, plants, nutrients) operate in a closed circular loop pattern and any portion of the waste will be used or converted to a value-added entity. Figure 4 illustrates the proposed model where several value-added processes were added to the organic integrated hydroponic and aquaponics to form a zero-waste circular economy.

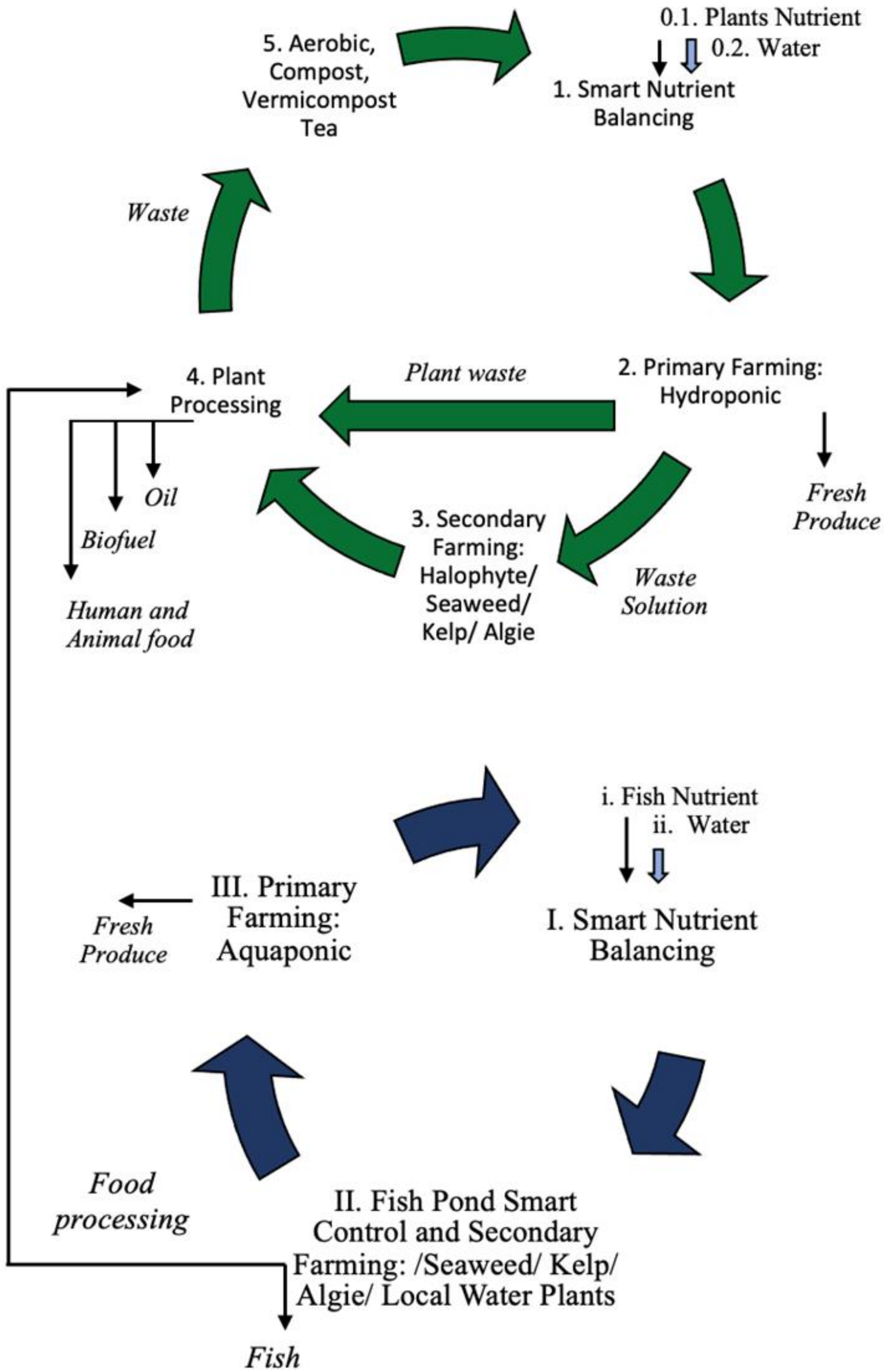


Figure 4. Proposed circular economy model for VF-based farming [USDA Grant Number 2020-38422-33097] [51]

2.4 Composting Process

The circular economy (CE) aims to reduce waste by implementing composting methods that allow for the recycling of organic waste back into the system. In this study, several composting methods were employed, including vermicomposting, aerobic compost, and quick compost to convert organic waste materials into nutrient-rich soil amendments. These methods promote the breakdown of organic waste materials through the use of microorganisms, worms, and other organisms, resulting in the production of compost, which can then be used to enrich the soil for plant growth. By utilizing these composting methods, the amount of organic waste can be reduced to minimize greenhouse gas emissions and create a closed-loop system that promotes sustainability and resource efficiency.

2.4.1 Vermicompost Tea

The waste products of earthworms, known as vermicompost, can help the health and nutritional condition of the soil. All forms of biodegradable wastes, including those from farms, kitchens, markets, agro-based enterprises, animals, and other sources, are transformed into nutrient-rich vermicompost throughout the vermiculture process. The technique known as vermicompost uses vermi worms as biological agents for consuming such wastes and depositing excreta [52]. The qualities of the source material affect the total amount of nutrients in vermicompost [53, 54]. Even so, vermicompost generated using the same source material often contains greater levels of micronutrients and macronutrients than regular compost [55-58]. This is because although microbes are primarily responsible for the decomposition of raw materials, earthworms can also have an impact on the process by directly feeding upon the microorganism [54, 59]. The interaction involving earthworms and related microbes results in the vermicompost process [60, 61]. In comparison to other forms of composts, vermicompost often has a finer structure, more nutrients, and better microbial growth. In the field and greenhouse, vermicompost has been found to boost crop yields and growth [62-66].

Vermicomposting is indeed a straightforward biotechnological method of composting that makes use of specific species of earthworms to speed up the waste-to-product conversion process. There are various ways that vermicomposting varies beyond composting [67]. This is a mesophilic technique that employs the use of earthworms and microorganisms that are active between 10 and 32 degrees Celsius. The procedure is quicker than composting, and since the content goes along through the earthworm's gut, a substantial but inexplicable transition occurs, leading to the production of earthworm castings (also known as worm manure), which are high in microbial activities, plant development regulators, as well as pest repellent properties [52]. Because of the earthworms' digestion and fragmentation, raw material that has undergone vermicomposting is often more granular in form and has a larger surface area [54, 68, 69].

Vermicompost tea is produced by combining vermicompost with water and then allowing it to ferment for a specific amount of time [70, 71]. Compost tea is divided into two categories: aerated and nonaerated. Nutrients as well as microorganisms are removed from compost during the steeping process in water. When microorganisms are present, insoluble nutrients are transformed into simpler compounds, and this availability of nutrients fosters a wide variety of organisms inside the brewing process of vermicompost tea. Both aerated and non-aerated techniques of making vermicompost tea require brewing mature compost with water for a specific amount of time and need to be filtered before being applied to plants [72].

Vermicompost tea is a nutrient-rich, organic liquid fertilizer that is produced by steeping vermicompost, or worm castings, in water. It is a highly effective way to boost soil health and plant growth, and it is widely used in organic farming and gardening. For the proposed circular economy model, the vermicompost tea was produced in-house, using a special vermicomposting setup. This setup involved using earthworms to break down organic waste materials, such as food scraps and yard waste, into nutrient-rich vermicompost. This vermicompost was then mixed with water to produce the vermicompost tea.

The use of in-house produced vermicompost tea in the circular economy system is an environmentally sustainable and cost-effective way to provide plants with essential nutrients, while also reducing waste and promoting soil health. This is an important aspect of the overall circular economy approach, as it allows for the reduction of dependence on external inputs such as chemical fertilizers.

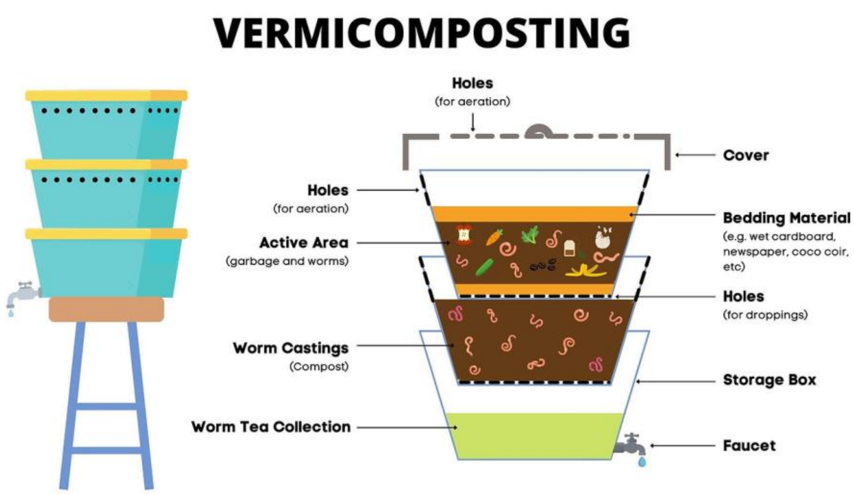


Figure 5. Vermicomposting setup [73]

2.4.2 Aerobic Compost

Composting is perhaps a biochemical process that transforms different elements of organic waste into reasonably stable humus-like compounds that may be utilized as either an organic fertilizer or soil supplement [74]. Aerated composting tea (ACT) is made from aerobic compost, which is floated under aerated water for 24-72 hours in a permeable bag or filter [75, 76]. To encourage the development of aerobic microorganisms, the main extract is often modified using nutrients [77]. ACT is sprayed on fruits, leaves, and/or soil to improve crop health and is commonly used by a limited segment of horticulture growers [78].

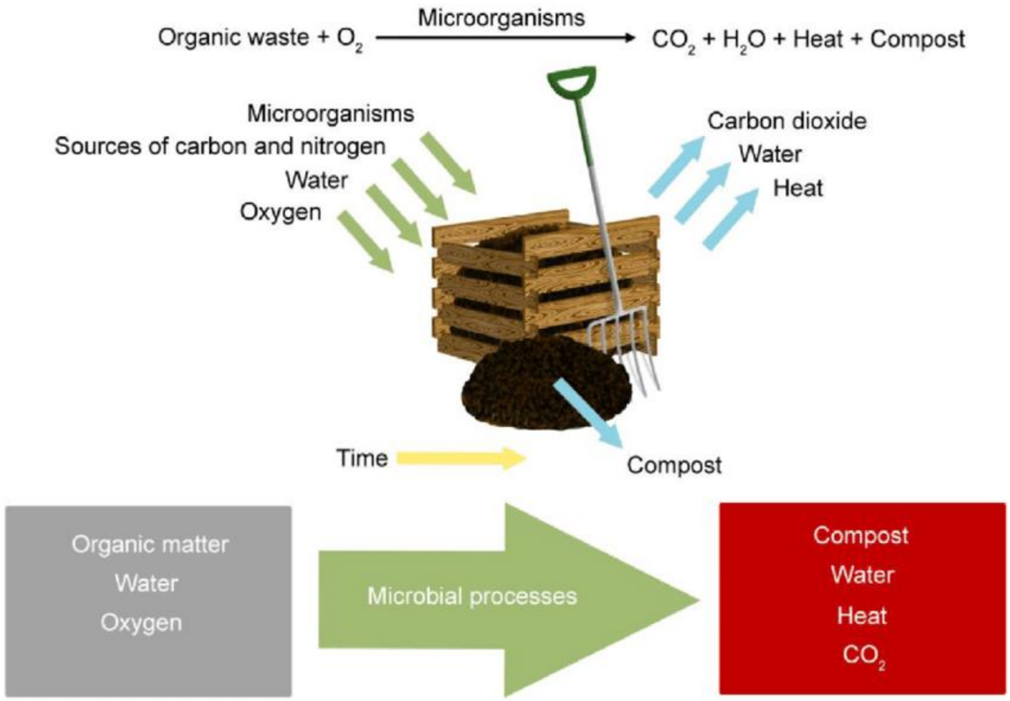


Figure 6. Aerobic composting principles [79]

Aerobic compost tea is a liquid fertilizer that contains a high concentration of beneficial microorganisms. Tea is created by extracting microorganisms from compost or other microbial sources and brewing them in a nutrient-rich solution. In this study, TeaLAB's complete brew kit [80] was utilized to create aerobic compost tea. The kit provided a convenient and efficient method for brewing tea. For each brewing, 2 gallons of water were used along with 2 cups of compost or microbe source. In addition, 1/8 cup of fish hydrolysate powder or microbe food was added to provide essential nutrients for the microorganisms. The resulting tea was rich in beneficial microorganisms that can help to improve soil health and plant growth. This method of compost tea brewing offers a sustainable approach to plant nutrition that can improve the overall health and yield of plants while reducing waste and environmental impact.

2.4.3 Quick Compost

In the circular economy system, a quick compost setup was implemented to efficiently process food or plant waste into nutrient-rich soil amendments. To achieve this, the Vitamix FoodCycler FC-50 [81] was used, which has a 2L capacity and can reduce the volume of food waste by up to 90%. This device is easy to operate and has a processing time of 4-8 hours while reaching temperatures as high as 158°F [82]. By using this method, it was feasible to divert a significant amount of waste from landfills and convert it into a valuable resource that can be used to enhance soil health and support plant growth.

Figure 7. Quick compost tea setup (Vitamix FoodCycler) [83]

2.5 Secondary Farming Process

Secondary farming is a sustainable agricultural method that utilizes different types of plants to maximize the use of resources and minimize waste. In this circular economy system, resilient plants were used that can grow in harsh conditions and nutrient-poor soil to consume the waste materials generated by the aquaponic and hydroponic systems. These plants were carefully selected for their ability to take up excess nutrients such as nitrogen and phosphorus, thus preventing them from becoming pollutants.

Through the use of secondary farming, the proposed circular economy system was able to reduce waste and increase the efficiency of resource use. By utilizing resilient plants that can grow in harsh conditions and consume excess nutrients, the system was able to transform waste into valuable products such as oil, compost, or human or animal food, creating a more sustainable and self-sufficient agricultural system.

2.5.1 Halophyte

One of today's most pressing worldwide issues, especially in desert areas, is obtaining sufficient land and water to meet the world's expanding demands for food. In general, agricultural fields in semi-arid and dry locations struggle with soil salinity. 37% of the farmed land on the planet is sodic, while 23% is saline. A third of the world's irrigated land is salt affected, primarily because of unsustainable irrigation systems. In many locations, salinity levels are continuously rising due to existing agricultural irrigation techniques, which are also fast depleting freshwater supplies. The already limited freshwater resources are being used more and more for drinking as a result of the pressure from the rapidly growing population. The development of non-traditional agricultural technology that might more efficiently use marginal, salty, and degraded land for agriculture by employing “so-called” low-quality water (such as wastewater and saltwater) has become necessary in this complicated situation [84].

Halophytes, plants that live in soil or water that are highly saline, have emerged as a significant choice in this circumstance. Plants such as halophytes can endure high salinity levels and may naturally live in salt-contaminated ecosystems [85]. They are highly specialized and developed organisms with well-suited physiological and morphological traits that enable them to thrive in soils with high salinity levels. Halophytic plants cover around 1% of the world's total flora. These are mostly found in dry and semi-arid interior regions as well as highly saline wetlands near subtropical and tropical coastlines [86].

These plants might be used to restore heavily salinized soils and to effectively use salt water. However, for saline agriculture to be profitable, it must meet two requirements. The first need is that it must grow productive crops with yields sufficient to cover the cost of pumping saline water. Second, researchers need to create effective agronomic methods for sustainably cultivating salty, water-irrigated plants. Additionally, these techniques must not do additional harm to the ecosystem. If successfully implemented, this strategy would result in the wild salt-tolerant plant domestication to be used as foods, forage crops, as well as oilseeds [84].

In the circular economy model, a secondary farming setup was incorporated using a diverse range of resilient plant species. Different types of seeds were utilized to cultivate plants capable of consuming and converting waste materials into valuable products. These seeds were carefully selected based on their hardiness and ability to grow in harsh conditions with minimal nutrient requirements.

By incorporating secondary farming into the proposed circular economy model, the aim was to enhance resource efficiency and reduce waste while generating additional benefits such as biofuels, feed for livestock, and medicinal plants. The use of resilient plant species in secondary farming provides an opportunity to increase food production and improve agricultural sustainability, especially in areas facing environmental challenges such as water scarcity and soil degradation.

Overall, the utilization of different types of seeds in the secondary farming setup is an important component of the circular economy system that contributes to enhancing the overall sustainability of the existing agricultural practices.

Table 1. Halophyte seed information

SL No	Commercial Name	Scientific Name	Maturity Size	Time to mature	Used in the experiment number
1	Alfalfa	Medicago sativa	24-35” [87]	4-8 years [88]	I, II
2	Winter Purslane	Claytonia perfoliata	10-20” [89]	42 days [90]	I, II
3	Purslane	Portulaca oleracea sativa	6-12” [91]	50 days [92]	I, II
4	Saltbush	Sarcobatus vermiculatus	3-5’ [93]	30-60 days [94]	I
5	Shadscale Saltbush	Atriplex confertifolia	1–3’ [95]	130 days [96]	I
6	Herb Saltwort	Salsola komarovii	12” [97]	55 days [98]	I, II
7	Lemongrass	Cymbopogon	2-4’ [99]	75-100 days [100]	II
8	Switchgrass	Panicum virgatum	2½-5’ [101]	3 years [101]	II
9	Starwort	Callitriche stagnalis	12” [102]	2 years [103]	II
10	Winter Rye	Secale cereale	20-48” [104]	90 days [105]	II
11	Vetiver	Chrysopogon zizanioides	8’ [106]	1-3 months [107]	II

Alfalfa, scientifically known as Medicago sativa, is a perennial flowering plant from the Fabaceae family that has gained significant importance as a forage plant in many countries worldwide [108]. It is used for hay, silage, cover crop, and as a source of green manure. On the other hand, the winter purslane (Claytonia perfoliata) is an easy-to-grow plant from herb seeds, native to the west coast of North America, rich in vitamin C, and known for its ability to prevent scurvy [89]. It has been used for culinary and medicinal purposes. Another plant called purslane (Portulaca oleracea sativa), also known as green purslane, is a perennial herb that is incredibly healthy and easy to cultivate [91]. Since ancient times, it has been grown in herb gardens in Europe. Its oval, juicy, sweet-sour leaves with a moderate taste are perfect for salads and taste fantastic with the stems. Saltbush (Sarcobatus vermiculatus) and shadscale saltbush (Atriplex confertifolia) leaves are valuable winter feed for both domestic animals and local herbivores in the form of leaves and fruits [95]. Furthermore, herb saltwort (Salsola komarovii) is a common culinary plant in Japan. It is a native of Japanese salt marshes and is famous for its lengthy and succulent leaves with a crunchy texture, making it highly attractive. It thrives in less salty soils, and the young delicate leaves are used in sushi and salads, while the larger stems can be steamed to make a delicious and nutritious side dish [98]. Lemongrass (Cymbopogon) is a fragrant, evergreen grass that grows in clumps and is commonly used in cooking in Southeast Asian countries. Its leaves and essential oil have been used for medicinal purposes for many years [99]. Meanwhile, switchgrass (Panicum virgatum), one of the common native prairie grasses of North America, is an ornamental grass and is also employed for soil conservation to prevent erosion. It is commonly used as forage or hay for cattle and has been explored as a potential biofuel [101]. Starwort (Callitriche stagnalis), which is also native to North America, Europe, and Asia, grows in shallow waters and provides valuable habitat for reptiles and amphibians [102]. Winter rye (Secale cereale) is a useful crop for taking up excess nitrogen, improving soil structure, suppressing weeds, and providing erosion control [105]. Finally, vetiver (Chrysopogon zizanioides), native to Asia but widely cultivated in tropical and subtropical regions, is known for its tolerance to disturbance and its ability to prevent soil erosion [106].

2.6 Infrastructure Implementation

2.6.1 Farming Facility

The experiment was set up in the Texas State University Greenhouse facility (Figure 8).

Figure 8. Texas State University Greenhouse facility

2.6.1.1 Hydroponic Process

The hydroponic process used in this circular economy model was an Ebb and Flow system that was employed in experiment I, which started on September 28, 2022. This process was able to grow a total of 30 pots of plants and was carefully monitored and maintained to ensure optimal growth conditions for the plants. In experiment II, which began on February 16, 2023, 24 plants were selected for each of the aquaponic setups to maintain consistency and fairness in the comparison of growth patterns between the hydroponic and aquaponic systems. This ensured that the results obtained from the experiments were accurate and reliable, providing valuable insights into the efficacy of different feeding mechanisms for growing halophytes in a circular economy system. Details of the process are illustrated in Figure 9.

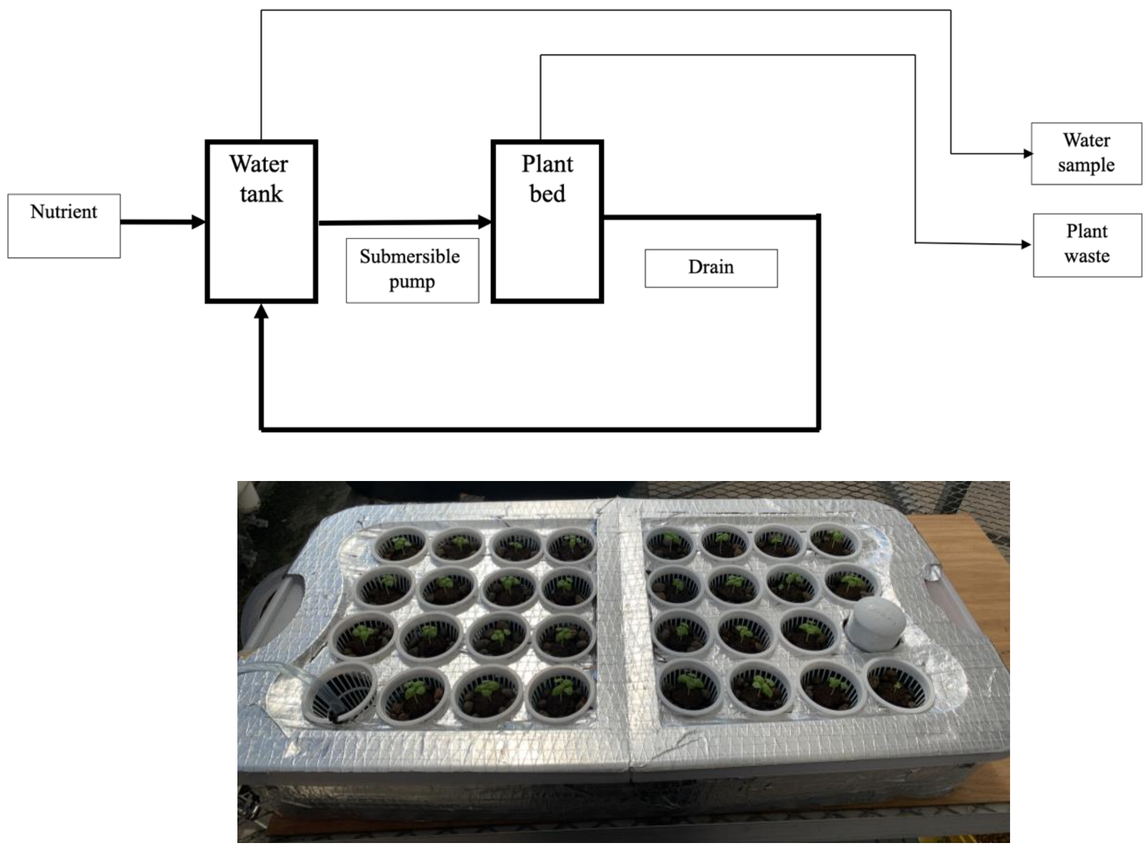
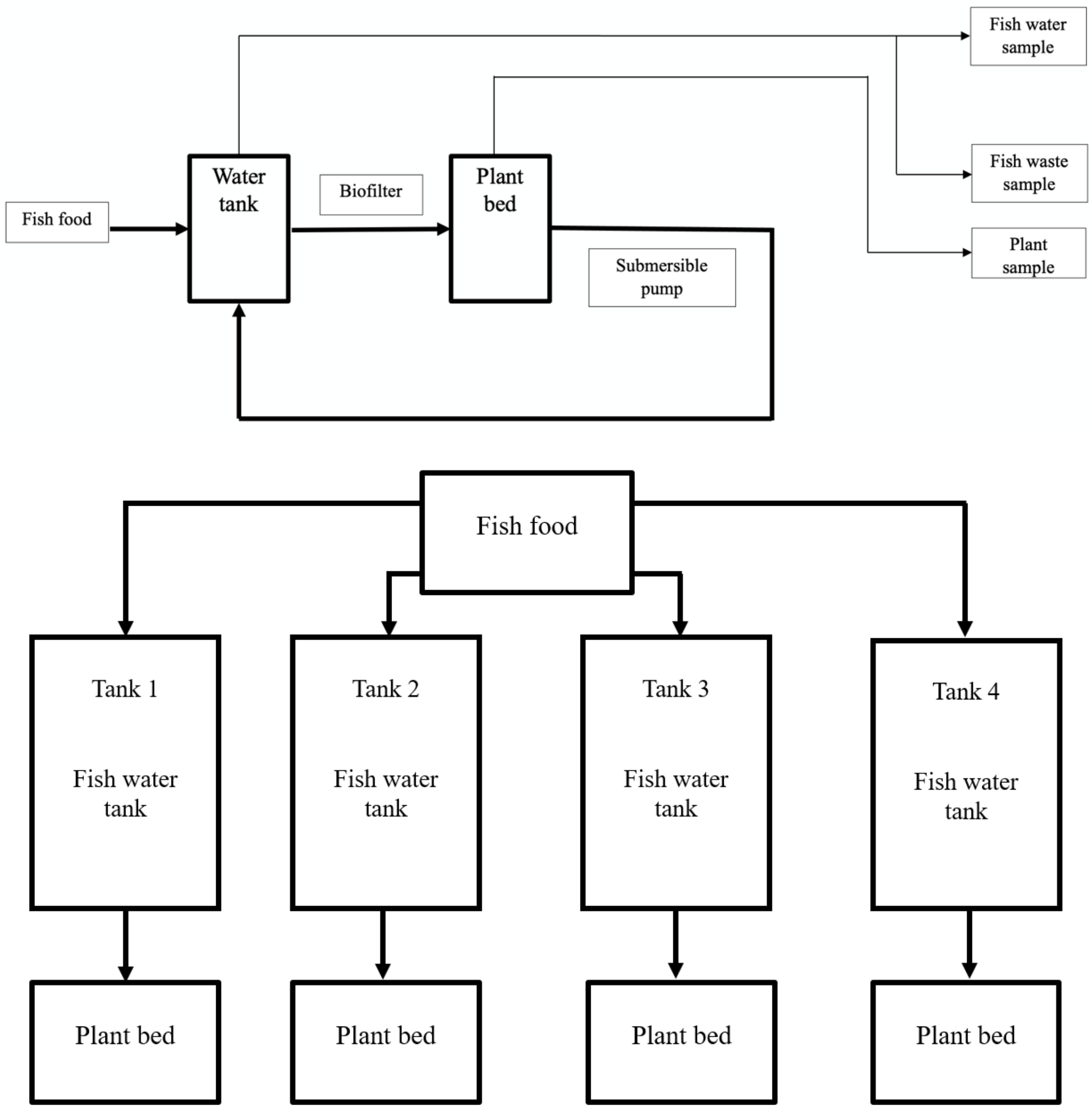


Figure 9. Hydroponic process layout

2.6.1.2 Aquaponic Process

The aquaponic process used in the proposed circular economy model was a closed-loop system that combined aquaculture and hydroponics. In this process, the waste generated by the fish was used as a nutrient source for the plants. The process included two main components: the fish tank and the plant bed. The fish tank contained the fish, and their waste was circulated through the plant bed by a pump. The plant bed was filled with plants. The water from the fish tank was pumped into the plant bed, where the plants absorb the nutrients from the fish waste. Furthermore, the aquaponic process is a sustainable and environmentally friendly method of food production, as it reduces the need for synthetic fertilizers and pesticides and minimizes the impact on the environment. Overall, the use of aquaponic processes in circular economy models is a promising approach to sustainable food production that has the potential to address some of the major challenges facing the global food system.

For both experiments I and II, the aquaponic process was able to grow 96 pots of plants. Details of the process are illustrated in Figure 10.



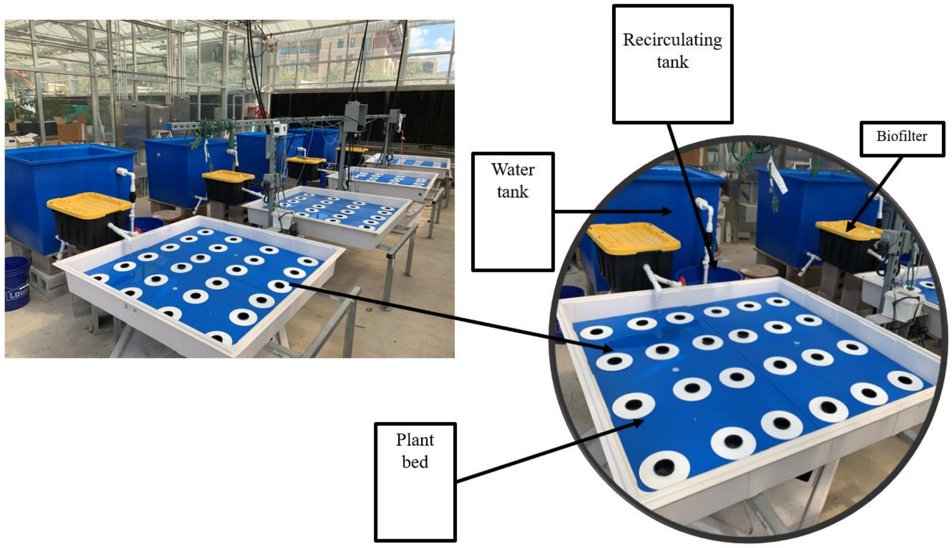


Figure 10. Aquaponic process layout

2.6.1.3 Secondary Farming Process

To further explore the potential for a circular economy in vertical farming, a secondary farming setup was implemented using containers to grow halophyte seeds. The setup consisted of four distinct sections, each receiving a different type of feeding: hydroponic waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost. The goal was to evaluate the feasibility of using these byproducts as nutrients for secondary crops, while also diverting waste from the main VF system.

The introduction of this secondary farming system aimed to investigate and identify potential opportunities for reducing waste and recovering resources in the vertical farming system. Additionally, the performance of halophyte crops in this context was evaluated to determine their suitability and potential benefits for the overall system. By implementing this system, the research sought to further advance the circular economy model of the vertical farming system and explore ways to improve its sustainability and efficiency.

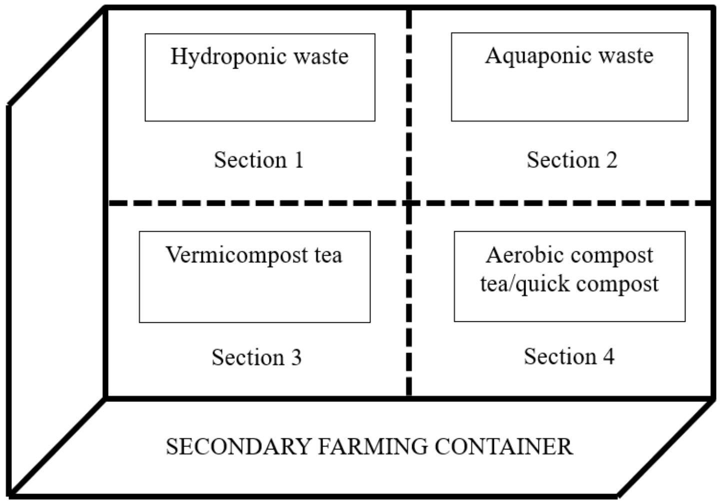


Figure 11. Secondary farming setup layout

2.6.2 Compost and Value-added Processing Units

The compost and value-added processing units play an important role in the proposed circular model for vertical farming. The Rapid Product and Process Development (RPD) center, as shown in Figure 12, is equipped with various units such as quick composting, distilling, cold oil extractors, hot oil extractors, and others to support the efficient utilization of byproducts and the production of high value-added products.

Quick composting is a process that rapidly breaks down organic waste into nutrient-rich compost within a few weeks. This process is achieved through the use of microorganisms and is an essential component of the circular economy model proposed in this research, as it allows for the efficient utilization of hydroponic and aquaponic waste. Distilling is a process that separates components of a mixture by heating and cooling, commonly used in the production of oils. This process can be used to extract essential oils from plants, which have high-value applications in the food, cosmetic, and fragrance industries. Cold oil extractors, on the other hand, are devices used to extract oil from plants without heat, often used in the production of high-quality edible oils. This method is considered to be more efficient and produces higher-quality oils than traditional heat-based extraction methods. Hot oil extractors and stillers are similar devices that use heat to extract oil from plants and separate the oil from any remaining plant material. These devices are commonly used in the production of essential oils or biofuels.

The RPD center provides an essential infrastructure for the production of value-added products from byproducts generated in the hydroponic and aquaponic systems. The use of these processing units in the circular model proposed in this research contributes to the efficient utilization of resources and reduces waste, while also generating additional revenue streams for the vertical farm.

Figure 12. Quick compost tea setup at Texas State University Rapid Product and Process Development (RPD) center

2.7 Discussion

The circular economy concept is a key focus of this chapter. The research questions aim to understand how a fully circular economy can be implemented in vertical farming and what components, parameters, and alternatives are needed for each stage of the VF circular economy. The circular economy concept is an economic framework that aims to produce the least amount of waste possible while maximizing the use of resources. The three R principles of reduce, reuse, and recycle are central to this concept. The circular economy paradigm proposes a shift from the traditional take-make-waste model to a closed material loop approach, which implies that resources are utilized further as bulk material, goods, or components.

To answer the research questions, the method utilized is the development of a cyber-physical system (CPS). The physical infrastructure and equipment, entities, and capacity were designed, implemented, measured, and demonstrated. The proposed model used aquaponic and hydroponic systems that operated in a closed circular loop pattern, where any portion of the waste was used or converted to a value-added entity. Different composting methods were envisioned in the circular economy to prevent any previous material from leaving the system as waste. Vermicompost tea, aerobic compost, and quick composting were utilized in this model. The secondary farming approach utilized resilient plants, such as halophytes, to consume waste materials in the system and convert them to valuable products. Halophytes were utilized in this study, and their ability to grow in harsh conditions and nutrition makes them ideal for converting waste materials into value-added products.

The proposed model, which incorporates the circular economy and secondary farming approach, demonstrates the feasibility of zero-waste vertical farming. By designing and implementing a closed-loop system, the model showed how a circular economy can be applied to vertical farming, reducing the environmental impact of agriculture while maximizing the use of resources. The circular economy approach has the potential to revolutionize the way of thinking about agriculture and sustainability, and the model presented in this chapter provides a promising example of how it can be done.

In addition to the proposed model, it is important to consider the economic and social implications of implementing a circular economy in vertical farming. Although the benefits of a circular economy are numerous, there may be challenges in implementing such a system on a large scale. For example, the initial costs of setting up a closed-loop system may be high, and there may be limitations on the availability of certain resources needed for the system to function effectively.

Furthermore, the success of a circular economy in vertical farming will rely heavily on the cooperation and involvement of various stakeholders, including farmers, suppliers, consumers, and policymakers. Education and awareness campaigns may be necessary to encourage the widespread adoption of circular farming practices. Another important consideration is the potential for vertical farming to become a key player in the global food system. As the global population continues to grow and climate change threatens traditional agricultural practices, alternative methods of food production such as vertical farming will become increasingly important. Implementing a circular economy in vertical farming can help to ensure that these practices are sustainable and environmentally friendly, while also increasing food security and reducing food waste.

Overall, the proposed model for a circular economy in vertical farming provides a promising example of how sustainable agriculture can be achieved through innovative and integrated approaches. As further exploration and refinement of these practices are carried out, it is essential to consider the economic, social, and environmental impacts of these systems to ensure their long-term viability and success.

3. PERFORMANCE MEASURES

3.1 Research Questions

This chapter is trying to address the research gap in vertical farming performance measures by validating the proposed circular economy concept in vertical farming to answer the following research question:

1. How can the circular economy concept be implemented in vertical farming and what performance measures should be used to assess its effectiveness?

3.2 Methodology

To implement the circular economy concept in vertical farming and assess its effectiveness, the methodology involved considering the measurable entities like nutrition and growth in terms of height, width, and chlorophyll from the vertical farming processes. This was executed by selecting a base product from each process and assessing it based on these entities to measure the effectiveness of the circular economy model. The performance measures included evaluating the nutrition content of the base product, determining the growth of vertical farming processes, and assessing the viability of the model. To determine the growth of the vertical farming processes, measurements were taken of the height, width, and chlorophyll content of the plants. These measurements were then compared to established growth benchmarks to determine whether the plants were growing properly and whether the circular economy model was effective in promoting growth. The results were then used to optimize the circular economy model and ensure that it was effective in achieving the goal of zero waste while also being financially viable for farmers.

3.2.1 Hydroponic Process

In this study, basil was selected as the base product for the hydroponic process because of its well-known capacity to thrive in a soilless system. The key to achieving healthy plant growth in hydroponic systems is to maintain an optimal balance of nutrients. To achieve this, Miracle-Gro® Water Soluble All Purpose Plant Food 24-8-16 [109] was used during experiment I. This nutrient contains 24% total Nitrogen (N) with 3.5% Ammoniacal Nitrogen and 20.5% Urea Nitrogen, 8% Phosphate (P_20_5), 16% Soluble Potash (K_20), 0.02% Boron (B), 0.07% Copper (Cu), 0.15% Iron (Fe), 0.05% Manganese (Mn), 0.0005% Molybdenum (Mo), and 0.06% water-soluble Zinc (Zn). To compare the performance with experiment I, only water was used in experiment II instead of the nutrient.

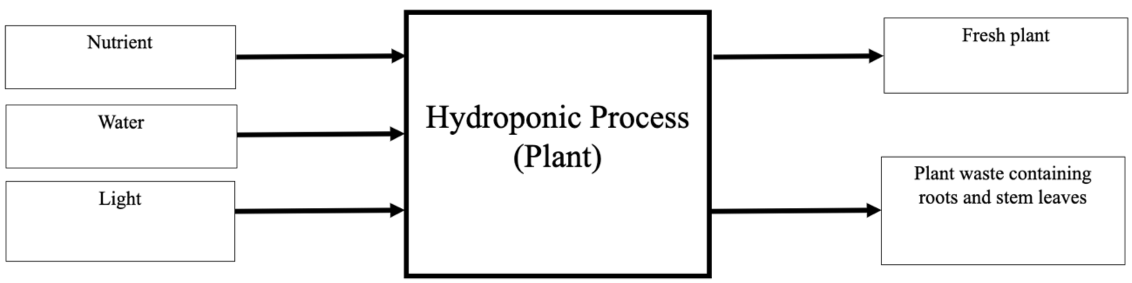


Figure 13. Hydroponic process flowchart

To apply the nutrient, 16 oz of Miracle-Gro® was added to a 50-gallon water tank. For each gallon of water, 2 teaspoons of Miracle-Gro® were added along with 1 teaspoon of Epsom salt to compensate for the deficiency of Mg, S, and Ca. The water was transferred from the 50-gallon water tank to the basil plant bed using a submersible pump with a fill time of 30 minutes and a drain time of 10 minutes and 58 seconds. After four weeks, Botanicare Cal-Mag Plus (128oz) [110] was used for foliar spray at the rate of 0.35 liters to mitigate Mg, K, and Fe deficiencies.

The hydroponic process for experiment I started in the greenhouse with 30 basil plants on September 28, 2022, while the hydroponic process for experiment II started in the greenhouse with 24 basil plants on February 16, 2023.

Figure 14. The operational hydroponic process from experiment I (Week 5)

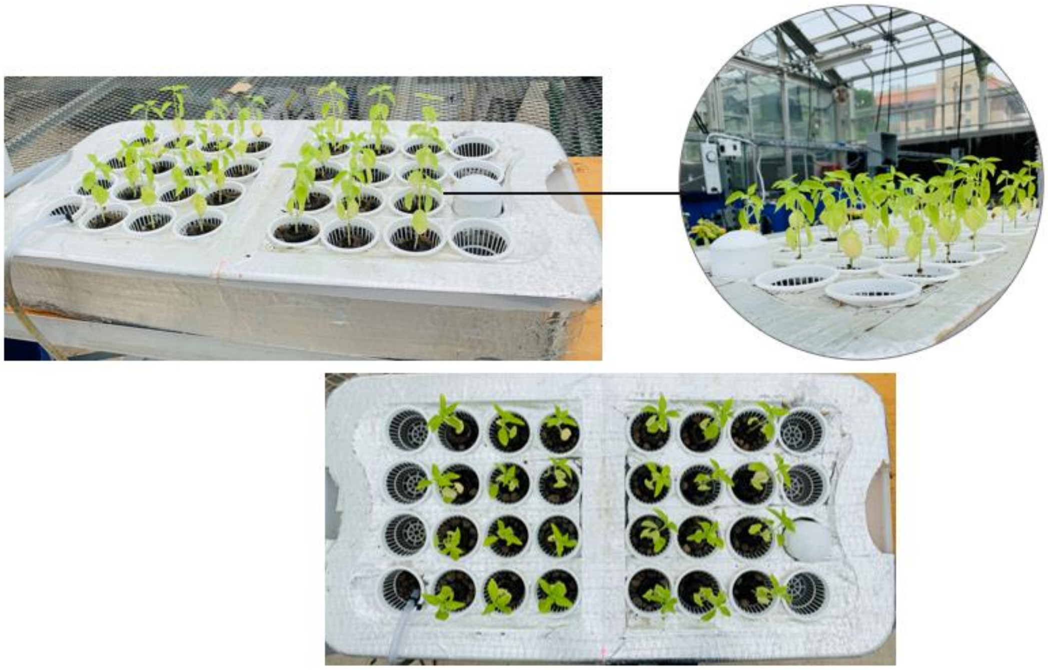


Figure 15. The operational hydroponic process from experiment II (Week 5)

3.2.2 Aquaponic Process

In the aquaponic process, basil was selected as the base product while goldfish was selected for the fish. Goldfish are known to thrive in the aquaponic system. The basil plant bed used for both experiments I and II contained a total of 96 basil plants. To support the fish and plant growth, four 400L tanks were used in the setup. For fish food, black soldier fly larvae (BSFL) were fed to the fish at a rate of 0.07 g per tank every day during the experiment I, which is a highly nutritious and sustainable food source for the fish. For experiment II, the aquaponic setup included the same amount of basil plants in four plant beds, each containing 24 basil plants, and four 400L tanks with goldfish. The fish were fed TetraPond Koi Growth 4.85 Pounds [111] every day in all tanks, but 25% of the fish food in Tank 3 and Tank 4 was replaced by BSFL to compare the growth between setups.

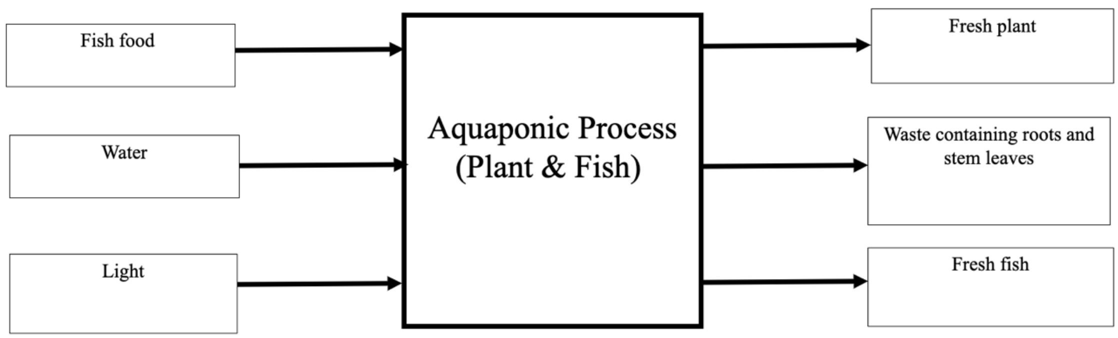


Figure 16. Aquaponic process flowchart

To ensure the basil plants receive adequate nutrients, Botanicare Cal-Mag Plus (128oz) was used for foliar spray at a rate of 0.35 liters per tank after four weeks. This helped mitigate the deficiencies of magnesium (Mg), potassium (K), and iron (Fe) in the system and promote healthy plant growth. The aquaponic process for experiment I started in the greenhouse with 96 basil plants on September 28, 2022, while the aquaponic process for experiment II with the same number of plants began on February 16, 2023. The use of aquaponic systems allows for a sustainable and efficient method of growing both plants and fish together in a closed-loop system.

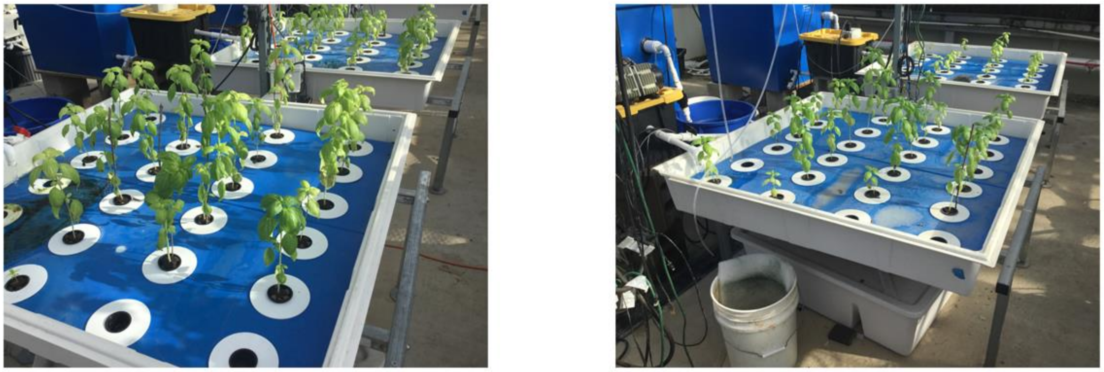


Figure 17. The operational aquaponic process from experiment I (Week 5)

Figure 18. The operational aquaponic process from experiment II (Week 5)

3.3 Results

3.3.1 Vertical Farming Nutrition Analysis

The study presents an in-depth analysis of the nutritional content of basil plants in both hydroponic and aquaponic processes grown according to the proposed circular economy model.

3.3.1.1 Hydroponic Process

Table 2 provides detailed information on the nutrient content of the basil plants, including water, protein, and other nutrients for the hydroponic process of 24 plants according to experiment II. The results are based on data collected from the FoodData central database of the U.S. Department of Agriculture [112]. The findings indicate that the proposed model can produce basil plants in the hydroponic process that are not only environmentally sustainable but also highly nutritious, thus contributing to the overall goal of developing a sustainable agricultural system that addresses both food security and health concerns. The insights gained from this analysis can contribute to further research on the nutritional content of crops grown in the hydroponic process and help optimize the model for maximum yield and nutritional quality.

3.3.1.2 Aquaponic Process

Detailed information on the nutritional content of the basil plant grown in the aquaponic process is demonstrated. The data also presented in Table 2 is based on the analysis of 96 plants from the aquaponic process. The nutritional content of the basil was obtained from the FoodData central database of the U.S. Department of Agriculture [112]. The table shows that the basil plant contains significant amounts of water, protein, total lipid (fat), ash, carbohydrates, and fiber. These findings highlight the potential of the aquaponic process as a means of producing high-quality, nutrient-rich crops that can contribute to healthy diets and food security.

Table 2. The nutrition information of basil from hydroponic and aquaponic processes

Hydroponic process		Aquaponic process	
Basil (5 leaves or 2.5 g average nutrients on each plant, containing a total of 120 leaves or 60 g nutrients on 24 basil plants) [112]	Nutrition (g) [112]	Basil (5 leaves or 2.5 g average nutrients on each plant, containing a total of 480 leaves or 240 g nutrients on 96 Basil plants) [112]	Nutrition (g) [112]
Water	55.2	Water	220.8
Protein	1.896	Protein	7.584
Total lipid (fat)	0.384	Total lipid (fat)	1.536
Ash	0.888	Ash	3.552
Carbohydrates, by the difference	1.584	Carbohydrates, by the difference	6.336
Fiber, total dietary	0.96	Fiber, total dietary	3.84
Sugars, total including NLEA	0.168	Sugars, total including NLEA	0.672
Glucose	0.024	Glucose	0.096
Fructose	0.024	Fructose	0.096
Galactose	0.168	Galactose	0.672

3.3.2 Vertical Farming Growth Analysis

3.3.2.1 Experiment I

The results of the vertical farming height data analysis (Figure 19) were presented, and it is evident that all five setups show growth. However, the hydroponic setup displays less growth after week 4 when compared to all four aquaponic setups. It is observed that the 4th aquaponic setup shows less height growth, which could be attributed to its placement near the wall mounted air filter. Similar trends are observed in the width data analysis (Figure 20) and chlorophyll data analysis (Figure 21). However, the hydroponic setup shows better chlorophyll data compared to all four aquaponic setups. A possible reason for this could be the use of Miracle-Gro® Water-Soluble All-Purpose Plant Food nutrient in the hydroponic setup. This nutrient may have contributed to the enhanced chlorophyll content in the plants.

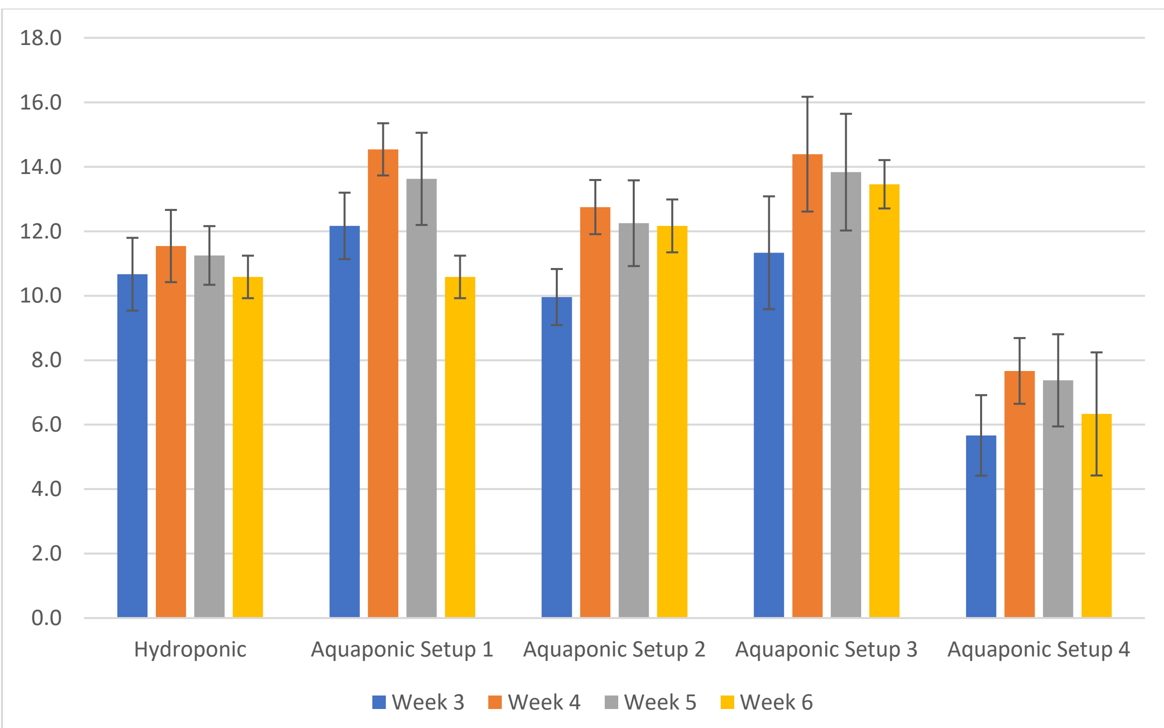


Figure 19. Vertical farming experiment I height data analysis

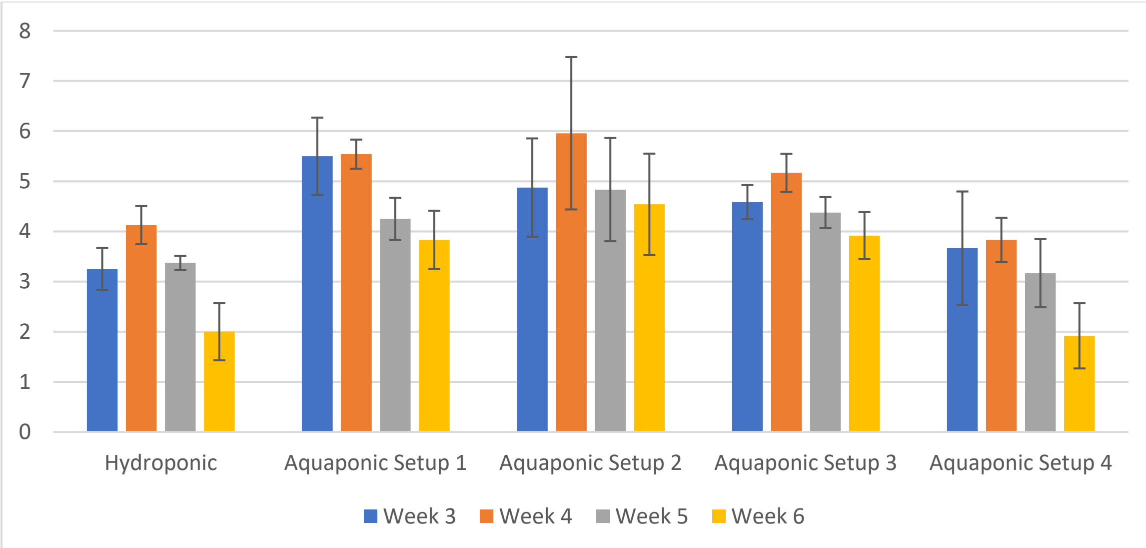


Figure 20. Vertical farming experiment I width data analysis

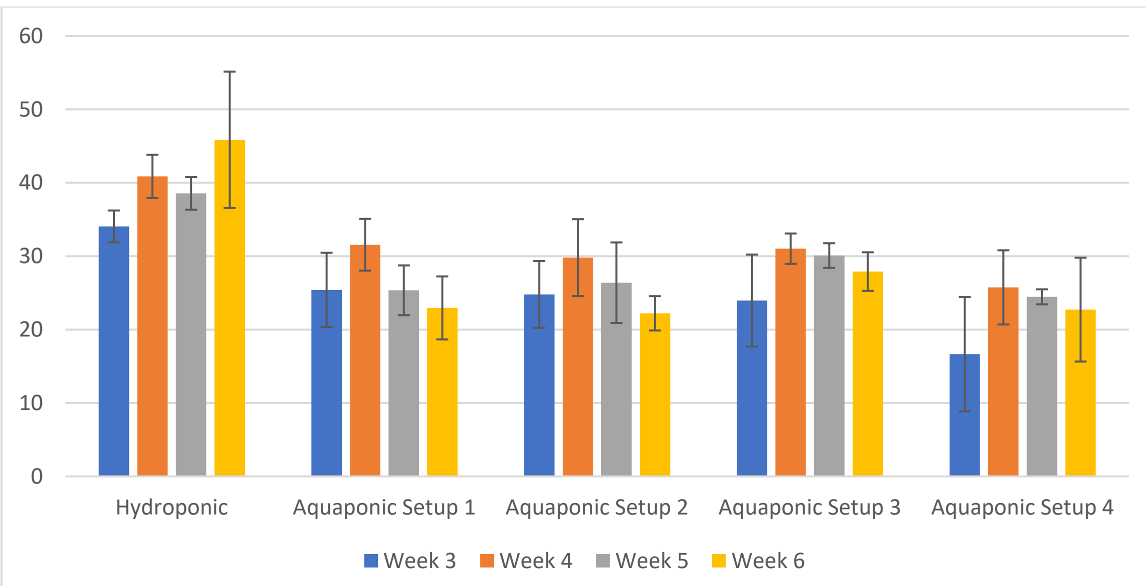


Figure 21. Vertical farming experiment I chlorophyll data analysis

During the implementation of the above experiments, several discrepancies were identified. The new experiment II focused on addressing the identified issues to obtain more reliable and accurate results. The first issue of non-uniform light distribution was resolved by adjusting the lighting system to provide a more even distribution of light throughout the growth area. The second issue of internal airflow inconsistency was tackled by implementing a more efficient ventilation system that ensured consistent air circulation throughout the growth area. Additionally, a consistent waiting period was implemented to ensure that the plants were given adequate time to grow and develop before being harvested. Overall, the new experiment II had the potential to provide more reliable and accurate data on the performance of vertical farming systems.

3.3.2.2 Experiment II

The height data analysis of experiment II (Figure 22) indicates that all five setups experienced growth, with the hydroponic setup showing the least growth compared to the four aquaponic setups. The least growth of the hydroponic process can be related to the lack of nutrient supply during experiment II. Among the aquaponic systems, the fourth setup had less height growth, which could be due to its placement near the wall mounted air filter. The width data analysis (Figure 23) and chlorophyll data analysis from week 4 and week 5 (Figure 24) also show similar scenarios. However, in terms of chlorophyll, the hydroponic and aquaponic setup 1 show better data compared to the other three aquaponic setups.

It is important to note that the height rate of the basil plants in all five setups began to increase after the fourth week unlike experiment I. However, the overall reason behind the less growth of basil plants in terms of width and chlorophyll till week 4 in all five setups, as observed in the earlier experiment, gives the reason for the maximum growth time of 4 weeks for this specific type of basil plant. This suggests that the maximum growth time for this specific type of basil plant is around four weeks, regardless of the type of system used.

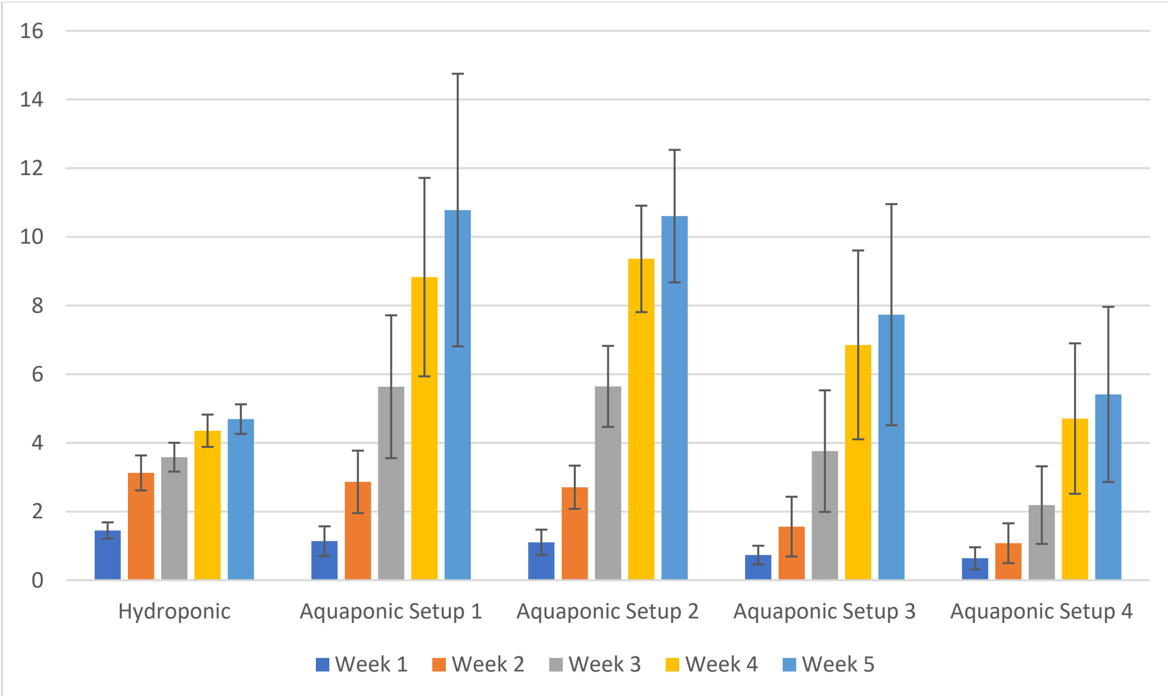


Figure 22. Vertical farming experiment II height data analysis

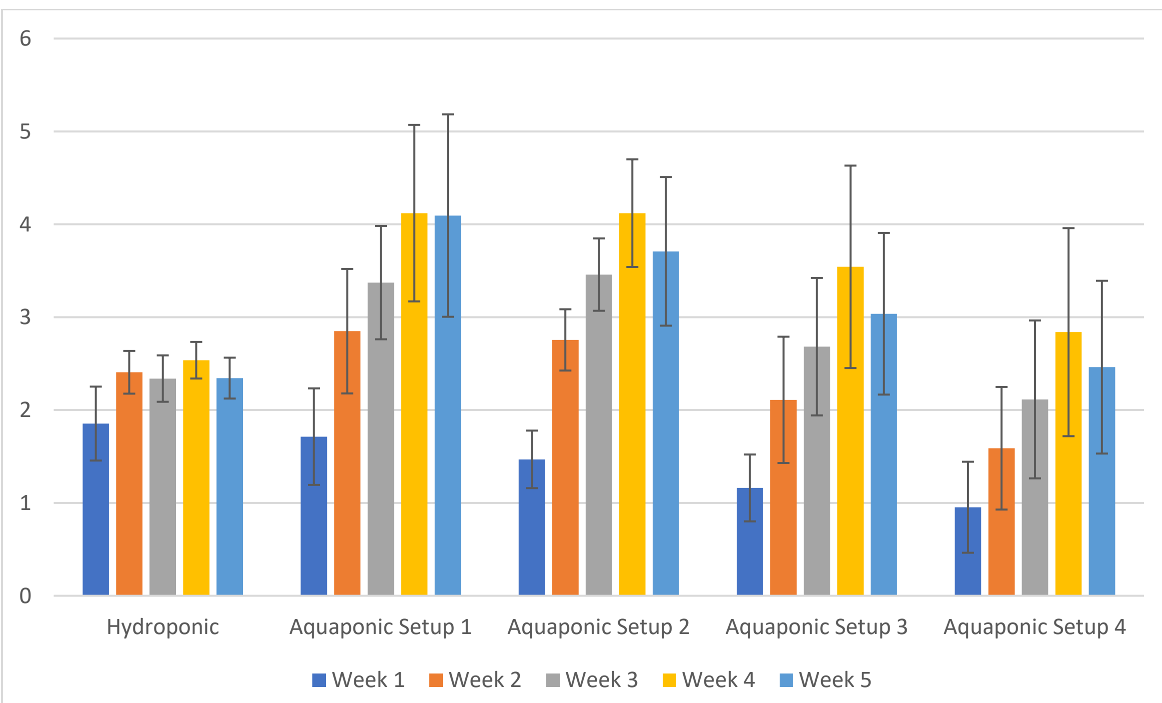


Figure 23. Vertical farming experiment II width data analysis

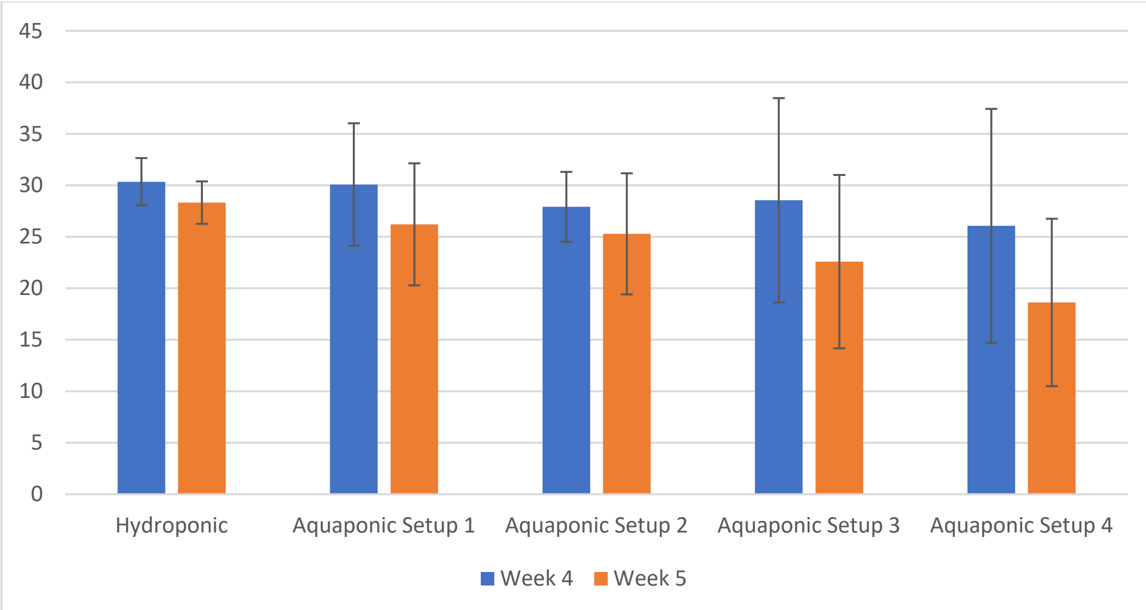


Figure 24. Vertical farming experiment II chlorophyll data analysis (Data recorded for week 4 and week 5)

3.4 Discussion

This chapter aimed to address the research gap in vertical farming performance measures by validating the proposed circular economy concept in vertical farming and answering the research question of how the circular economy concept can be implemented in vertical farming and what performance measures should be used to assess its effectiveness.

The hydroponic and aquaponic processes showed promising results in terms of plant growth and nutrition content, which suggests that these methods can be used to produce high-quality crops sustainably. From experiment I, it can be inferred that the possible cause for the overall less growth of basil plants in terms of height, width, and chlorophyll after week 4 in all five setups could be attributed to the cold weather from week 5 in Texas or the maximum growth time of 4 weeks for this specific type of basil plant. These results have important implications for the adoption and optimization of value-added methods in circular economy practices in vertical farming, especially for the growth of basil plants. Further research can focus on investigating the impact of different nutrient solutions, light sources, and other environmental factors on the growth of basil plants in vertical farming systems. Overall, the results of the experiment suggest that while all five setups showed growth over time, the hydroponic setup performed better in terms of chlorophyll content, while the aquaponic setups demonstrated more consistent growth in height and width.

The results from experiment II suggest that aquaponic setups are more effective than hydroponic setups for the growth of basil plants in a vertical farming system, and the fourth setup in aquaponic systems may require further investigation addressed in Chapter 4. The analysis of the vertical farming growth data from experiment II highlights the importance of considering various factors that can affect plant growth, such as light distribution, airflow, seed quality, and nutrient levels. By conducting more precise experiments and analyzing the data carefully, we can gain a better understanding of the strengths and limitations of different vertical farming systems and optimize their performance to achieve higher yields and better-quality crops.

One important consideration when evaluating the effectiveness of the circular economy model in vertical farming is the economic feasibility of the model. While the goal of zero waste is admirable, it must also be financially sustainable for farmers to implement in practice. This study used performance measures such as plant growth and nutrition content to optimize the circular economy model and ensure that it was both environmentally and economically beneficial. The use of hydroponic and aquaponic systems allowed for the production of high-quality crops with minimal waste, as both systems recycle water and nutrients to support plant growth. This is in contrast to traditional farming methods, which can result in significant waste and environmental degradation.

The use of performance measures in this study was effective in assessing the circular economy concept in vertical farming. The measures used, including plant height, width, and chlorophyll content, as well as nutritional content, were able to provide insight into the effectiveness of the circular economy model in promoting healthy plant growth and minimizing waste. Future studies could explore the use of additional performance measures, such as yield and crop quality, to further assess the circular economy concept in vertical farming. The results of this study have important implications for the future of agriculture and food production. As the global population continues to grow and resources become increasingly scarce, it is critical to developing more sustainable and efficient methods of producing food. Vertical farming has the potential to play a significant role in this effort, and the circular economy model offers a promising framework for achieving this goal.

Overall, this study showed that the circular economy concept can be successfully implemented in vertical farming and can be assessed using various performance measures such as nutrition content and plant growth. The use of both hydroponic and aquaponic systems allows for a sustainable and efficient method of growing plants, and the results can be used to optimize the circular economy model in the future.

Finally, it is important to note that while this study focused on the implementation of the circular economy concept in vertical farming, there is still much work to be done in this field. Further research is needed to refine and optimize the model and to explore its potential applications in different contexts and settings. However, the results of this study provide a strong foundation for future work in this area.

In conclusion, this chapter presented a detailed analysis of the performance measures for both hydroponic and aquaponic systems. The results demonstrated that the proposed approach could provide valuable insights into the performance of vertical farming systems, which can help in developing more efficient and sustainable farming practices. Further research can focus on exploring other performance measures and optimizing the circular economy concept to improve the overall performance of vertical farming systems.

4. HYDROPONIC AND AQUAPONIC GROWTH COMPARISON

4.1 Research Questions

This chapter is trying to resolve the research gap in vertical farming by investigating the comparative performance of hydroponic and aquaponic processes to answer the following research questions:

1. Is there a significant difference in the performance of aquaponic processes with and without the use of black soldier fly larvae (BSFL)?
2. Apart from BSFL, what other factors contribute to growth variation in aquaponic setups?
3. Is the location of the growth area a significant factor in the performance of the aquaponic setup?
4. What is the growth comparison among hydroponic, aquaponic (with BSFL), and aquaponic (without BSFL) setups?

4.2 Methodology

The methodology of this study involves the comparison of hydroponic and aquaponic growth methods through statistical analysis, utilizing the Minitab® statistics package [113] for the design of experiments. Along with the hydroponic process setup in the greenhouse, four setups of the aquaponic process were considered. The data collected over six weeks during experiment II was analyzed to evaluate the growth comparison. In this study, the design of experiments conducted on the Minitab® involved the use of one-way analysis of variance (ANOVA) [114] to analyze the week 5 height data of hydroponic and aquaponic setups, which were collected from the greenhouse experiment II that started on February 16, 2023.

Table 3. One-way ANOVA method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

The hydroponic setup consisted of 24 basil plants with Miracle-Gro® Water Soluble All Purpose Plant Food 24-8-16 [109], while the aquaponic setup included 96 basil plants in four plant beds, each containing 24 basil plants, and four 400L tanks with goldfish. The fish were fed TetraPond Koi Growth 4.85 Pounds [111] every day in all tanks, but 25% of the fish food in Tank 3 and Tank 4 was replaced by black soldier fly larvae (BSFL) to compare the growth between setups.

4.3 Results

4.3.1 Effect of Black Soldier Fly Larvae (BSFL) on Aquaponic Performance

To analyze the effect of black soldier fly larvae (BSFL) on the growth of basil plants in the aquaponic process, the experiment was divided into two factors: Aquaponic 1 + Aquaponic 2 and Aquaponic 3 + Aquaponic 4, each with the same feeding method.

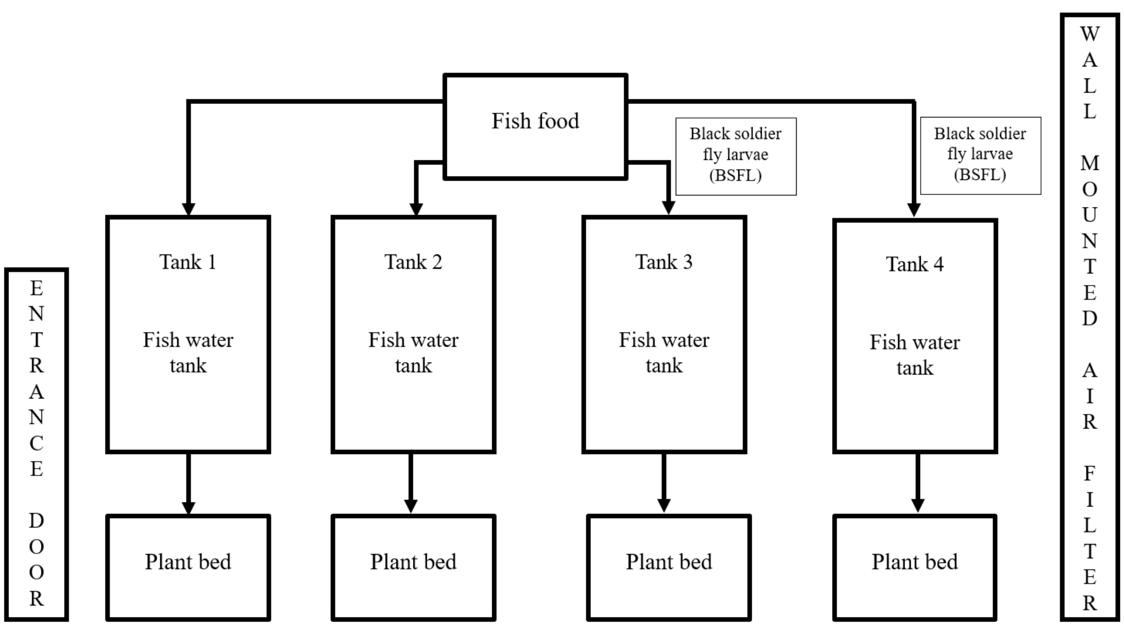


Figure 25. The layout of four aquaponic process setups from experiment II

Aquaponic process setup 1 and setup 2 had the same feeding method of fish food without BSFL, whereas aquaponic process setup 3 and setup 4 had the same feeding method of fish food with BSFL The growth of basil plants was monitored and analyzed using statistical methods to understand the impact of these factors. Figure 26 depicts the four operational aquaponic process setups used in experiment II.

Aquaponic Setup 1 (Week 5) | Aquaponic Setup 2 (Week 5) | Aquaponic Setup 3 (Week 5) | Aquaponic Setup 4 (Week 5)

Figure 26. Four operational aquaponic process setups from experiment II

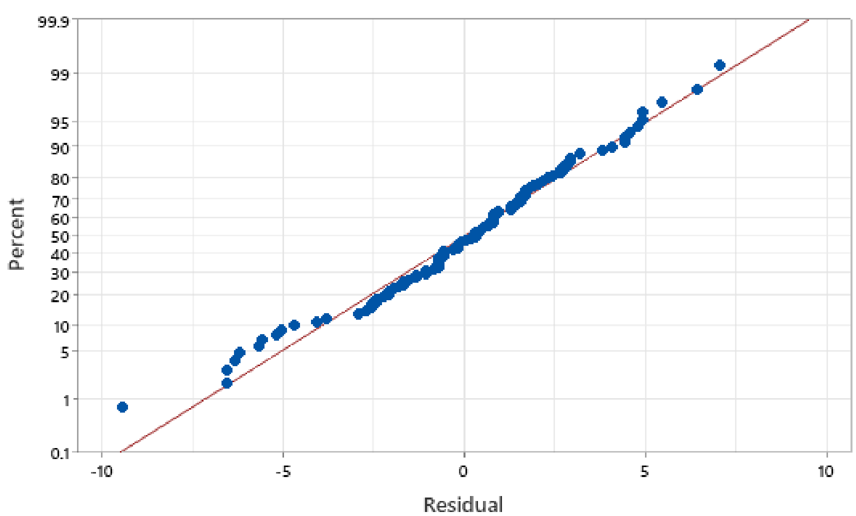


Figure 27. Normal probability plot for the growth analysis of four aquaponic processes

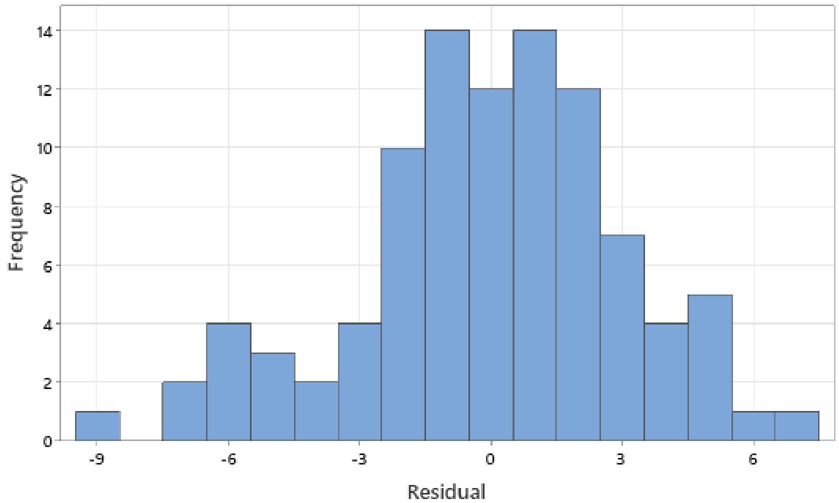


Figure 28. Residual histogram for the growth analysis of four aquaponic processes

The normal probability plot and residual histogram, as depicted in Figure 27 and Figure 28, respectively, demonstrated a nearly linear pattern, indicating that the dataset was acceptable for further analysis in this study.

Table 4. Analysis of variance for aquaponic process growth analysis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	407.3	407.344	42.48	0.000
Error	94	901.3	9.589		
Total	95	1308.7			

The results of the analysis of variance (ANOVA) presented in Table 4 showed that the use of black soldier fly larvae (BSFL) had a significant effect on the growth of the aquaponic processes. The null hypothesis was rejected at a significance level of 5%, indicating that the use of BSFL had a significant impact on the growth of basil plants in the aquaponic process.

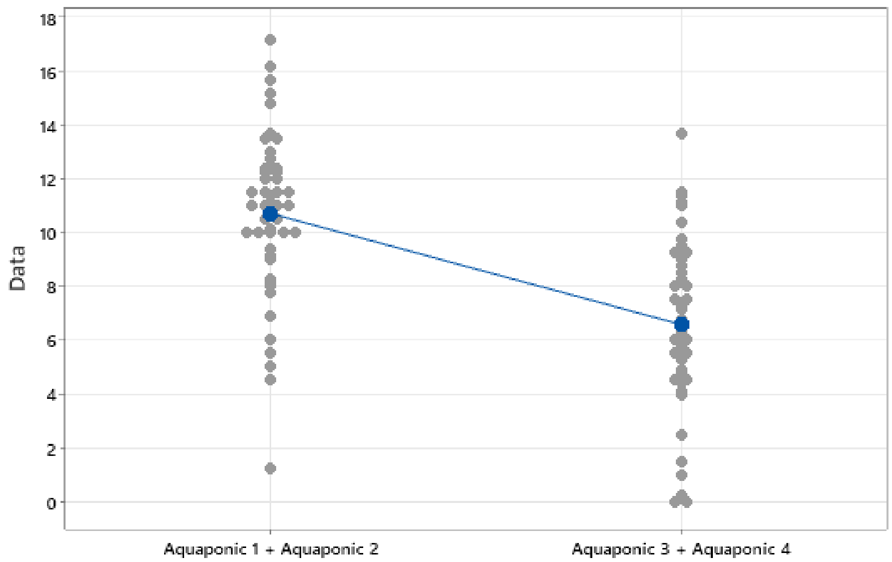


Figure 29. Individual value plot for aquaponic process growth analysis

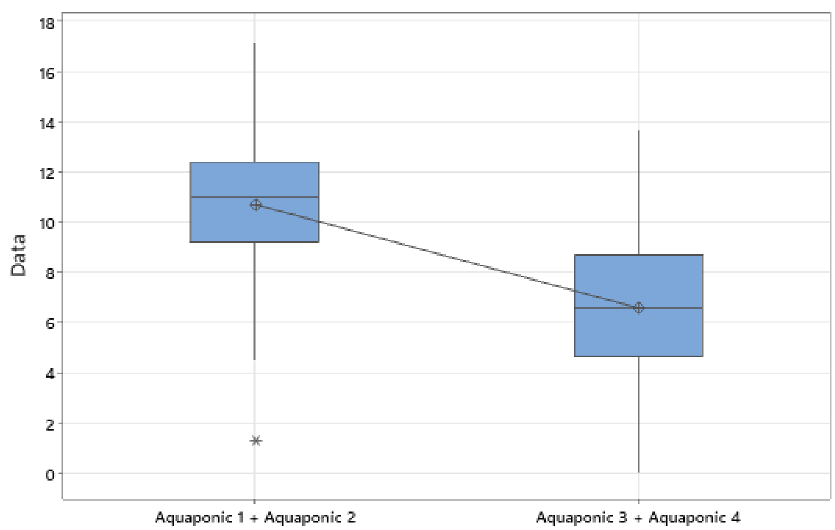


Figure 30. Boxplot for aquaponic process growth analysis

To further analyze the growth of the basil plants in the two different sets of aquaponic processes with the same feeding method, a comparison was made between the two sets of processes. The individual value plot and boxplot shown in Figure 29 and Figure 30, respectively, revealed that black soldier fly larvae (BSFL) might be influencing the growth of these two sets of aquaponic processes.

The individual value plot showed that the use of BSFL reduced the growth of the aquaponic processes in setups 3 and 4. However, in the set of processes 1 and 2, it was evident that the growth was significantly higher without the use of BSFL compared to setups 3 and 4. Overall, the findings of this study suggest that the use of black soldier fly larvae in aquaponics may not always lead to higher plant growth and may even impact the growth of certain plants.

Further research is needed to fully understand the mechanisms behind the observed effects of BSFL on aquaponic plant growth. However, these results suggest that careful management of BSFL feeding and nutrient levels may be necessary to optimize plant growth in aquaponic systems. In addition, these findings highlight the potential for BSFL to be used as a tool for nutrient management in aquaponics, but more research is needed to determine the optimal conditions for their use.

4.3.2 Identification of the Other Factor Affecting Aquaponic Growth

The results highlight the complexity of the aquaponic process and the importance of considering multiple factors when analyzing plant growth. While the use of black soldier fly larvae (BSFL) was found to influence plant growth, other variables must be considered to fully optimize the growth of aquaponic plants.

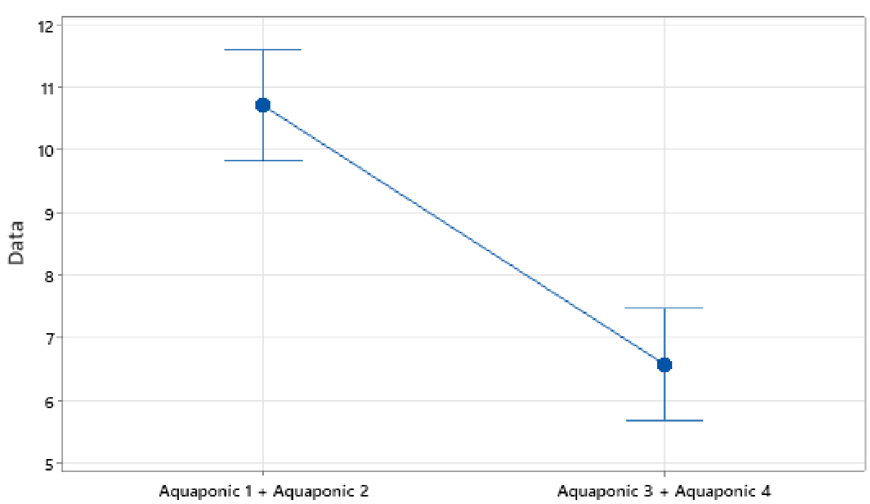


Figure 31. Interval plot for aquaponic process growth analysis

The results of the interval plot in Figure 31 suggest that another factor is also responsible for the growth differences among the setups. It is noteworthy that aquaponic 1 and 2, which were located near the entrance door and far from the wall-mounted air filter unit, showed better growth compared to aquaponic 3 and 4, which were located farther away from the entrance door and closer to wall-mounted air filter unit. This observation indicates another important factor that needs to be taken into account when optimizing aquaponic growth.

Further investigation is necessary to determine the exact factor responsible for the observed growth differences. One possible explanation is that the two setups located near the entrance door and far from the wall-mounted air filter unit experienced more consistent environmental conditions, such as airflow and temperature, which could have contributed to their better growth. Additionally, it is possible that other factors, such as water quality or lighting, may have played a role in the observed differences. Future studies could focus on controlling these factors to better isolate their individual effects on plant growth.

Overall, the findings suggest that while BSFL is an important factor to consider in optimizing aquaponic growth, it is not the only factor. Other environmental and operational factors can also play a significant role in plant growth, highlighting the need for a more comprehensive approach to aquaponic system design and management. By identifying and controlling these factors, it may be possible to further improve the efficiency and sustainability of aquaponic systems, ultimately leading to more consistent and reliable plant growth.

4.3.3 Effect of Location on Aquaponic Performance

To determine the effect of location on the performance of the aquaponic setups, a comparative analysis was conducted between Aquaponic 1 and Aquaponic 2, as well as between Aquaponic 3 and Aquaponic 4. By conducting a side-by-side assessment, it was possible to observe the differences in growth rates and overall performance between the setups located in different areas. This information can be crucial for optimizing the placement of aquaponic setups and improving their efficiency. These assessments were conducted over several weeks, during which plant growth and other parameters such as water quality and temperature were monitored.

4.3.3.1 Aquaponic 1 vs Aquaponic 2

To investigate the impact of location on the growth of basil plants in the aquaponic process, a comparison was made between the factors Aquaponic 1 and Aquaponic 2, each with a different location setup but the same feeding method without BSFL.

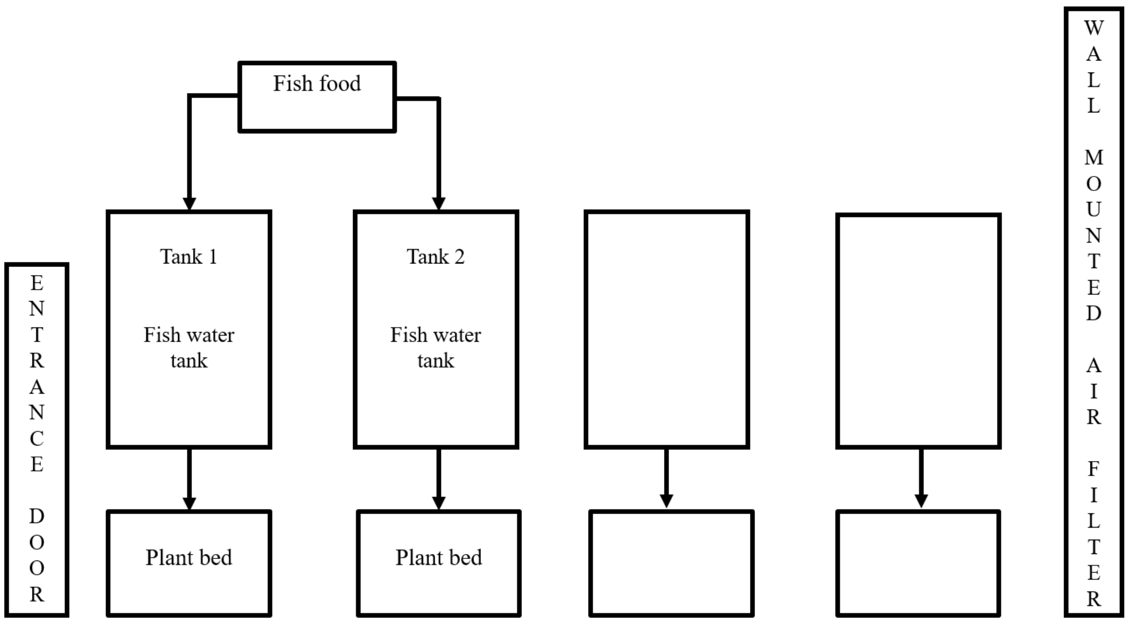


Figure 32. Operational aquaponic process setup 1 and setup 2 layouts from experiment II

The experiment was designed to assess the effect of location by keeping the feeding method constant while varying the location of the aquaponic setup. Statistical analysis was conducted to carefully monitor and assess the significance of the effect of location on the growth of basil plants of aquaponic process setup 1 and setup 2. The experimental setups used in the study are shown in Figure 33.

Figure 33. Operational aquaponic process setup 1 and setup 2 from experiment II

Table 5. Analysis of variance for the comparison of aquaponic process setup 1 and setup 2

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	0.376	0.3763	0.04	0.845
Error	46	447.497	9.7282		
Total	47	447.874			

According to the ANOVA analysis results presented in Table 5, the growth of basil plants in aquaponic process setups 1 and 2 was not significantly affected by location. The statistical analysis indicated that the null hypothesis could not be rejected at a 5% significance level since the F-Value of 0.04 and P-Value of 0.845 showed that there was no significant difference in the growth of plants based on location in these setups. Therefore, it can be concluded that the location had no significant impact on the performance of aquaponic process setups 1 and 2 in terms of basil plant growth.

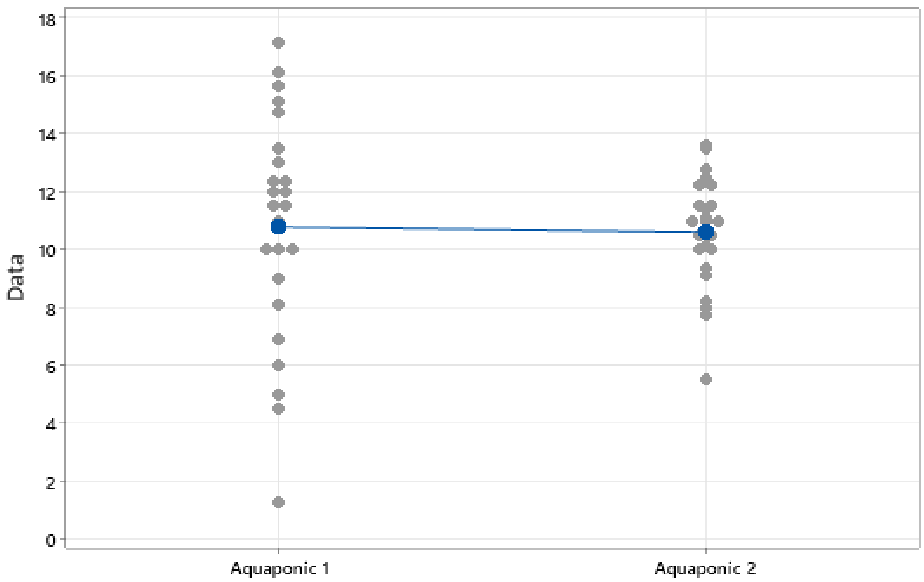


Figure 34. Individual value plot for the comparison between aquaponic process setup 1 and setup 2

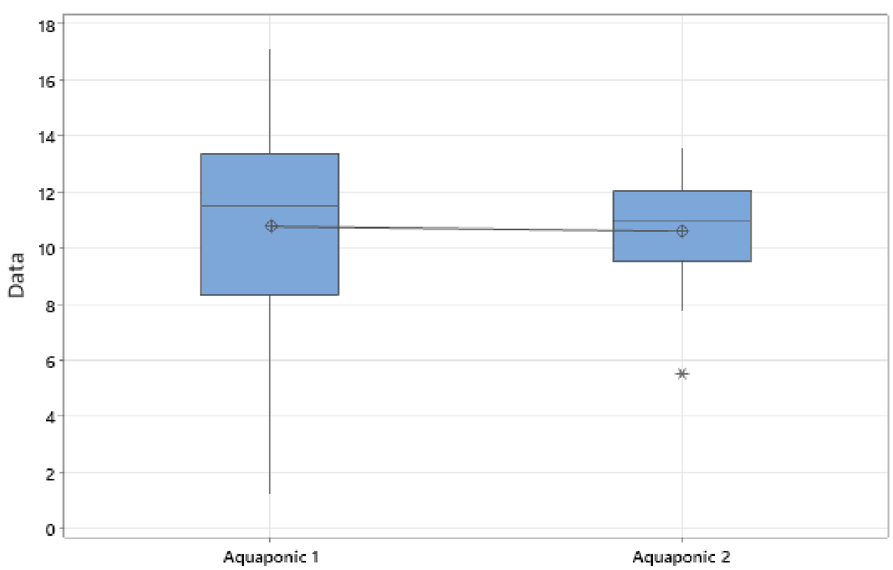


Figure 35. Box plot for the comparison between aquaponic process setup 1 and setup 2

Figure 34 and Figure 35 show the individual value plot and box plot respectively, for the side-by-side comparison between aquaponic process setup 1 and setup 2 with the same feeding method. The results indicate that aquaponic setup 1, which was located near the entrance door, had slightly higher growth compared to aquaponic setup 2, which was located farther away from the door.

Furthermore, the difference in growth rates between these two aquaponic setups may also be attributed to variations in light exposure, temperature, and humidity levels, as these environmental factors can significantly impact plant growth. It is possible that the location of aquaponic setup 1 provided better access to natural light or had more stable temperature and humidity levels, which could have contributed to the observed differences in plant growth. However, further experimentation and data collection would be needed to confirm these hypotheses.

4.3.3.2 Aquaponic 3 vs Aquaponic 4

To assess the effect of location on the growth of basil plants in aquaponic process setup 3 and setup 4, the experiment was divided into two factors: Aquaponic 3 and Aquaponic 4, each with distinct growth setups but the same feeding method with BSFL.

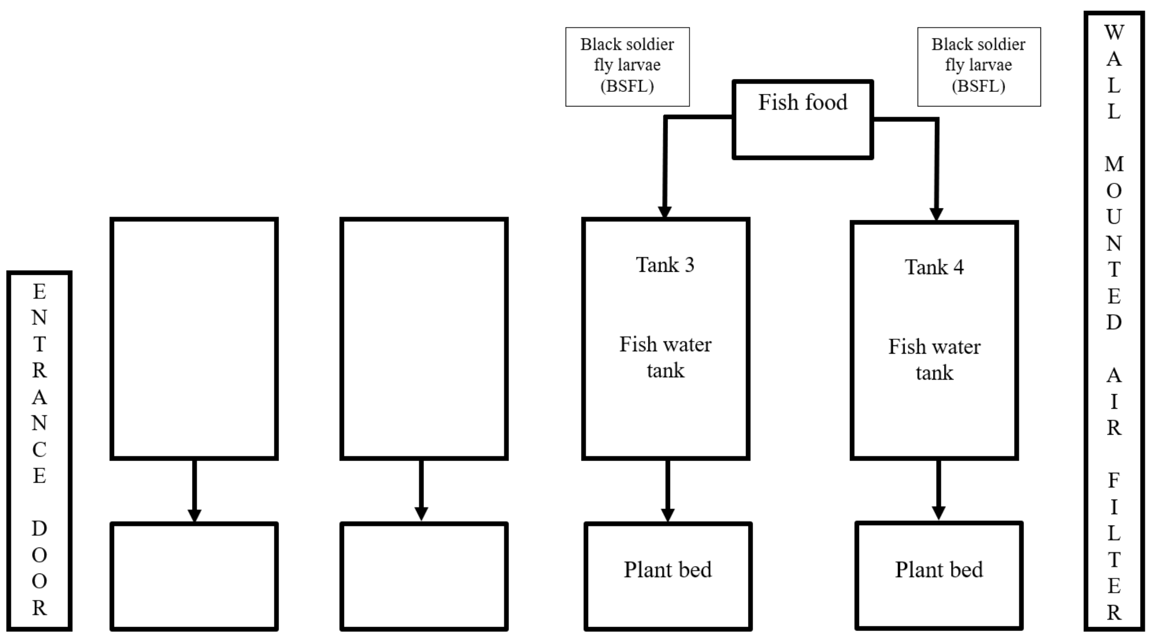


Figure 36. Aquaponic process setup 3 and setup 4 layouts from experiment II

The statistical analysis of plant growth was carried out by closely monitoring the growth of basil plants. Figure 37 illustrates the operational aquaponic process setup 3 and setup 4 used in experiment II.

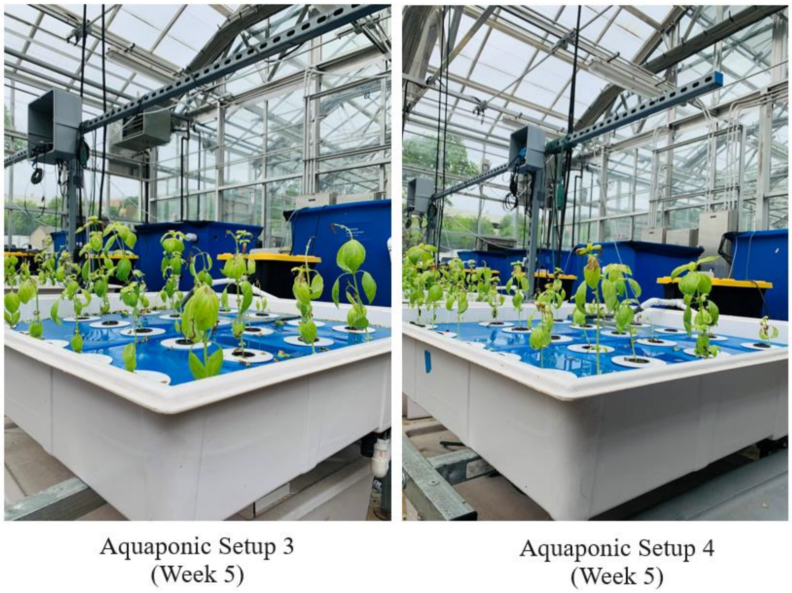


Figure 37. Operational aquaponic process setup 3 and setup 4 from experiment II

Table 6. Analysis of variance for the comparison of aquaponic process setup 3 and setup 4

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	64.75	64.751	7.66	0.008
Error	46	388.71	8.450		
Total	47	453.46			

Table 6 presents the results of the analysis of variance (ANOVA) comparing the growth of basil plants in aquaponic process setups 3 and 4. The statistical analysis revealed that the location significantly influenced the growth of basil plants in these setups. The null hypothesis was rejected at a significance level of 5%, indicating that there was a significant difference in the growth of basil plants in aquaponic process setups 3 and 4 at different locations.

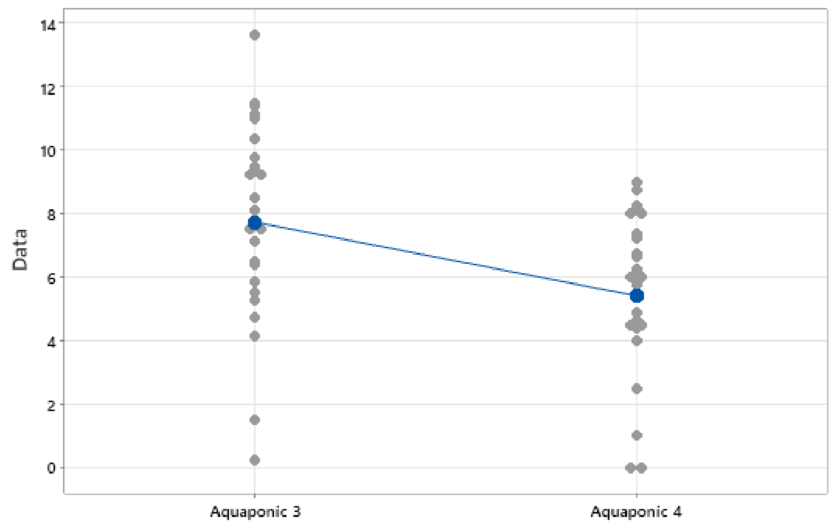


Figure 38. Individual value plot for the comparison between aquaponic process setup 3 and setup 4

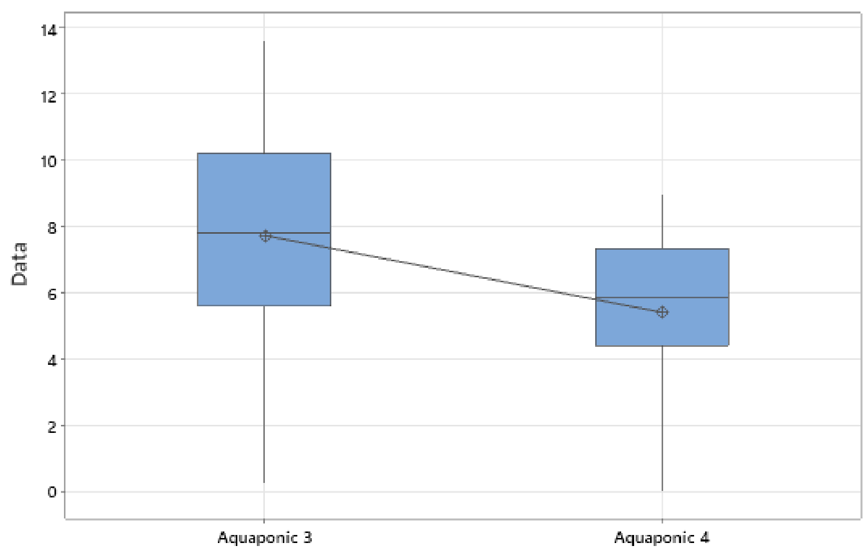


Figure 39. Box plot for the comparison between aquaponic process setup 3 and setup 4

The individual value plot in Figure 38 and the box plot in Figure 39 clearly show that aquaponic process setup 4 had significantly lower growth compared to aquaponic process setup 3. This suggests that location may be a contributing factor, as both setups had the same feeding method but exhibited different levels of growth.

It is important to note that the findings of this study have implications beyond just the growth of basil plants. Other plants grown using aquaponic systems may also be affected by location, and these findings could be applied to a variety of different crops. Additionally, the impact of location on aquaponic systems may not be limited to just plant growth; factors such as fish health and water quality could also be affected.

Overall, the results of this study highlight the importance of carefully considering the location of aquaponic systems to maximize plant growth and overall system efficiency. Future research could focus on identifying specific environmental factors that are impacted by location and how these factors can be optimized for better plant growth. By further developing the understanding of the impact of location on aquaponic systems, sustainable and efficient systems for plant production can be created.

4.3.4 Comparative Growth Analysis of Hydroponic and Aquaponic Setups

In this study, the growth of plants in hydroponic and aquaponic setups was compared across five different setups with three factors.

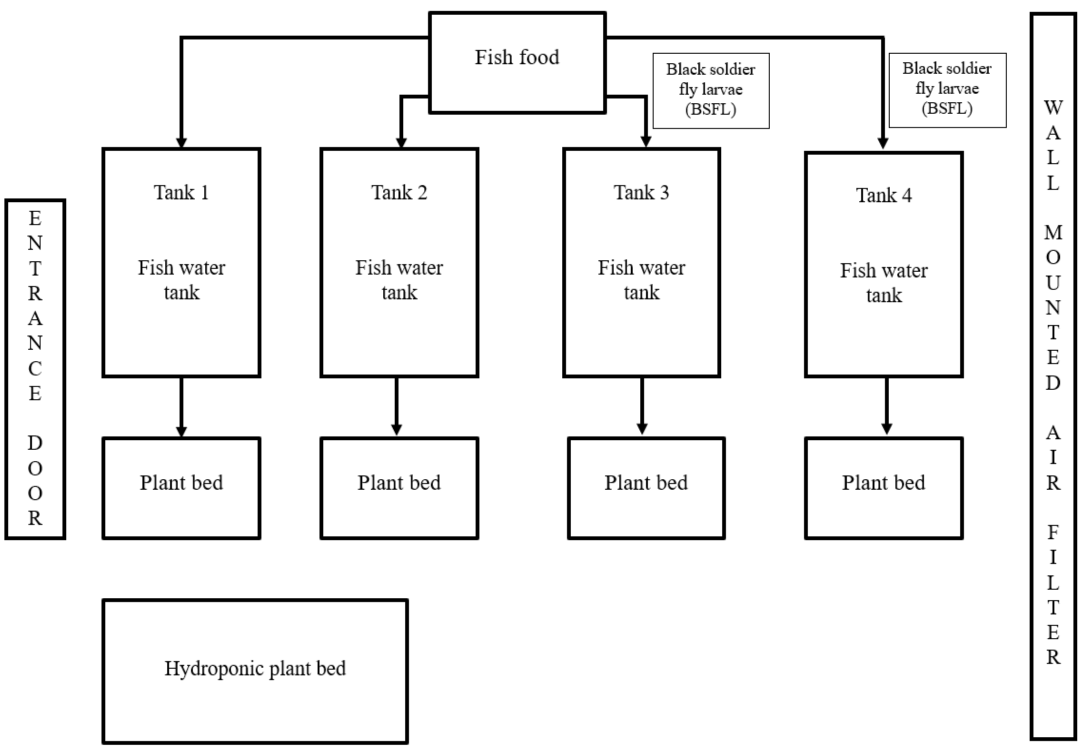


Figure 40. Hydroponic and aquaponic process layout from experiment II

The factors were Hydroponic, Aquaponic 1 + Aquaponic 2, and Aquaponic 3 + Aquaponic 4. The operational setups for the hydroponic and all aquaponic processes used in experiment II are depicted in Figure 41.

Hydroponic Setup (Week 5) | Aquaponic Setup 1 (Week 5) | Aquaponic Setup 2 (Week 5) | Aquaponic Setup 3 (Week 5) | Aquaponic Setup 4 (Week 5)

Figure 41. Operational hydroponic and aquaponic process setups from experiment II

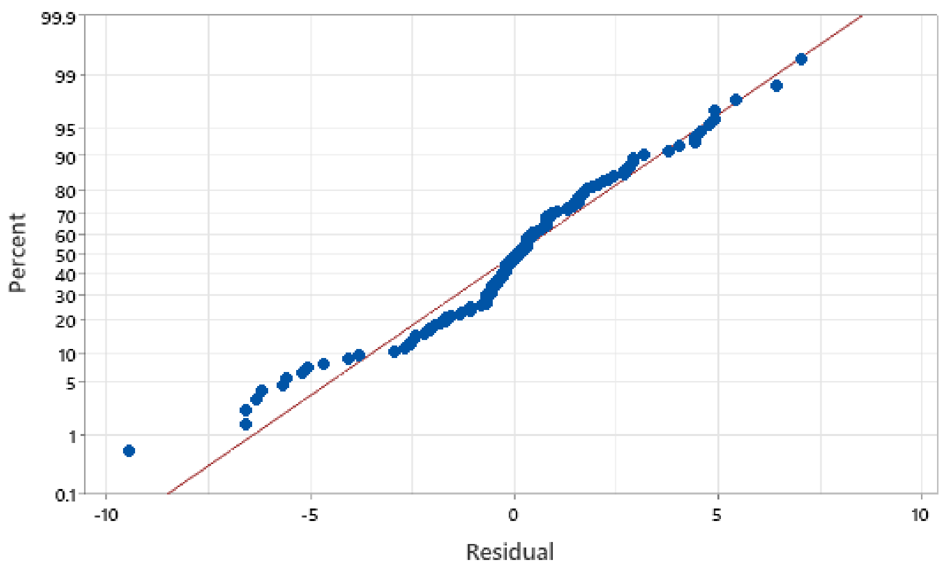


Figure 42. Normal probability plot for the comparative growth analysis of hydroponic and aquaponic setups

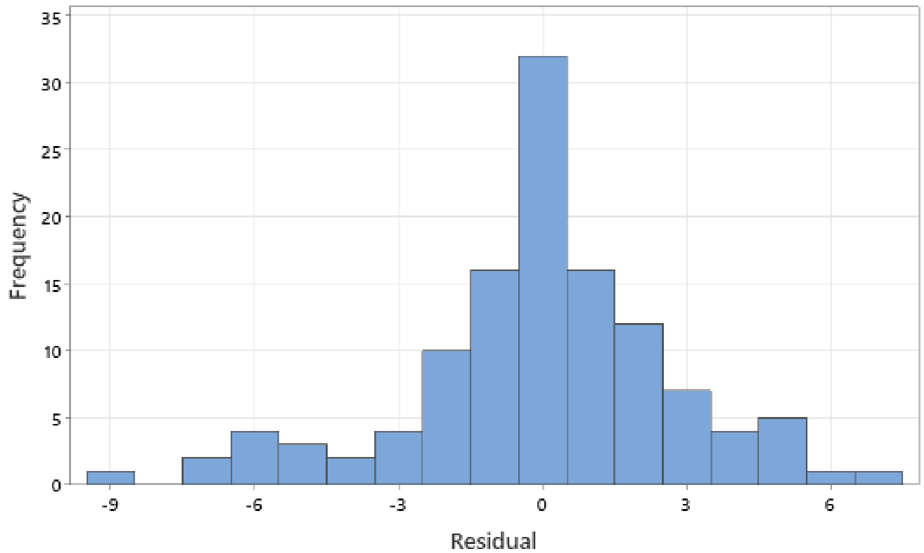


Figure 43. Residual histogram for the comparative growth analysis of hydroponic and aquaponic setups

The normal probability plot (Figure 42) and residual histogram (Figure 43) provide a visual representation of the data distribution and indicate that the dataset was acceptable for further analysis in this study. The nearly linear pattern in both plots suggests that the data conforms to a normal distribution, which is essential for conducting accurate statistical analysis.

Table 7. Analysis of variance for the hydroponic and aquaponic process growth analysis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	705.4	352.707	45.57	0.000
Error	117	905.5	7.739		
Total	119	1610.9			

The statistical analysis, as presented in Table 7, demonstrates that there is a significant difference in growth between the hydroponic and aquaponic process setups. The F-value of 45.57 and P-value of 0.000 indicate that the difference in growth is statistically significant. Therefore, it can be concluded that hydroponic and aquaponic setups exhibit distinct impacts on plant growth based on the findings.

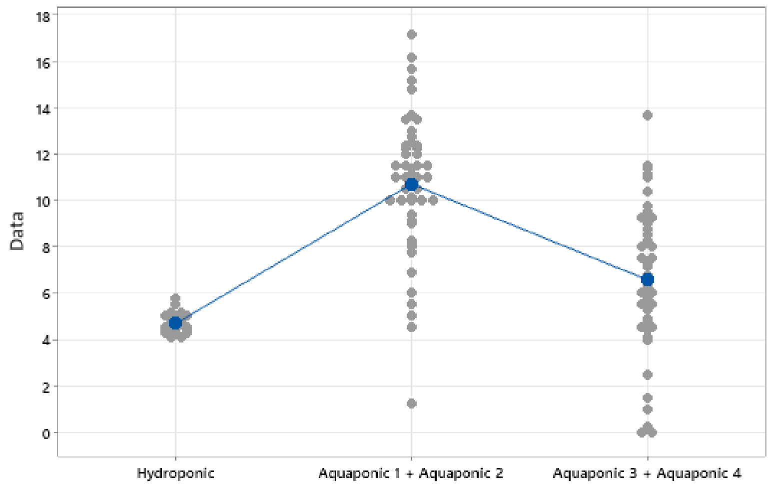


Figure 44. Individual value plot for the hydroponic and aquaponic process growth analysis

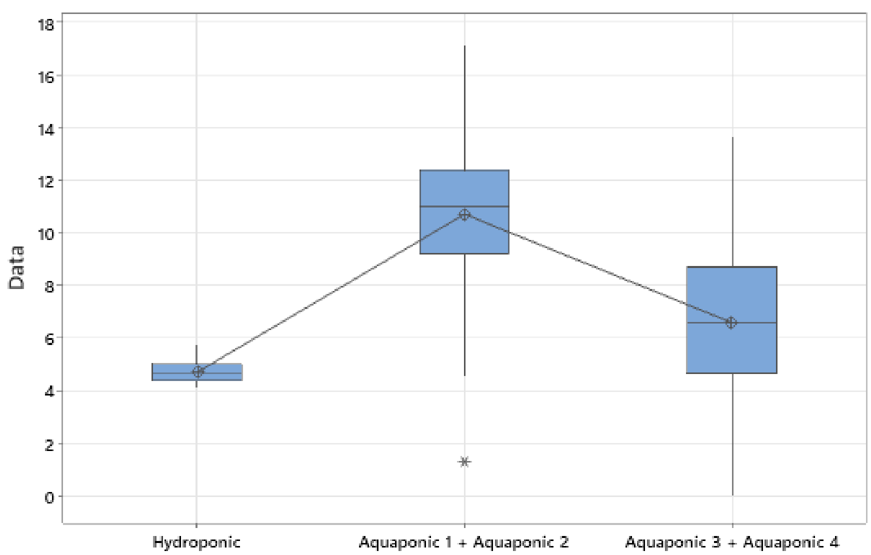


Figure 45. Boxplot for the hydroponic and aquaponic process growth analysis

The individual value plot (Figure 44) and boxplot (Figure 45) clearly illustrate the superior performance of both sets of aquaponic processes over the Hydroponic process. The aquaponic setups, especially Aquaponic 1 and Aquaponic 2 where only fish food was provided without BSFL, exhibit significantly better growth compared to the Hydroponic process. This suggests that the addition of fish and their waste products in the aquaponic systems provides nutrients that promote plant growth. Besides, the lack of nutrient supply could be a reason for less growth of plants in the Hydroponic process.

It is interesting to note that Aquaponic 3 and Aquaponic 4, where fish food was used in combination with BSFL, had slightly less growth compared to Aquaponic 1 and Aquaponic 2. This may indicate that the introduction of BSFL in the aquaponic systems did not provide a significant boost to plant growth, or that the effects of BSFL were offset by other factors such as location, airflow, and temperature. However, despite this slight decrease in growth, the aquaponic systems with BSFL are still superior to the Hydroponic system in terms of plant growth.

Overall, the results of the hydroponic and aquaponic process growth comparison indicate that aquaponic systems, with or without BSFL, are more effective in promoting plant growth compared to the hydroponic system.

4.4 Discussion

The results of the study are analyzed to answer the research questions stated in section 4.1. The first research question focused on whether there was a significant difference in the performance of aquaponic processes with and without the use of black soldier fly larvae (BSFL). The results of the statistical analysis showed that the use of BSFL had a significant negative effect on the growth of the aquaponic processes. This finding suggests that the use of BSFL in aquaponic systems is not an effective strategy for enhancing plant growth.

The second research question investigated whether there were any other factors, aside from BSFL, that affect the growth variation in aquaponic setups. The individual value plot and boxplot revealed that location might be a factor, with Aquaponic 1 and Aquaponic 2 located near the entrance door and far from the wall-mounted air filter unit showing better growth compared to Aquaponic 3 and Aquaponic 4 which are located farther away from the entrance door and near the wall mounted air filter unit. These findings suggest that airflow, light, and optimum temperature may be contributing to growth differences among aquaponic setups, making the location an important distinguishing factor for all the aquaponic processes studied.

The third research question aimed to determine whether the location of the growth area was a significant factor in the performance of the aquaponic setup. The side-by-side comparison between Aquaponic 3 and Aquaponic 4 also shows that location may be a factor even when the feeding method was kept the same. The results of the analysis revealed that the location of the growth area can be a significant factor, as discussed above.

Finally, the fourth research question asked about the growth comparison among hydroponic, aquaponic (with BSFL), and aquaponic (without BSFL) setups. The individual value plot and box plot showed that all the aquaponic processes were much more effective than the hydroponic process. Particularly, Aquaponic 1 and Aquaponic 2 had the highest growth rates, while Aquaponic 4 had the lowest growth rate. In experiment II, the least growth of the hydroponic process can be related to the lack of nutrient supply. These results suggest that aquaponic systems, especially those without the use of BSFL and optimal location, can be an effective alternative to hydroponic systems for plant growth.

The study highlights the potential of aquaponic systems, especially those without the use of BSFL and optimal location, as a promising alternative to hydroponic systems for plant growth. The findings of this study can have practical implications for the development and optimization of sustainable and efficient urban agriculture systems. Further research can be conducted to explore other factors that may affect the growth of aquaponic systems, such as pH levels and nutrient concentrations, to optimize the performance of aquaponic systems for plant growth.

Based on the results of the analysis, it can be concluded that the use of black soldier fly larvae (BSFL) significantly decreases the growth of plants in the aquaponic process. However, location also plays an important role in the growth variation observed in the aquaponic setups. Factors such as airflow, light, and optimum temperature may also have an impact on the growth of plants in aquaponic systems, making the location an important distinguishing factor to consider in aquaponic setups.

These findings suggest that aquaponics may be a more efficient and sustainable way of cultivating plants compared to traditional hydroponics. The results of this study contribute to the existing knowledge on the comparative performance of hydroponic and aquaponic processes in vertical farming. The insights gained from this research can be used to inform decision-making in the development and implementation of sustainable and efficient vertical farming systems.

5. VALUE-ADDED METHODS IN CIRCULAR ECONOMY

5.1 Research Questions

This chapter is trying to address the research gap in vertical farming by exploring the better-performing plant with the study on the impact of each waste type on the growth of each type of plant to address the following research question:

1. What is the flow of value-adding components in the circular economy of vertical farming?

5.2 Methodology

In this research, value-added methods were examined through the secondary farming process, which involved the use of hydroponic waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost in the cultivation of halophyte plants. The hydroponic waste and aquaponic waste were generated from both the vertical farming methods of hydroponic and aquaponic processes.

The methodology for this study involved conducting experiments to determine the most effective way of utilizing the waste products from vertical farming and composting methods. Halophyte plants were grown using various combinations of hydroponic waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost. The plants were then analyzed by determining growth performance. The data collected from the experiments were used to develop a circular economy model for vertical farming. Hydroponic waste and aquaponic waste were also used to produce vermicompost and aerobic compost/quick compost, which were in turn used to grow halophyte plants. Through this methodology, the flow of value-adding components in the circular economy of vertical farming was analyzed and optimized.

Two different experiments were conducted to evaluate the performance of the secondary farming setup. In experiment I, six specific types of halophyte seeds, including Alfalfa, Winter Purslane, Purslane, Shadscale Saltbush, Saltbush, and Herb Saltwort, were grown in the containers. In experiment II, nine different types of halophyte seeds, including Alfalfa, Winter Purslane, Purslane, Herb Saltwort, Lemongrass, Switchgrass, Starwort, Winter Rye, and Vetiver, were used to assess the versatility of the setup across different crops. As the feeding method of the secondary farming processes, hydroponic waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost were used in the secondary farming container in each section. The feeding rate of each of the four feeding methods was maintained consistently throughout the experiments.

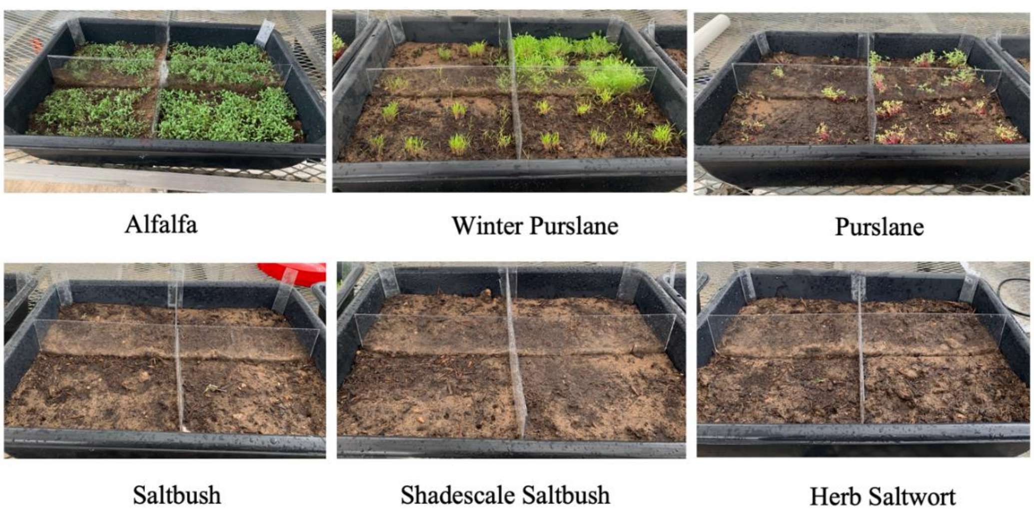


Figure 46. Secondary farming setup from experiment I (Week 5)

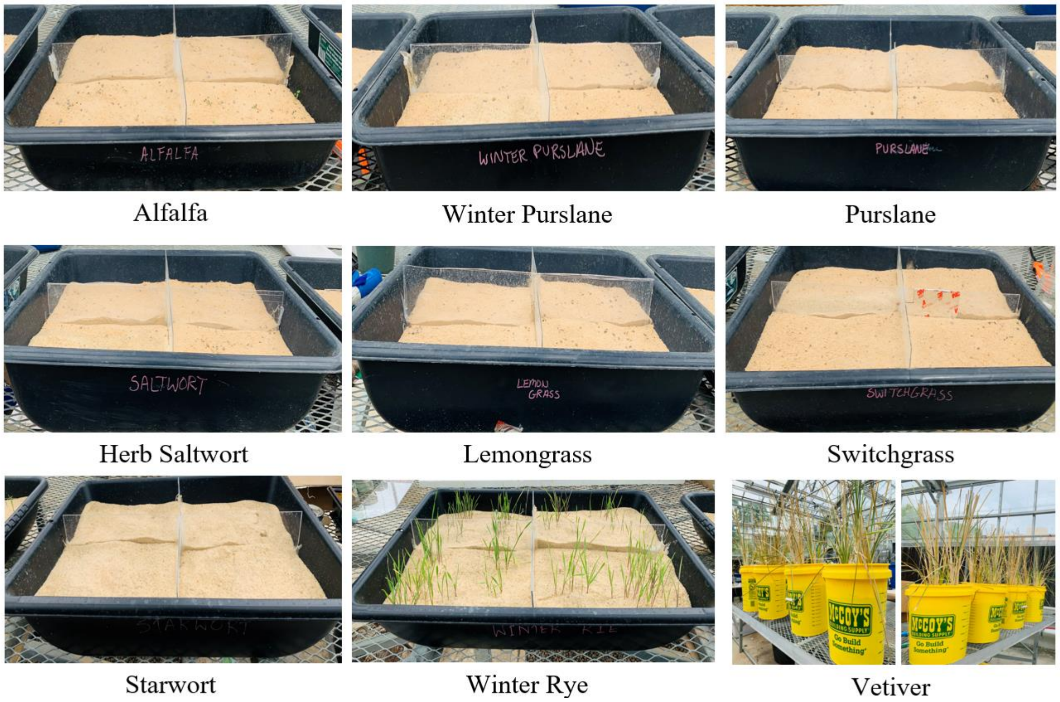


Figure 47. Secondary farming setup from experiment II (Week 5)

5.3 Results

The recorded plant height data from the four sections of the halophyte plants were analyzed for both experiments I and II. The results of the analysis provided insights into the performance of the halophyte plants under different conditions. Through the normalized analysis, the better-performing system among the halophyte plants studied was identified. The data on plant height also allowed for comparisons to be made between the different value-added components in the circular economy of vertical farming, such as the use of hydroponic waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost.

5.3.1 Experiment I

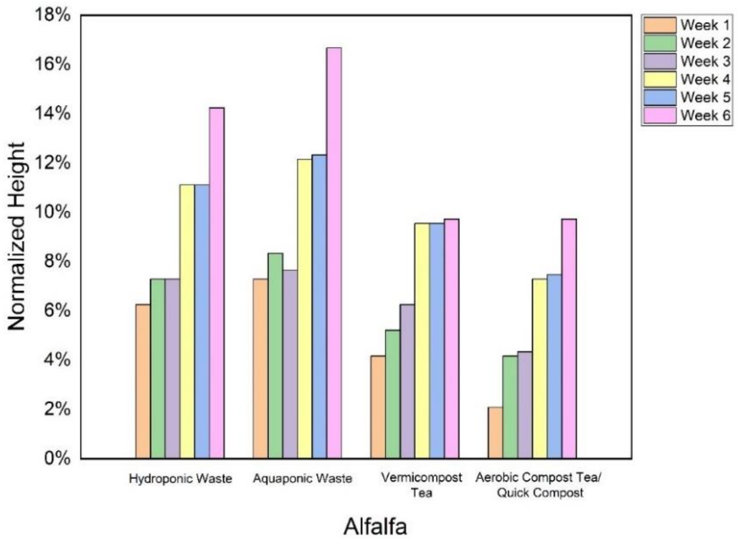


Figure 48. Alfalfa normalized height analysis

The results showed that the Alfalfa plants grown using aquaponic waste exhibited the highest growth rates (as depicted in Figure 48), while those grown using hydroponic waste showed the second-highest growth rates. In terms of the normalized height data analysis, both types of waste showed almost similar growth in week 6 when the vermicompost tea and aerobic compost tea/quick compost feeding system were used.

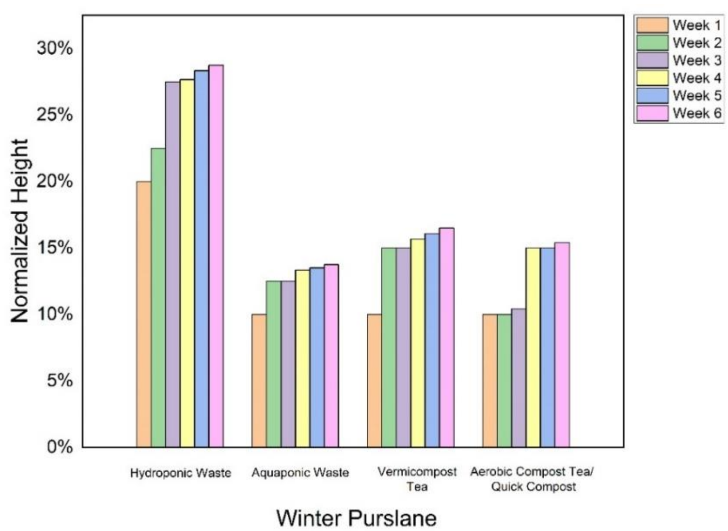


Figure 49. Winter Purslane normalized height analysis

The analysis of the Winter Purslane normalized height data revealed that the hydroponic waste feeding method resulted in the highest growth among all the feeding methods. This is demonstrated in Figure 49, where the height growth for the hydroponic waste feeding method exhibits a higher trend compared to the other feeding methods. At the end of week 6, all the other feeding methods showed similar growth, with no significant difference among them. These results suggest that the feeding method of hydroponic waste is particularly effective for promoting growth in Winter Purslane plants.

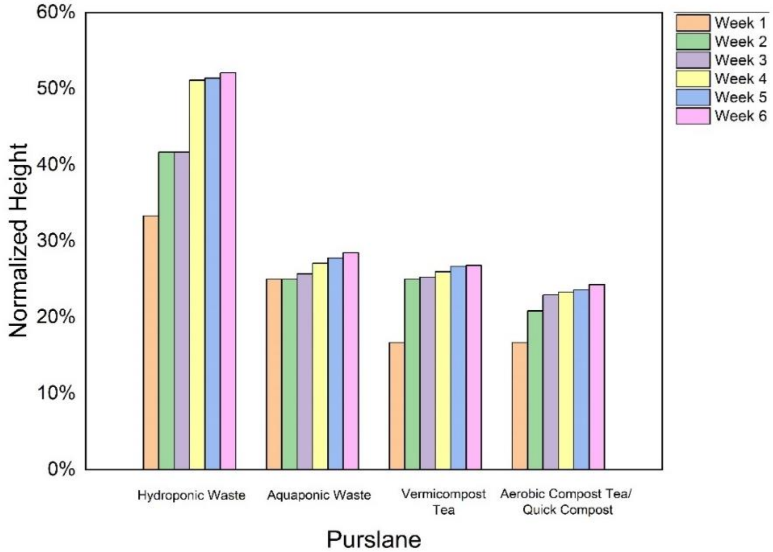


Figure 50. Purslane normalized height analysis

The results of the normalized height analysis (Figure 50) for Purslane demonstrated a trend of the highest growth in the hydroponic waste feeding method, which is similar to the findings for Winter Purslane. This indicates that hydroponic waste is a favorable feeding method for these two types of plants. The other feeding methods showed comparable growth rates, but none were as effective as hydroponic waste.

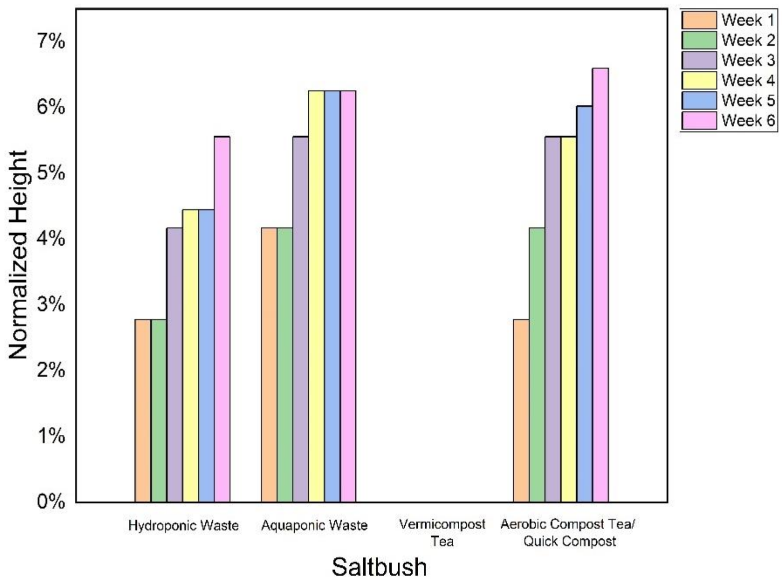


Figure 51. Saltbush normalized height analysis

The findings of the normalized height analysis showed a different trend for Saltbush growth (Figure 51) compared to the other halophyte plants studied. Unlike Purslane and Winter Purslane, the highest peak in the normalized height analysis was not observed in the hydroponic waste feeding method. Instead, the feeding method of aerobic compost tea/quick compost resulted in the highest growth, with the second highest growth observed in the aquaponic feeding method. Interestingly, there was no growth observed in the vermicompost tea feeding method for Saltbush. These results indicate that different halophyte plants respond differently to the types of waste used as a nutrient source.

However, no plant growth was observed in any of the feeding methods for Shadscale Saltbush. This result suggests that further research is required to understand the reasons behind this lack of growth. It could be due to a variety of factors such as bad seed, wrong season, bad growth conditions, or other environmental factors that could affect plant growth. Further analysis and experimentation could help to identify the underlying causes and provide insights into how to improve the growth of Shadscale Saltbush in the future.

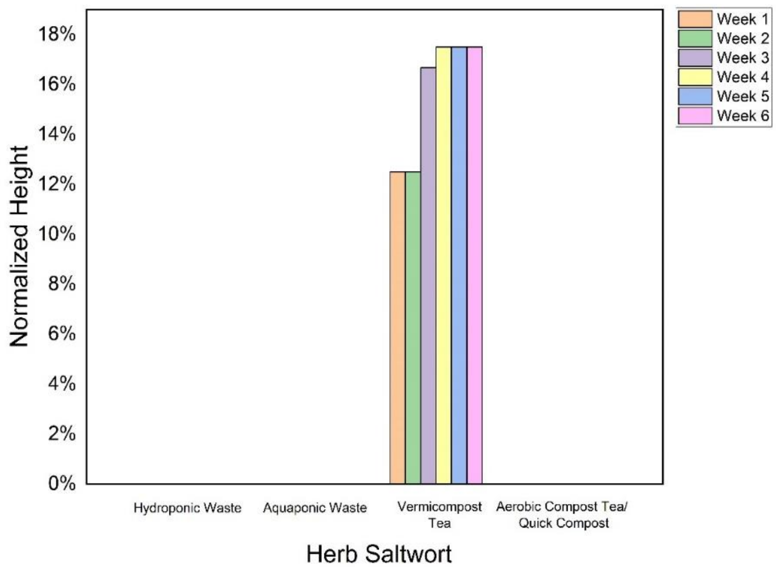


Figure 52. Herb Saltwort normalized height analysis

The findings from the analysis of Herb Saltwort height data (Figure 52) revealed that growth was exclusively observed in the vermicompost tea feeding method, with no growth detected in the other feeding methods. These outcomes imply that vermicompost tea could be the most appropriate feeding method for Herb Saltwort. However, additional research is required to identify the underlying factors that contribute to the compatibility of vermicompost tea with this plant species.

The results from the normalized height data analysis of the halophyte plants in experiment I suggest that the type of waste used had a significant impact on plant growth. Although growth data were observed for most of the halophytes in the secondary farming process, discrepancies were identified in experiment I, including the use of rich soil instead of weak soil, poor quality seeds, and improper draining and sealing of secondary farming containers. Despite the discrepancies, experiment I provided comprehensive insights into the value-added methods of using hydroponic waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost in the cultivation of halophyte plants.

The results of the height data analysis also suggest that some halophyte plants may be more suited to certain types of waste than others. For example, the highest peak in the normalized height analysis for Purslane and Winter Purslane was observed in the hydroponic waste feeding method, whereas the highest peak for Saltbush growth was observed in the feeding method of aerobic compost tea/quick compost.

Overall, the findings of experiment I highlight the potential of using various types of waste materials in the cultivation of halophyte plants in circular economy systems. However, more research is needed to better understand the specific factors that contribute to plant growth and to optimize the use of waste materials in these systems.

5.3.2 Experiment II

Experiment II was conducted to address the discrepancies that were found in experiment I by using nine halophyte plants instead of six and starting the experiment in spring instead of fall. However, unlike in experiment I where significant growth was observed among most of the halophytes, no significant growth was observed in experiment II even after six weeks. Several factors, such as irregular water supply and deep seed placement, could be the reasons for the absence of growth until week 6. Further research is needed to determine the specific factors that led to the lack of growth in experiment II and to identify methods for improving the success of the secondary farming process for halophyte plants.

5.4 Discussion

The findings of this chapter contribute to the existing literature on circular economy practices in vertical farming by highlighting the potential of value-added methods. The use of hydroponic waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost in secondary farming could provide a sustainable solution to waste management while also promoting plant growth. The findings of this study provide valuable insights into the use of value-added methods in circular economy practices in vertical farming. The results suggest that different waste types may have varying impacts on the growth of different types of plants, highlighting the need for tailored approaches to nutrient management in secondary farming processes. The secondary farming process used in this study demonstrates how waste products can be repurposed to create value in other systems, providing a sustainable approach to resource management. These findings could inform the development of more efficient and sustainable farming practices that contribute to the circular economy.

It was found that Alfalfa plants performed better with the use of aquaponic waste as a feeding method, while Winter Purslane and Purslane plants showed better growth with the use of hydroponic waste. However, the results for Saltbush and Herb Saltwort demonstrated that different halophyte plants respond differently to the types of waste used as a nutrient source, with aerobic compost tea/quick compost showing the highest growth rates for Saltbush. Herb Saltwort displayed better growth with the use of vermicompost tea as the feeding method. These findings suggest that different types of halophyte plants may have different requirements for nutrients and waste types to achieve optimal growth.

The use of waste products as a source of nutrients for plant growth is a key aspect of circular economy practices in vertical farming. The secondary farming process used in this study demonstrates how waste from one system can be used to create value in another system, creating a closed-loop system that minimizes waste and maximizes resource efficiency. This approach has important implications for sustainability in agriculture and could be applied in other farming systems to reduce waste and improve resource management.

Furthermore, the results of the data analysis indicate that the type of waste used for feeding the halophyte plants can have a significant impact on their growth. However, it is also important to note that several factors, such as environmental conditions and growth time, can influence the performance of halophyte plants. These findings highlight the importance of carefully selecting and managing the input factors in circular economy practices in vertical farming to achieve optimal results. Therefore, future research can focus on investigating the impact of different environmental factors on the growth of halophyte plants in circular economy practices in vertical farming. Further analysis of the data collected from the secondary farming process revealed interesting insights regarding the impact of each waste type on the growth of each type of halophyte plant.

In conclusion, this chapter provides insights into the potential of value-added methods in circular economy practices to promote sustainable waste management and enhance plant growth in vertical farming. The findings of this study can inform the development and implementation of circular economy practices in vertical farming to achieve optimal results and contribute to a more sustainable food system.

6. VERTICAL FARMING CIRCULAR ECONOMY MODEL

6.1 Research Questions

This chapter is trying to address the research gap in vertical farming by proposing and analyzing a computer model of the circular economy of VF to address the following research questions:

1. How can a circular economy model be developed for vertical farming?
2. What are the optimal settings and capacities required in each stage to achieve balance and minimize waste in the circular economy of vertical farming?

6.2 Methodology

The modeling process has been an iterative one, which involves multiple cycles of refining and adjusting the model based on the outcomes of simulations and experiments. Models are essential tools that enable researchers to creatively think about and understand the real system. Through modeling, it is possible to simulate various scenarios, test different assumptions, and optimize the overall process to achieve the desired outcomes. The developed models in this research helped to identify and evaluate the key factors affecting the circular economy system and provided insights into the optimal resource allocation and management strategies. Additionally, modeling allowed for the prediction of the system's behavior under various conditions and assisted in the decision-making process for the selection of value-added products.

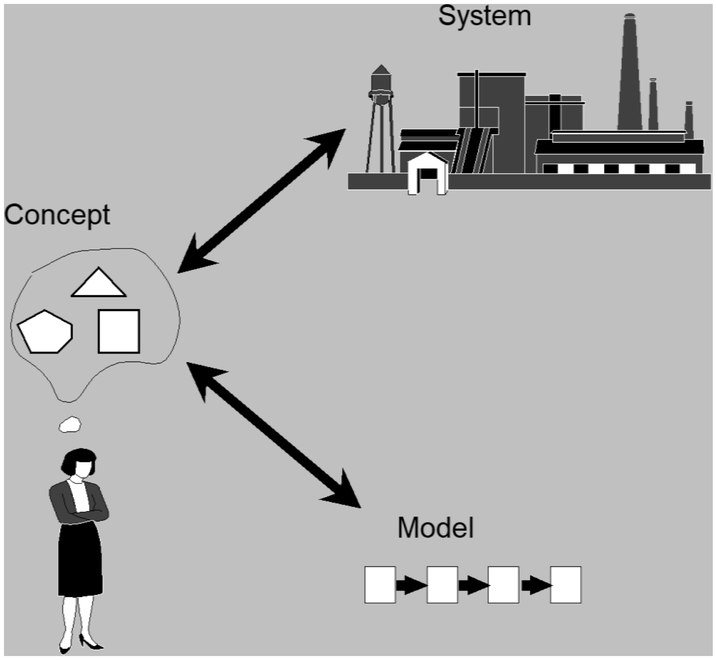


Figure 53. Model demonstration [115]

The major steps in a simulation model study involve [115]:

1. Problem formulation

2. Setting of objectives and overall project plan

3. Model conceptualization

4. Data collection

5. Model translation

6. Verification

7. Validation

8. Experimental design

9. Production runs and analysis

10. More runs

11. Documentation and reporting

12. Implementation

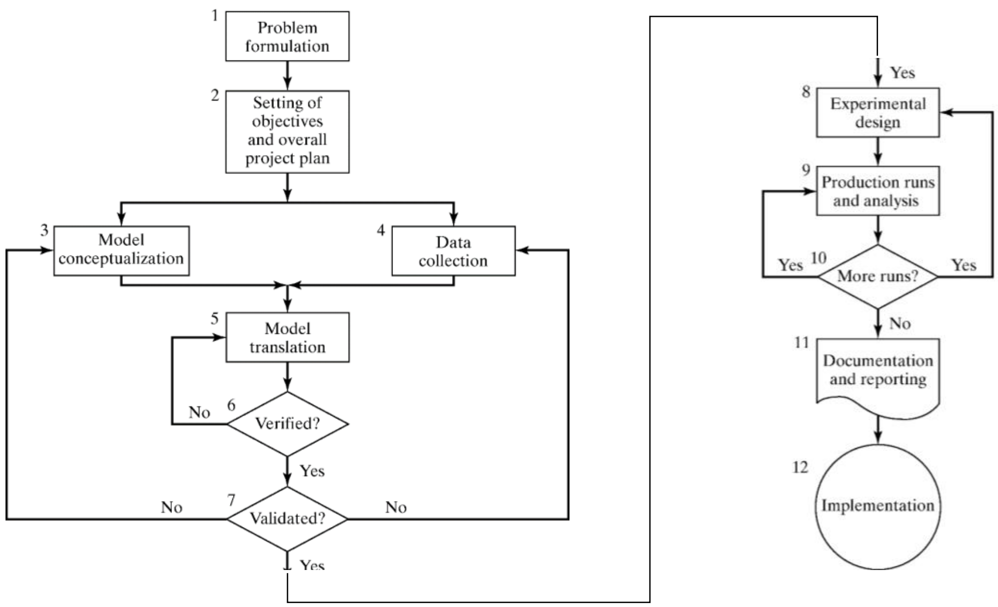


Figure 54. Steps in a simulation study [115]

6.3 Results

6.3.1 Problem Formulation

The problem formulation section is a key part of this research as it sets the foundation for the entire simulation model. The problem formulation step aimed to identify the key challenges faced by traditional vertical farming methods and to develop a sustainable and efficient circular economy model that addresses these issues. The research emphasized the importance of evaluating the byproducts of the process and studying the balancing of resources and capacities in each stage. Additionally, the research focused on selecting high value-added products, optimizing resource utilization, and minimizing waste.

The problem formulation (step 1) was developed by considering various factors such as environmental conditions, resource availability, and market demand. The research identified the need for effective resource management, optimal process design, and the selection of high-value products to ensure the success of the circular economy model. The goal was to develop a comprehensive understanding of the circular economy model and its various components to identify potential areas for improvement. By developing a sustainable and efficient circular economy model, this research aimed to make soilless agriculture, particularly vertical farming, more financially viable, environmentally sustainable, and capable of contributing to food security in the face of a growing population and climate change.

6.3.2 Setting of Objectives and Overall Project Plan

To establish the ideal setting and capacity for each stage of the integrated organic hydroponic-aquaponic farming system, a comprehensive analysis of the requirements was conducted in the second step. The objectives were designed to ensure a balance between stages, minimize waste and achieve maximum profitability at a minimum cost. The analysis considered resource availability, environmental factors, and market demand, taking into account the unique characteristics and requirements of each stage of the system.

The objectives were formulated to address the challenges faced by the traditional vertical farming method, such as high investment costs, maintenance costs, energy consumption, and waste generation. By identifying the optimum settings and capacity for each stage, the research aimed to improve the overall efficiency of the system while also addressing environmental concerns. The overall project plan was developed to guide the research toward achieving the set objectives. The plan included a detailed schedule for data collection, experimentation, model translation, and analysis. The plan also considered potential challenges and contingencies, ensuring that the research would progress smoothly and effectively. The established objectives and project plan provided a clear roadmap for the research, ensuring that it was conducted in a structured and systematic manner.

6.3.3 Model Conceptualization

The model conceptualization step is an essential part of the simulation process, and it involves creating a conceptual model that represents the real-world system being studied. In this step (step 3), the conceptual model was formulated based on the experimental data collected during the research. The conceptual model served as the foundation for developing the simulation model in the next step. It allowed for the identification of the key variables, their relationships, and the processes that affected the system.

For the simulation model in this research, the Arena® simulation software package [116] was utilized. This software is widely used in the field of operations research and allows for the creation of a detailed model of the system being studied. The software provided a user-friendly interface to build the simulation model, where the conceptual model was translated into a computational model. This process involved defining the system components, their interactions, and the rules governing their behavior. The resulting simulation model allowed for the exploration of different scenarios and the evaluation of the circular economy system's performance.

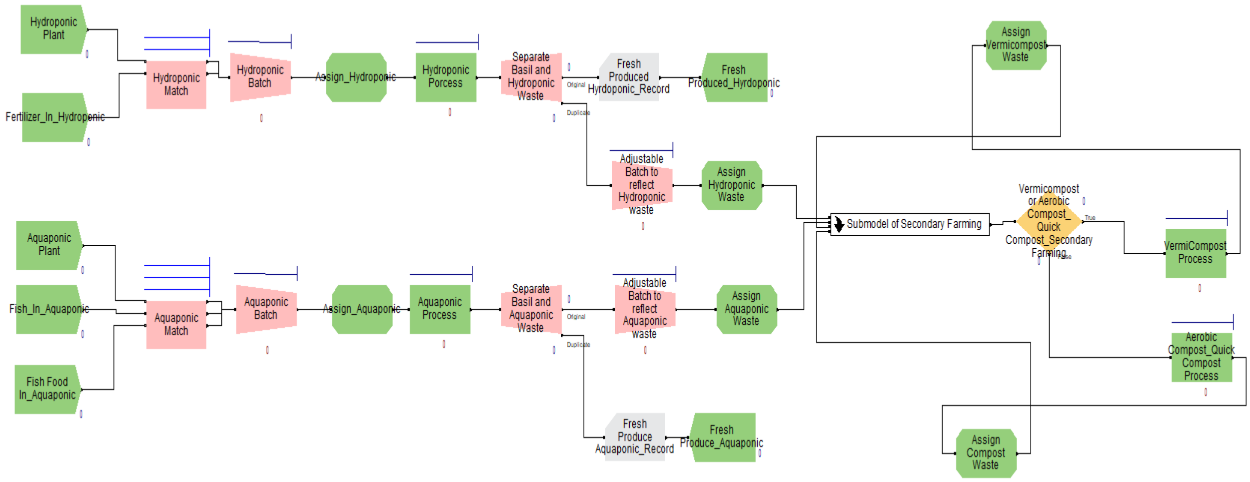


Figure 55. Arena model

6.3.4 Data Collection

The data collection process (step 4) was important in obtaining accurate and reliable data to validate the simulation model. To ensure the collection of high-quality data, a detailed data collection plan was developed that included the selection of appropriate measurement tools and instruments, data recording protocols, and data management strategies. The experiment was carried out with great care and attention to detail, following the experimental design. The data collected from each process, including hydroponics, aquaponics, vermicomposting, aerobic compost tea/ quick compost, and secondary farming, were used to refine the simulation model. The data collected during the experiment were thoroughly analyzed to extract meaningful insights and to identify any trends or patterns that may be relevant to the circular economy of the VF. The data collected was used to evaluate the feasibility of a zero-waste circular economy and to develop a comprehensive model that considers all aspects of the VF.

6.3.4.1 Hydroponic Process

(1) Input: Hydroponic Plant

Entity Type: Basil

Type: Constant

Value: 28 Days

Entities Per Arrival: 24

Max Arrivals: infinite

(2) Input: Fertilizer_In_Hydroponic

Entity Type: Fertilizer_Hydroponic

Type: Constant

Value: 28 Days

Entities Per Arrival: 24

Max Arrivals: infinite

Resource:

Name: Hydroponic Pot

Capacity Type: Fixed Capacity

Capacity: 24

Process:

Name: Hydroponic Process

Type: Standard

Action: Seize Delay Release

Delay Type: Constant

Allocation: Value Added

Value: 28

Unit: Days

Output:

(1) Fresh produce_hydroponic

(2) Hydroponic waste

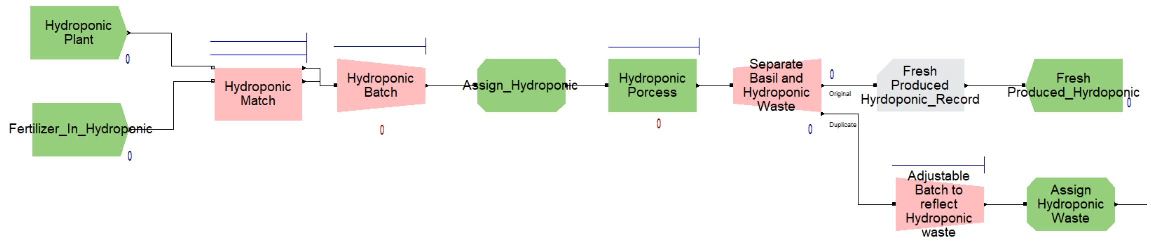


Figure 56. Hydroponic process model

6.3.4.2 Aquaponic Process

(1) Input: Aquaponic Plant

Entity Type: Basil

Type: Constant

Value: 28 Days

Entities Per Arrival: 96

Max Arrivals: infinite

(2) Input: Fish Food In_Aquaponic

Entity Type: Fish_Food_Aquaponic

Type: Constant

Value: 28 Days

Entities Per Arrival: 96

Max Arrivals: infinite

(3) Input: Fish_In_Aquaponic

Entity Type: Fish_Aquaponic

Type: Constant

Value: 28 Days

Entities Per Arrival: 96

Max Arrivals: infinite

Resource:

Name: Aquaponic Pot

Capacity Type: Fixed Capacity

Capacity: 96

Process:

Name: Aquaponic Process

Type: Standard

Action: Seize Delay Release

Delay Type: Constant

Allocation: Value Added

Value: 28

Unit: Days

Output:

(1) Fresh produce_Aquaponic

(2) Aquaponic waste

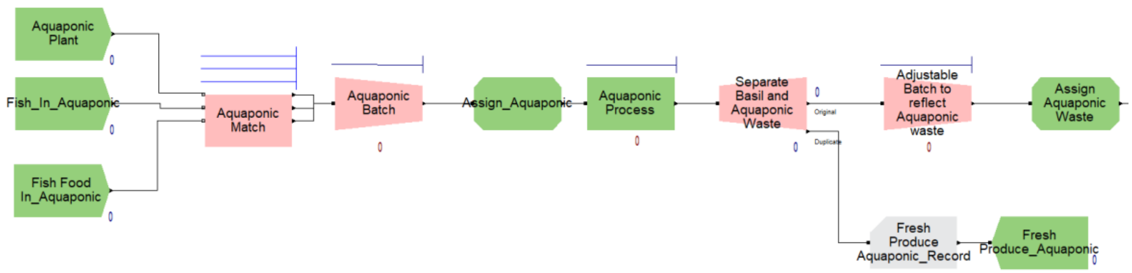


Figure 57. Aquaponic process model

6.3.4.3 Composting Process

6.3.4.3.1 Vermicompost Tea

Input: Secondary farming plant waste

Name: VermiCompost Process

Type: Standard

Action: Seize Delay Release

Delay Type: Constant

Allocation: Value Added

Value: 14

Unit: Days

Output: Vermicompost Waste

6.3.4.3.2 Aerobic Compost Tea/ Quick Compost

Input: Secondary farming plant waste

Name: Aerobic Compost_Quick compost Process

Type: Standard

Action: Seize Delay Release

Delay Type: Constant

Allocation: Value Added

Value: 14

Unit: Days

Output: Compost Waste

6.3.4.4 Secondary Farming Process

In the secondary farming process (Figure 58), four feeding methods were considered including hydroponic waste, aquaponic waste, vermicompost waste, and compost waste. This study will allow for the exploration of different scenarios and potential outcomes based on various input parameters for future decision-making and optimization of the secondary farming process.

(1) Input: Hydroponic waste

(2) Input: Aquaponic waste

(3) Input: Vermicompost waste

(4) Input: Compost waste

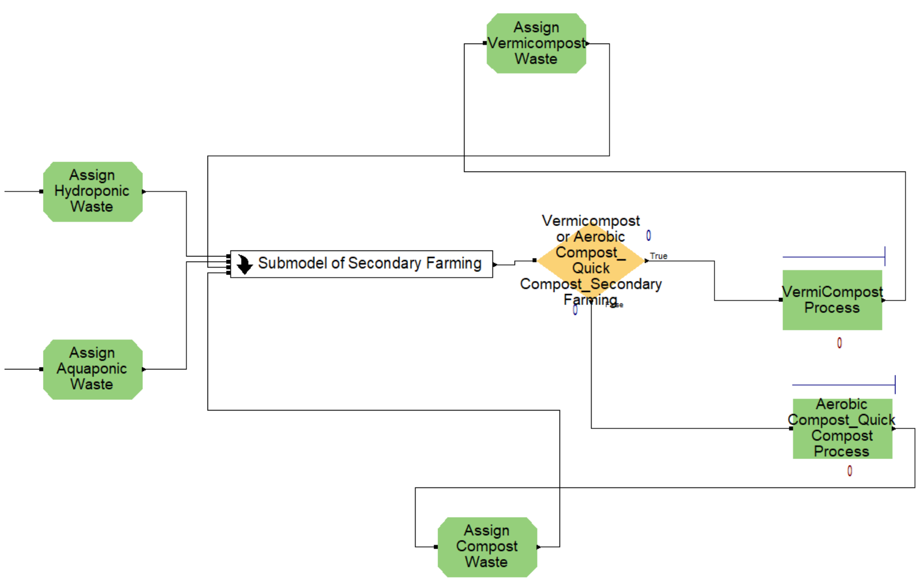


Figure 58. Secondary farming process model with four inputs

The submodel of secondary farming includes four different types of secondary farming based on each of the feeding methods. These farming types generate both fresh produce and waste, with the waste being directed to the decision module for distribution between vermicompost and aerobic compost tea/quick compost processes. The simplified version of the secondary farming sub-model is presented using the experiment data for demonstration purposes. However, the sub-model can be expanded in the future to incorporate additional farming types as per requirement. This submodel provides a valuable tool for understanding the potential outcomes of different feeding methods and their impact on the secondary farming process.

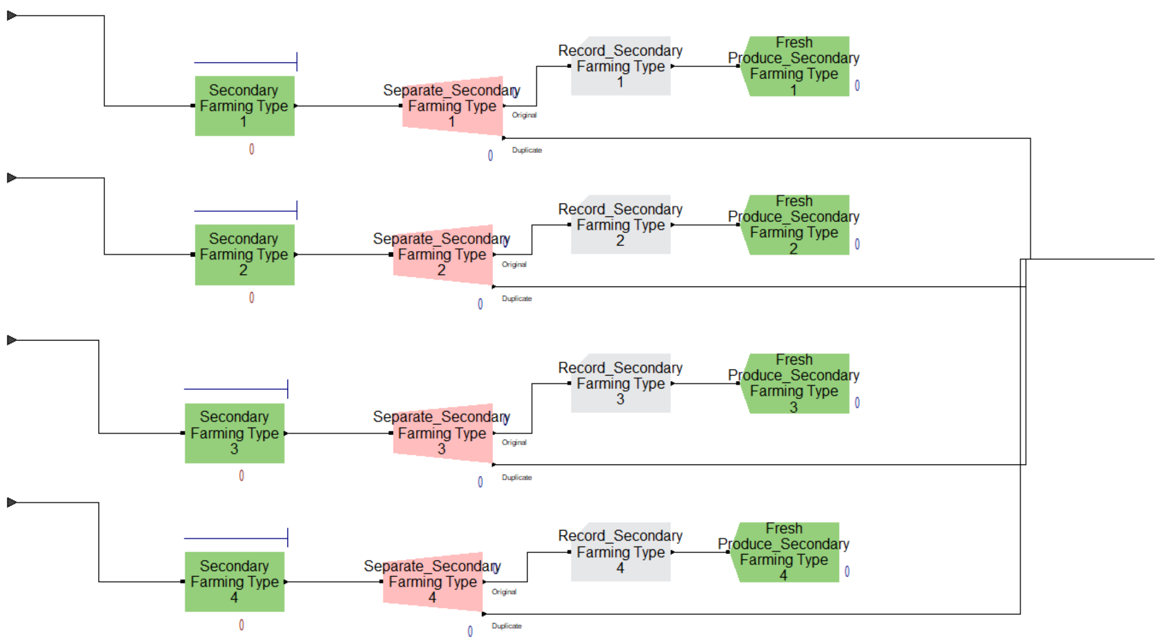


Figure 59. Submodel of the secondary farming process

6.3.5 Model Translation

Model translation (step 5) involves transforming the conceptual model into a computer-based simulation model. In this step, the conceptual model was translated into a working simulation model that can be run and analyzed using Arena software. For this research, the model translation step involved integrating all the processes related to hydroponic, aquaponic, composting, and secondary farming into a single-running arena model. This step was done by anticipating the model conceptualization and data collection steps together, allowing for a smooth and efficient transition from the conceptual model to the simulation model. The integrated arena model allowed for the analysis of the circular economy of VF, evaluating the various components and alternatives of the circular economy model, byproducts, and balancing of resources and capacities in each stage. By combining all these processes into a single simulation model, the optimum settings/capacity were evaluated in each stage to achieve an optimum balance between stages and minimize waste.

Overall, the model translation step was critical in the research as it enabled the creation of a working simulation model that can be used to evaluate the feasibility of a zero-waste circular economy in VF. The integrated arena model provides a powerful tool for evaluating and optimizing the various components of the circular economy model, which can help farmers achieve maximum profitability while also reducing waste and promoting sustainability.

6.3.6 Verification

In the verification process, it is important to ensure that all processes are connected and that all resources and entities are accounted for. The model accurately reflects the real-world system being simulated.

	Name	Entity Type	Type	Value	Units	Entities per Arrival	Max Arrivals	First Creation
1	Fertilizer_In_Hydroponic	Fertilizer_Hydroponic	Constant	28	Days	24	infinite	0.0
2	Hydroponic Plant	Basil	Constant	28	Days	24	infinite	0.0
3	Aquaponic Plant	Basil	Constant	28	Days	96	infinite	0.0
4	Fish Food In_Aquaponic	Fish_Food_Aquaponic	Constant	28	Days	96	infinite	0.0
5	Fish_In_Aquaponic	Fish_Aquaponic	Constant	28	Days	96	infinite	0.0

Figure 60. Resource verification

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	Hydroponic Pot	Fixed Capacity	24	0.0	0.0	0.0		0 rows	☑
2	Aquaponic Pot	Fixed Capacity	96	0.0	0.0	0.0		0 rows	☑
3	plant waste_Vermicompost	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
4	plant waste_Aerobic Compost_Quick Compost	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
5	Secondary_Farming_Type_1	Fixed Capacity	Infinite	0.0	0.0	0.0		0 rows	☑
6	Secondary_Farming_Type_2	Fixed Capacity	Infinite	0.0	0.0	0.0		0 rows	☑
7	Secondary_Farming_Type_3	Fixed Capacity	Infinite	0.0	0.0	0.0		0 rows	☑
8	Secondary_Farming_Type_4	Fixed Capacity	Infinite	0.0	0.0	0.0		0 rows	☑

Figure 61. Resource capacity verification

Additionally, it was ensured that process flows are error-free and that the time units used in the simulation are correct for the entire model. Finally, it was tested whether the program behaves as expected and meets the objectives set out in the simulation design. These checks are important to ensure that the simulation results are accurate and reliable and can be used to make informed decisions about the real-world system being modeled.

6.3.7 Validation

The goal of the validation process was to demonstrate that the developed arena simulation model is reliable and accurate. To achieve this, different scenarios were observed within the research, and compared the model output with the given data to ensure its accuracy. The criteria used in the model were correlated with the expected results to ensure that the model output is consistent with the requirements.

In the circular economy model, the output is directly proportional to the utilization of resources. This means that to achieve 10 times more output,10 times more resources were utilized, and similarly, 100 times more resources were utilized to achieve 100 times more output from the process.

To validate the model, the model output was observed with the expected results to ensure that it meets the desired requirements. Through this process, confidence was gained in the accuracy of the model to make informed decisions about the circular economy system under study. The validation process ensured that a model is a reliable tool for assessing the performance of the circular economy system in vertical farming.

6.3.8 Experimental Design

The experimental design for the simulation study was a critical aspect of ensuring the accuracy and reliability of the results. To begin with, a thorough review was conducted to identify the key variables and resources relevant to the circular economy model. This review helped ensure that the model was based on the most up-to-date and relevant information available.

Next, the simulation model was tested using numerous resource parameters derived from the review and the conceptual model. This allowed to assess the model's sensitivity to different resource parameters and identify the most important factors affecting the circular economy model. The experimental design criteria included the correlation between the model and actual data, as well as the extent to which the model output met the research objectives.

The simulation study involved testing the model under different scenarios with varying resource parameters, such as the replication length of experiments, the number of hydroponic and aquaponic plants, and the amount of vermicompost and aerobic compost used. Table 8 provides a demonstration of the experimental design, showing the different input parameters that were tested in the simulation model.

Table 8. Experimental design table for the Arena model

SL No	Resources						Replication Length (Days)	Utilization				No of Basil
	Hydroponic Plant		Aquaponic Plant		plant waste_Vermicompost	plant waste_Aerobic Compost_Quick Compost		Hydroponic Pot	Aquaponic Pot	plant waste_Vermicompost	plant waste_Aerobic Compost_Quick Compost	
	Entry per arrival	Capacity	Entry per arrival	Capacity								
1	24	24	96	96	1	1	180	100%	100%	84%	84%	1560
2	24	24	96	96	1	1	300	100%	100%	90%	90%	2520
3	24	48	96	120	1	1	300	50%	80%	90%	90%	2520
4	48	72	120	144	1	1	300	67%	83%	90%	90%	3528
5	72	96	144	168	1	1	300	75%	86%	90%	90%	4536
6	96	120	168	192	1	1	300	80%	88%	90%	90%	5544
7	120	144	192	216	1	1	300	83%	89%	90%	90%	6552
8	144	168	216	240	1	1	300	86%	90%	90%	90%	7560
9	168	192	216	240	1	1	300	88%	90%	90%	90%	8064
10	192	216	216	240	1	1	300	89%	90%	90%	90%	8568
11	216	240	216	240	1	1	300	90%	90%	90%	90%	9072

Each experiment was replicated for a varied time duration, and the results of each experiment were carefully analyzed to ensure that the model output was consistent with the research objectives and the available data. A rigorous fine-tuning approach was used by comparing the model outputs with different resource parameters, to achieve the set target of balance utilization close to 90% output.

Overall, the experimental design process for the simulation study followed a systematic approach to ensure the accuracy and validity of the results. The use of multiple input parameters and careful analysis of the model outputs helped identify the most critical variables affecting the circular economy model and ensure that the results were reliable and meaningful.

6.3.9 Production Runs and Analysis Part

In this section, the production runs were conducted using the validated simulation model. The purpose of these runs was to evaluate the performance of the circular economy model under different scenarios and to identify areas where improvements could be made. The production runs were conducted using a range of input parameters that reflect different operating conditions and scenarios. For each set of input parameters, the simulation model was run for a period to generate output data. The output data from the production runs were analyzed to identify trends and patterns in the data. This analysis helped to identify areas where the model could be improved or optimized. In addition, the data were used to generate performance metrics that could be used to evaluate the overall effectiveness of the circular economy model. Overall, the production runs and subsequent analysis demonstrated that the circular economy model was effective in achieving its goals of minimizing waste and maximizing profitability. The model was able to generate high-value products from waste streams and optimize the use of resources across different stages of the process. These results have important implications for the design and implementation of circular economy systems in similar settings.

6.3.10 More Runs

To further optimize the model, numerous production runs were executed under different scenarios and conditions. The simulation was carried out several times with diverse parameters, such as varied production scales, to evaluate the model's output under different circumstances. Through these additional runs, the model was examined for its robustness, sensitivity, and accuracy toward different production scales.

To conduct these additional runs, a table was designed that includes different production scales, resources, replication length, output, and the number of basil plants. The results obtained from these runs were carefully examined and compared to the experimental data. Any inconsistencies were identified, and necessary adjustments were made to the model.

Table 9. More runs table for the Arena model

Scale	Resources						Replication Length (Days)	Utilization				No of Basil
	Hydroponic Plant		Aquaponic Plant		plant waste_Vermicompost	plant waste_Aerobic Compost_Quick Compost		Hydroponic Pot	Aquaponic Pot	plant waste_Vermicompost	plant waste_Aerobic Compost_Quick Compost	
	Entry per arrival	Capacity	Entry per arrival	Capacity								
2X	432	480	432	480	2	2	300	90%	90%	90%	90%	18144
4X	864	960	864	960	4	4	300	90%	90%	90%	90%	36288
10X	2160	2400	2160	2400	10	10	300	90%	90%	90%	90%	90720

The additional runs facilitated the exploration of various production scales to optimize the use of resources and output from the process. The model was used to compare and assess the impact of different production scales, leading to the identification of the most sustainable and efficient approaches for basil plant production.

Overall, more runs provided significant insights into the model's behavior and performance, leading to further refinement and optimization of the simulation. Table 9 included in this section summarizes the results obtained from the additional runs, which demonstrate the impact of production scale on resource utilization and plant output.

6.3.11 Documentation and Reporting

The simulation model is a complex system that requires careful documentation and reporting to ensure that the results are reproducible and that the model can be verified and validated by other researchers. The documentation and reporting section of the simulation involved documenting the simulation design, assumptions, input data, and model output in detail. The report included a detailed analysis of the results, including the comparison of different scenarios and sensitivity analysis of key parameters.

To document the simulation model, we developed detailed documentation that includes the model resources, processing time, and output. This documentation ensures that anyone can understand the model and reproduce the results. Comprehensive reports were generated that detail the results of the simulation model.

The documentation and reporting process is crucial for the simulation model's accuracy and reproducibility. Without this documentation, it would be challenging to verify and validate the model's results, making it difficult to use the simulation model for future research or decision-making processes. Overall, the documentation and reporting section of the simulation is crucial for communicating the results of the simulation to stakeholders, and for ensuring transparency and reproducibility of the simulation methodology and results.

6.3.12 Implementation

The simulation model developed in this study can serve as a tool for decision-making and optimization in a real-world system. To implement the results and recommendations from the simulation study, several steps can be taken:

First, the simulation model can be used to identify the optimal capacity and configuration of each stage of the circular economy process, which can then be used as a guide for the design and construction of the physical system.

Second, the simulation results can inform the selection of production scale and the allocation of resources within the system.

Third, the simulation model can be used to develop operational strategies for the real-world system, such as scheduling production runs and inventory management.

Fourth, the simulation model can be updated and refined over time as new data becomes available, allowing for ongoing optimization and improvement of the circular economy process.

Overall, the implementation of the simulation model can help ensure the efficient and effective operation of the circular economy system, leading to improved environmental sustainability and economic profitability.

6.4 Discussion

The focus of this chapter is on proposing and analyzing a computer model of the circular economy of vertical farming (VF). The research questions addressed in this chapter are how a circular economy of VF can be modeled, and what the optimum settings/capacity in each stage are to achieve an optimal balance between stages and minimize waste.

The methodology used in this research is an iterative modeling process that involves multiple cycles of refining and adjusting the model based on the outcomes of simulations and experiments. The developed models in this research helped to identify and evaluate the key factors affecting the circular economy system and provided insights into the optimal resource allocation and management strategies. The simulation model is based on the Arena software.

The simulation study followed a twelve-step process, which includes problem formulation, setting of objectives and overall project plan, model conceptualization, data collection, model translation, verification, validation, experimental design, production runs and analysis, more runs, documentation, reporting, and implementation. In the problem formulation step, various factors such as environmental conditions, resource availability, and market demand were considered to develop a comprehensive understanding of the circular economy model and its various components. To establish the ideal setting and capacity for each stage of the integrated organic hydroponic-aquaponic farming system, a comprehensive analysis of the requirements was conducted in the second step. The objectives were designed to ensure a balance between stages, minimize waste, and achieve maximum profitability at a minimum cost. The overall project plan was developed to guide the research toward achieving the set objectives. The model conceptualization step involved creating a conceptual model that represents the real-world system being studied. The conceptual model served as the foundation for developing the simulation model in the next step. It allowed for the identification of the key variables, their relationships, and the processes that affect the system. Data collection was a crucial step in obtaining accurate and reliable data to validate the simulation model. A detailed data collection plan was developed that included the selection of appropriate measurement tools and instruments, data recording protocols, and data management strategies. The experiment was carried out with great care and attention to detail, following the experimental design. The data collected from each process was used to refine the simulation model. The data collected during the experiment were thoroughly analyzed to extract meaningful insights and to identify any trends or patterns that may be relevant to the circular economy of the VF. In addition to collecting data, the simulation model was developed by translating the conceptual model into a mathematical representation. This translation process involved identifying the necessary variables, parameters, and relationships to be included in the simulation model. The simulation model was developed using the Arena simulation software, which allowed for the creation of a detailed model of the system being studied. Once the simulation model was developed, it was verified and validated. Verification involved ensuring that the simulation model was programmed correctly and produced the expected results. Validation involved comparing the simulation results with real-world data to ensure that the model accurately represented the real system. The experimental design was an important step in the modeling process as it involved testing the simulation model under various scenarios and conditions to identify the optimal settings and capacity for each stage of the circular economy model. The experimental design was developed based on the established objectives and project plan and aimed to identify the most effective resource allocation and management strategies for each stage. The production runs and analysis step involved running the simulation model under the experimental design to generate results. The results were analyzed to extract meaningful insights and to identify any trends or patterns that may be relevant to the circular economy of the VF. The data collected during the experiment were used to refine the simulation model and to evaluate the feasibility of a zero-waste circular economy.

The modeling process concluded with the documentation and reporting step, where the results of the simulation model were documented and reported. The documentation and reporting of the simulation model were crucial to ensure that the research was conducted in a structured and systematic manner and that the results were reproducible and reliable.

Overall, the modeling process was an iterative one that involved multiple cycles of refining and adjusting the model based on the outcomes of simulations and experiments. The developed models in this research helped to identify and evaluate the key factors affecting the circular economy system and provided insights into the optimal resource allocation and management strategies.

In summary, the proposed circular economy model of VF has the potential to address the challenges faced by the traditional vertical farming method, such as high investment costs, maintenance costs, energy consumption, and waste generation. By identifying the optimum settings and capacity for each stage, the research aimed to improve the overall efficiency of the system while also addressing environmental concerns. The model developed in this research can be used as a tool for decision-making in the selection of high value-added products and resource allocation and management strategies.

7. CONCLUSION AND FUTURE WORKS

7.1 Conclusion

This research presents an integrated organic hydroponic-aquaponic circular model for vertical farming that has the potential to address the growing challenges of traditional agriculture. By utilizing a zero-waste circular economy approach, the research aimed to achieve profitability through the efficient utilization of byproducts, balancing of resources and capacities in each stage, and selection of high value-added products. The research questions were answered and justified through a simulation study, which demonstrated the feasibility of the proposed model.

The study provided insights into the components, parameters, and alternatives for each stage of the vertical farming circular economy. The optimum setting/capacity in each stage were identified to achieve the balance between stages and minimize waste. The findings of this research can contribute to the development of a sustainable agricultural system that is environmentally friendly and economically viable. The circular economy approach can be applied to other sectors as well, promoting the efficient utilization of resources and reducing waste. The findings of this research have important implications for the future of agriculture, particularly in the context of the growing concerns around climate change, food security, and sustainability. The circular economy model proposed in this study can serve as a blueprint for farmers and investors to adopt more sustainable and efficient farming practices that not only reduce waste but also generate profits. This research demonstrates that the integration of hydroponic and aquaponic systems can lead to a zero-waste circular economy in vertical farming that is financially sustainable. The use of byproducts such as hydroponic plant waste, aquaponic waste, vermicompost tea, and aerobic compost tea/quick compost in the growth of halophyte plants can reduce waste and operational costs, while also producing high-value products. However, it is important to note that the proposed circular economy model is context-specific and may require modifications based on local conditions and market demand. Future research should focus on further refining and testing the model in different settings and with different crops to assess its generalizability and scalability.

In conclusion, this research presents a viable solution for the challenges facing traditional agriculture and provides a roadmap for the implementation of a zero-waste circular economy in vertical farming. The circular economy model proposed in this research offers a promising solution to the challenges facing the traditional agriculture industry and can contribute to the development of more sustainable and efficient farming practices that ensure food security, reduce waste, and generate profits.

7.2 Future Works

The future work scope of this research is promising, as it provides a roadmap for the implementation of a zero-waste circular economy in vertical farming. The proposed model has the potential to revolutionize the agricultural sector, contributing significantly to food security, resource conservation, and economic growth. However, there is a need for further research to refine and test the model in different settings and with different crops to assess its generalizability and scalability. Future studies can focus on the following areas:

7.2.1 Scaling up the Model

While the feasibility of the circular economy model was demonstrated through the simulation study, it is important to test the model in newer real-world scenarios. Future research should focus on scaling up the model to assess its viability and efficiency in large-scale vertical farming operations.

7.2.2 Optimization of Resources

The circular economy approach emphasizes the efficient utilization of resources. Future research can focus on optimizing the use of resources such as water, nutrients, and energy in the vertical farming system to further reduce waste and operational costs.

7.2.3 Assessment of the Environmental Impact

The circular economy model proposed in this study aims to be environmentally friendly. Future research can assess the environmental impact of the model, such as its carbon footprint and water usage, to ensure its sustainability.

7.2.4 Market Demand Analysis

The circular economy model proposed in this study is context-specific and may require modifications based on local conditions and market demand. Future research can focus on analyzing the market demand for high-value halophyte plants to ensure the economic viability of the model.

7.2.5 Comparison with Traditional Agriculture

While the circular economy model proposed in this study showed promising results, it is important to compare it with traditional agriculture practices in terms of productivity, cost-effectiveness, and environmental impact. Future research can focus on conducting a comparative analysis of the two approaches to evaluate the potential benefits of the circular economy model.

Overall, the proposed circular economy model presents a promising solution to the challenges facing the traditional agriculture industry. It offers a roadmap for the development of sustainable and efficient farming practices that ensure food security, reduce waste and generate profits. Future research can build on this work to further refine and test the model, contributing to the development of a more sustainable agricultural system.

REFERENCES

1. Azizoglu, U., et al., The fate of plant growth-promoting rhizobacteria in soilless agriculture: Future perspectives. 3 Biotech, 2021. 11(8): p. 1-13.
2. Manos, D.-P. and G. Xydis, Hydroponics: are we moving towards that direction only because of the environment? A discussion on forecasting and a systems review. Environmental Science and Pollution Research, 2019. 26(13): p. 12662-12672.
3. Avgoustaki, D.D. and G. Xydis, How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety?, in Advances in Food Security and Sustainability. 2020, Elsevier. p. 1-51.
4. Despommier, D., The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. Journal für Verbraucherschutz und Lebensmittelsicherheit, 2011. 6(2): p. 233-236.
5. Mulatu, D.W., The impact of CO2 emissions on agricultural productivity and household welfare in Ethiopia: A Computable general equilibrium analysis. 2016: Environment for Development Initiative.
6. Pimentel, D. and M. Burgess, An environmental, energetic and economic comparison of organic and conventional farming systems, in Integrated Pest Management. 2014, Springer. p. 141-166.
7. Gruda, N.S., Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy, 2019. 9(6): p. 298.
8. Eigenbrod, C. and N. Gruda, Urban vegetable for food security in cities. A review. Agronomy for Sustainable Development, 2015. 35(2): p. 483-498.

9. Sakamoto, T., et al., Development of nanostructured water treatment membranes based on thermotropic liquid crystals: molecular design of sub-nanoporous materials. Advanced Science, 2018. 5(1): p. 1700405.

10. Olesen, J.E. and M. Bindi, Consequences of climate change for European agricultural productivity, land use and policy. European journal of agronomy, 2002. 16(4): p. 239-262.

11. Entezari, A., et al., Sustainable agriculture for water-stressed regions by air-water-energy management. Energy, 2019. 181: p. 1121-1128.

12. Zhou, P., et al., Discovery of a novel coronavirus associated with the recent pneumonia outbreak in humans and its potential bat origin. BioRxiv, 2020.

13. Lovell, S.T., Multifunctional urban agriculture for sustainable land use planning in the United States. Sustainability, 2010. 2(8): p. 2499-2522.

14. Orsini, F., et al., Urban agriculture in the developing world: a review. Agronomy for sustainable development, 2013. 33(4): p. 695-720.

15. Caplow, T., Building integrated agriculture: Philosophy and practice. Urban futures, 2009. 2030: p. 48-51.

16. Specht, K., et al., Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agriculture and human values, 2014. 31(1): p. 33-51.

17. Sambo, P., et al., Hydroponic solutions for soilless production systems: issues and opportunities in a smart agriculture perspective. Frontiers in Plant Science, 2019. 10: p. 923.

18. Gonnella, M. and M. Renna, The Evolution of soilless systems towards ecological sustainability in the perspective of a circular economy. Is it really the opposite of organic agriculture? Agronomy, 2021. 11(5): p. 950.

19. Gruda, N., Do soilless culture systems have an influence on product quality of vegetables? 2009.

20. Despommier, D., Farming up the city: the rise of urban vertical farms. Trends Biotechnol, 2013. 31(7): p. 388-389.

21. Germer, J., et al., Skyfarming an ecological innovation to enhance global food security. Journal für Verbraucherschutz und Lebensmittelsicherheit, 2011. 6(2): p. 237-251.

22. Mok, H.-F., et al., Strawberry fields forever? Urban agriculture in developed countries: a review. Agronomy for sustainable development, 2014. 34(1): p. 21-43.

23. Moghimi, F. and B. Asiabanpour, Economics of vertical farming in the competitive market. Clean Technologies and Environmental Policy, 2023: p. 1-19.

24. Moghimi, F. and B. Asiabanpour, Economics of Vertical Farming: Quantitative Decision Model and a Case Study for Different Markets in the USA. 2021.

25. Brechner, M. and A. Both, Cornell Controlled Environment Agriculture. Cornell Univ, 2014.

26. Reja, M.H., et al., Vertical Farming: A New Prospect of Landless Farming. Indian Farmer, 2019. 6: p. 108-112.

27. Beacham, A.M., L.H. Vickers, and J.M. Monaghan, Vertical farming: a summary of approaches to growing skywards. The Journal of Horticultural Science and Biotechnology, 2019. 94(3): p. 277-283.

28. Roberts, J.M., et al., Vertical farming systems bring new considerations for pest and disease management. Annals of Applied Biology, 2020. 176(3): p. 226-232.

29. Bridgewood, L., Hydroponics: Soilless gardening explained. 2002: Crowood Press (UK).

30. Savvas, D., et al., Soilless Culture. FAO Plant Production and Protection. Paper, 2013(217).

31. Böhme, M. Influence of closed systems on the development of cucumber. in ISOSC proceedings. 1996.

32. Gül, A., et al. Soilless culture of cucumber in glasshouses: I. A comparison of open and closed systems on growth, yield and quality. in International Symposium Greenhouse Management for Better Yield & Quality in Mild Winter Climates 491. 1997.

33. Van Os, E., M. Ruijs, and P. Van Weel. Closed business systems for less pollution from greenhouses. in II Symposium on Horticultural Substrates and their Analysis, XXIII IHC 294. 1990.

34. Pradhan, B. and B. Deo, Soilless farming-the next generation green revolution. Current Science (00113891), 2019. 116(5).

35. AlShrouf, A., Hydroponics, aeroponic and aquaponic as compared with conventional farming. American Academic Scientific Research Journal for Engineering, Technology, and Sciences, 2017. 27(1): p. 247-255.

36. Savvas, D. and H. Passam, Hydroponic production of vegetables and ornamentals. 2002: Embryo publications Athens.

37. 10 New Trends In Hydroponics: What To Expect In 2017 And Beyond — AGRITECTURE. Available from: https://www.agritecture.com/blog/2017/12/1/10-new-trends-in-hydroponics-what-to-expect-in-2017-and-beyond.

38. How Does Aeroponics Work? - Modern Farmer. Available from: https://modernfarmer.com/2018/07/how-does-aeroponics-work/.
39. Savidov, N., E. Hutchings, and J. Rakocy. Fish and plant production in a recirculating aquaponic system: a new approach to sustainable agriculture in Canada. in International Conference and Exhibition on Soilless Culture: ICESC 2005 742. 2005.
40. The Big Idea_ Hydroponics & Aquaponics – Envision – College of Agriculture Magazine at Purdue University. Available from: https://ag.purdue.edu/envision/the-big-idea-hydroponics-aquaponics/.
41. Fletcher, O., The future of agriculture may be up. The Wall Street Journal, 2012. 13.
42. Abel, C., The vertical garden city: towards a new urban topology. CTBUH journal, 2010. 2(1): p. 20-30.
43. Kalantari, F., et al. A review of vertical farming technology: A guide for implementation of building integrated agriculture in cities. in Advanced engineering forum. 2017. Trans Tech Publ.
44. Banerjee, C. and L. Adenaeuer, Up, up and away! The economics of vertical farming. Journal of Agricultural Studies, 2014. 2(1): p. 40-60.
45. Benke, K. and B. Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture. Sustainability: Science, Practice and Policy, 2017. 13(1): p. 13-26.
46. Deutz, P., Circular Economy. 2020.
47. Ying, J. and Z. Li-jun, Study on green supply chain management based on circular economy. Physics Procedia, 2012. 25: p. 1682-1688.

48. Lahti, T., J. Wincent, and V. Parida, A definition and theoretical review of the circular economy, value creation, and sustainable business models: where are we now and where should research move in the future? Sustainability, 2018. 10(8): p. 2799.

49. Commission, E., D.-G.f. Research, and Innovation, Accelerating the transition to the circular economy : improving access to finance for circular economy projects. 2019: Publications Office.

50. Mentink, B., Circular business model innovation: a process framework and a tool for business model innovation in a circular economy. 2014.

51. Recent Awards. Available from: https://portal.nifa.usda.gov/lmd4/recent_awards?report_title=Recent%20Awards&from_site=NIFA&search_label=Awards%20Listing.

52. Adhikary, S., Vermicompost, the story of organic gold: A review. 2012.

53. Yadav, K.D., V. Tare, and M.M. Ahammed, Vermicomposting of source-separated human faeces for nutrient recycling. Waste Management, 2010. 30(1): p. 50-56.

54. Lim, S.L., et al., The use of vermicompost in organic farming: overview, effects on soil and economics. Journal of the Science of Food and Agriculture, 2015. 95(6): p. 1143-1156.

55. Bhat, M. and S. Limaye, Nutrient status and plant growth promoting potential of prepared vermicompost. International Journal of Environmental Sciences, 2012. 3(1): p. 312-321.

56. Morales-Corts, M.R., M.Á. Gómez-Sánchez, and R. Pérez-Sánchez, Evaluation of green/pruning wastes compost and vermicompost, slumgum compost and their mixes as growing media for horticultural production. Scientia Horticulturae, 2014. 172: p. 155-160.

57. Lakshmi, R., et al., Manurial value of different vermicomposts and conventional composts. Global Advanced Research Journal of Agricultural Science, 2013. 2(2): p. 9-64.

58. Pattnaik, S. and M.V. Reddy, Nutrient status of vermicompost of urban green waste processed by three earthworm species—Eisenia fetida, Eudrilus eugeniae, and Perionyx excavatus. Applied and Environmental soil science, 2010. 2010.

59. Gómez-Brandón, M. and J. Domínguez, Recycling of solid organic wastes through vermicomposting: microbial community changes throughout the process and use of vermicompost as a soil amendment. Critical Reviews in Environmental Science and Technology, 2014. 44(12): p. 1289-1312.

60. Sherman, R.L., -The Suppression of Plant Pathogens by Vermicomposts, in Vermiculture Technology. 2010, CRC Press. p. 188-205.

61. Edwards, C., et al., The Use and effects of aqueous solutions from vermicomposts (‘Teas’) on crop yields in the greenhouse. Vermiculture technology: earthworms, organic wastes, and environmental management, 235–48. 2011, Boca Raton, FL: Taylor and Francis.

62. Arancon, N.Q., et al., Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. Bioresource Technology, 2004. 93(2): p. 139-144.

63. Arancon, N.Q., et al., Influences of vermicomposts, produced by earthworms and microorganisms from cattle manure, food waste and paper waste, on the germination, growth and flowering of petunias in the greenhouse. Applied soil ecology, 2008. 39(1): p. 91-99.

64. Arancon, N.Q., et al., Effects of vermicomposts on growth and marketable fruits of field-grown tomatoes, peppers and strawberries: the 7th international symposium on earthworm ecology· Cardiff· Wales· 2002. Pedobiologia, 2003. 47(5-6): p. 731-735.
65. Arancon, N.Q., et al., Effects of vermicomposts produced from cattle manure, food waste and paper waste on the growth and yield of peppers in the field. Pedobiologia, 2005. 49(4): p. 297-306.
66. Arancon, N.Q., et al., Effects of humic acids from vermicomposts on plant growth. European journal of soil biology, 2006. 42: p. S65-S69.
67. Gandhi, M., Composting of household wastes with and without earthworms. Environment and ecology, 1997. 15: p. 432-434.
68. Lim, P.N., et al., A potential bioconversion of empty fruit bunches into organic fertilizer using Eudrilus eugeniae. International journal of environmental science and technology, 2015. 12(8): p. 2533-2544.
69. Lim, S.L., T.Y. Wu, and C. Clarke, Treatment and biotransformation of highly polluted agro-industrial wastewater from a palm oil mill into vermicompost using earthworms. Journal of agricultural and food chemistry, 2014. 62(3): p. 691-698.
70. Edwards, C.A., et al., Suppressing plant parasitic nematodes and arthropod pests with vermicompost teas. Biocycle, 2007. 48(12): p. 38-39.
71. Force, C.T.T., Compost tea task force report. 2004, National Organic Standards Board, Washington DC.
72. Yatoo, A.M., et al., Sustainable management of diseases and pests in crops by vermicompost and vermicompost tea. A review. Agronomy for Sustainable Development, 2021. 41(1): p. 1-26.

73. Urban Composting: How to Compost in An Indoor Living Area. Available from: https://www.projectplanetid.com/post/urban-composting-how-to-compost-in-an-indoor-living-area.

74. Jeong, Y.-K. and J.-S. Kim, A new method for conservation of nitrogen in aerobic composting processes. Bioresource technology, 2001. 79(2): p. 129-133.

75. Touart, A.P., Time for (compost) tea in the northwest. BioCycle, 2000. 41(10): p. 74-74.

76. Scheuerell, S. and W. Mahaffee, Compost tea: principles and prospects for plant disease control. Compost Science & Utilization, 2002. 10(4): p. 313-338.

77. Ingham, E., Compost tea. 2003: Soil Foodweb Incorporated.

78. Palmer, A., et al., Potential for growth of E. coli in aerobic compost extract. Compost science & utilization, 2010. 18(3): p. 152-161.

79. Verweij, P.E., et al., The one health problem of azole resistance in Aspergillus fumigatus: Current insights and future research agenda. Fungal Biology Reviews, 2020. 34(4): p. 202-214.

80. Compost Tea Brewer Kits by TeaLAB. Available from: https://www.composttealab.com/store/p1/compost-tea-brewer-kits.html.

81. Vitamix® FoodCycler® FC-50. Available from: https://www.vitamix.com/us/en_us/shop/foodcycler-fc-50.

82. Vitamix FoodCycler Review. Available from: https://www.seriouseats.com/vitamix-foodcycler-review-6265352.

83. A Hands-On Review of The Vitamix FoodCycler FC-50. Available from: https://saltpepperskillet.com/tools/vitamix-foodcycler-fc-50-review/.

84. Khan, M. and N. Duke, Halophytes-A resource for the future. Wetlands Ecology and Management, 2001. 9(6): p. 455.
85. Etesami, H. and G.A. Beattie, Mining halophytes for plant growth-promoting halotolerant bacteria to enhance the salinity tolerance of non-halophytic crops. Frontiers in microbiology, 2018. 9: p. 148.
86. Kumari, A., et al., Proteomics, metabolomics, and ionomics perspectives of salinity tolerance in halophytes. Frontiers in Plant Science, 2015. 6: p. 537.
87. Medicago sativa. Available from: https://www.fs.usda.gov/database/feis/plants/forb/medsat/all.html.
88. Medicago sativa L_. Available from: https://www.gbif.org/species/113603764.
89. Purslane Seed - Winter Purslane Herb Seeds. Available from: https://www.outsidepride.com/seed/herb-seed/purslane/purslane-winter.html.
90. Miner'S Lettuce Miners Seed _ Territorial Seed. Available from: https://territorialseed.com/products/miners-lettuce-miners.
91. Portulaca Green Purslane Herb Garden Plant Seeds. Available from: https://www.outsidepride.com/seed/herb-seed/purslane/purslane.html.
92. How to Plant and Grow Purslane _ Gardener's Path. Available from: https://gardenerspath.com/plants/herbs/grow-purslane/.
93. Greasewood (Sarcobatus vermiculatus) _ USDA ARS. Available from: https://www.ars.usda.gov/pacific-west-area/logan-ut/poisonous-plant-research/docs/greasewood-sarcobatus-vermiculatus/.
94. Species_ Sarcobatus vermiculatus. Available from: https://www.fs.usda.gov/database/feis/plants/shrub/sarver/all.html.

95. Shadscale Saltbush Seeds atriplex Confertifolia 100seeds - Etsy. Available from: https://www.etsy.com/listing/520649127/shadscale-saltbush-seeds-atriplex.

96. Atriplex confertifolia. Available from: https://www.fs.usda.gov/database/feis/plants/shrub/atrcon/all.html.

97. Salsola komarovii, Okahijiki Seeds. Available from: https://www.seedaholic.com/okahijiki-saltwort-or-land-seaweed.html.

98. Herb Saltwort 200 Non-GMO, Heirloom Seeds – David's Garden Seeds®. Available from: https://davidsgardenseeds.com/products/herb-saltwort-200-non-gmo-heirloom-seeds.

99. Lemongrass (Cymbopogon citratus). Available from: https://www.gardenia.net/plant/cymbopogon-citratus.

100. How to Grow Lemongrass _ Gardener’s Path. Available from: https://gardenerspath.com/plants/herbs/grow-lemongrass/.

101. Switch Grass, Panicum virgatum – Wisconsin Horticulture. Available from: https://hort.extension.wisc.edu/articles/switch-grass-panicum-virgatum/.

102. Water Starwort Facts, Care & Planting Guide (Callitriche palustris) - Pond Informer. Available from: https://pondinformer.com/water-starwort-callitriche-palustris/.

103. Callitriche stagnalis (pond water-starwort)_ Go Botany. Available from: https://gobotany.nativeplanttrust.org/species/callitriche/stagnalis/.

104. Grass Species Detail Page. Available from: https://cals.arizona.edu/yavapaiplants/SpeciesDetailGrass.php?genus=Secale&species=cereale.

105. Sustainable and Organic Agriculture Program _ Resources _ Sustainable and Organic Topics _ Rye Grain (Cereal Rye). Available from: https://cms.ctahr.hawaii.edu/soap/Resources/Sustainable-and-Organic-Topics/Rye-Grain-Cereal-Rye.

106. Chrysopogon zizanioides (Vetiver). Available from: https://www.gardenia.net/plant/chrysopogon-zizanioides.

107. Chrysopogon zizanioides - Wikipedia. Available from: https://en.wikipedia.org/wiki/Chrysopogon_zizanioides.

108. Alfalfa - Wikipedia. Available from: https://en.wikipedia.org/wiki/Alfalfa.

109. Amazon.com_ Miracle-Gro VB02196 Water Soluble 8 oz, 2-Pack All Purpose Plant Food.5 lb, _ Everything Else. Available from: https://www.amazon.com/dp/B08NRN67F2/.

110. Cal-Mag Plus ™ – Botanicare. Available from: https://www.botanicare.com/products/cal-mag-2-0-0/.

111. TetraPond Koi Growth 4.85 Pounds, Soft Sticks, Pond Fish Food. Available from: https://www.amazon.com/TetraPond-Koi-Growth-Food-4-85/dp/B00025K0ZS?th=1.

112. U.S. Department of Agriculture: FoodData Central. Available from: https://fdc.nal.usda.gov/fdc-app.html#/food-details/172232/nutrients.

113. Data Analysis, Statistical & Process Improvement Tools _ Minitab. Available from: https://www.minitab.com/en-us/.

114. What is ANOVA_ - Minitab. Available from: https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistical-modeling/anova/supporting-topics/basics/what-is-anova/.

115. What is a Simulation? . Available from: https://www2.isye.gatech.edu/~rbilling/courses/isye3044/Slides/Chapter01.pdf?cv=1.

116. Arena Simulation Software _ Arena Simulation Software. Available from: https://www.rockwellautomation.com/en-us/products/software/arena-simulation.html.