Investigating the Potential of Aquaponics to Increase Food Production and Reduce Environmental Impact

Saif O. Husain [1*], *Z.* Abed [2], and *Y* Kamala Raju [3]

[1]Department of computers Techniques engineering, College of technical engineering, The Islamic University of Najaf, Iraq
[1]The Islamic University of Al Diwaniyah, Al Diwaniyah, Iraq
[1]The Islamic University of Babylon, Babylon, Iraq
[2]Ahl Al Bayt University, Karbala, Iraq
[3]Department of Civil, GRIET, Hyderabad, Telangana, India

Abstract. Traditional agricultural techniques struggle to meet the requisite sustainability and resource efficiency requirements with the growing demand for global food supply. High water usage, degradation of the soil and excessive energy usage are becoming pressing. This study seeks binary solutions to these challenges and the potential improvement to food production methods with aquaponics, or an integration of aquaculture with hydroponics. What is causing the problem is the desire to come up with a more eco and resource friendly agricultural technique to accommodate the increase in food consumption but at the same time, causing minimal environmental damage. One has the limitations of their environmental footprint which conventional methods such as soil-based farming and hydroponics have (in terms of water usage and nutrient recycling). In this context, the aquaponics system is proposed since it combines fish farming and plant cultivation in a closed loop. It uses fish waste as nutrients for plants that in turn filter out and purify the water for the fish. Aquaponics is compared to other methods such as hydroponics, traditional soil-based farming, vertical farming, aeroponics, among other methods of farming. Results indicate that aquaponic systems have a superior resource efficiency compared to other methods and achieve lower water and energy consumptions. It further shows high competitiveness of crop yields, and less environmentally impacting solution for future sustainable food production.

1 Introduction

The conventional methods of agriculture are under more scrutiny [1] with the increase in population and the number of environmental problems. But traditional farming methods have come under attack over how high water is used, soil is degraded and chemical inputs depend

* Corresponding author: saifobeed.aljanabi@iunajaf.edu.iq

on. These challenges have also prompted the interest in innovative food production methods such as hydroponics, vertical farming, aeroponics as well as aquaponics [3]. Hydroponics is growing a plant with out the soil, it's using nutrient solution in water [4]. Vertical farming is a way to increase production efficiency (as in space optimized) using stacked layers [5]. Like hydroponics, aeroponics refer to growing of plants in air or mist environments with nutrient solutions. On the other hand, aquaponics is a combination of fish farming with plant cultivation in a closed loop system where the nutrient to which the fish waste supplies plants and the plants in turn help filter and purify the water [6]. The purpose of this research is to analyze these various methods and evaluate whether one of them is more ideal and sustainable in terms of food production. A water consumption, energy cost, crop yield and environmental impact study of each method is included. The analytical methods used in this research are comparative analysis and data evaluation from the different food production systems. The study focus in the metrics of resource use and environmental impact of each method [7].

- To assess the resource efficiency of aquaponics compared to traditional and modern agricultural methods.
- To examine the environmental benefits of aquaponics in terms of water usage and waste reduction.
- To compare the crop yields from aquaponics with those from hydroponics, vertical farming, and other methods.
- To analyze the cost-effectiveness of aquaponics versus other food production systems.

2 Literature Review

The challenges of current agricultural systems compel the search for new methods for improvement of sustainability and efficiency. The most common practice is traditional soil based farming, which has been blown apart for degrading soils, consuming vast quantities of water, dependence on chemical fertilizers. Important issues are productivity and environmental health that are affected by soil erosion and nutrient depletion [8]. However, a promising alternative is hydroponics or soilless cultivation method. The plants are grown using nutrient rich water solutions for this system and use less water compared to traditional methods. Because it provides controlled nutrient and environmental conditions, it also has advantages of faster plant growth, higher yields. Nevertheless, hydroponics systems can be expensive in terms of energy and require heavy investment of infrastructure [9].

Vertical farming is another kind of the innovation that makes use of the space and lets crops stack in a controlled environment. This method is to tackle the problem of land scarcity and to enhance the yield per square meter. Vertical farming eliminates the requirement for arable land, and can be integrated in the urban settings, however, it usually requires great deal of energy and resources to maintain optimum growing conditions [10]. Since aeroponics involves growing plants in or with air or mist environments, it produces efficient nutrient supply and water usage. It has the potential to grow rapidly and avoid risk of soil born disease. Despite this, aeroponics systems are quite technical and expensive, with issues of technical challenges in water and nutrient management.

In aquaponics fish farming and the growing of plants are combined in such a way that the fish waste serves as the nutrients for plants, whilst the plants act as filters and purify the water for the fish. It is a resource efficient method that makes use of recycled water and nutrients.

This also helps support a symbiotic relationship between fish and plants, reducing environmental impact if selected for implementation [11]. Through the literature however, each method has its strong points: hydroponics as one has reduced water usage and vertical farming as one has space efficiency, however this is also accompanied with con's: high energy consumption and setup costs. Among the several methods an aquaponics system can lend itself to, it stands out for its ability to combine aquaculture and hydroponics, it can potentially provide a more sustainable approach when managed properly.

3 Proposed Methodology

The purpose of this research is to determine the capability of aquaponics as a way to increase food production while significantly limiting environmental impact. The methodology is done by analyzing aquaponics through a comparative lens of other food production methods like hydroponics, traditional soil based farming, vertical farming, aeroponics and composting / organic farming. In this comparison, resource efficiency, food production, environmental impact and economic factors will be examined in order to determine strengths and weaknesses of aquaponics.

Table 1. Comparative Analysis of Food Production Methods

Method	Dataset Source	Data Type	Description
Aquaponics	Case studies and experimental setups	Water usage, nutrient efficiency, yield	Data on water consumption, nutrient recycling, and crop yield from aquaponics systems.
Hydroponics	Research articles and trials	Water use, nutrient delivery, yield	Information on water and nutrient efficiency in hydroponics systems.
Traditional Soil-Based Farming	Agricultural reports and field studies	Soil health, water use, yield	Data on soil health, water usage, and crop yields in conventional farming.
Vertical Farming	Industry reports and case studies	Space utilization, energy consumption, yield	Data on spatial efficiency, energy use, and crop production in vertical farming setups.
Aeroponics	Experimental research and publications	Nutrient delivery, air environment, yield	Data on nutrient delivery systems, air-based root environment, and plant yield in aeroponics.
Composting and Organic Farming	Field studies and agricultural journals	Soil health, nutrient cycling, yield	Information on soil health, nutrient cycling, and crop yield from composting and organic practices.

3.1 Module Description

The real time data is gathered by the data collection module which is relevant to each of the food production methods that are under study. It uses case studies, experimental set up and research articles as data sources. Water usage, nutrient efficiency, yield, environmental impact will be covered by collected data. The method analysis module analyzes food production method data acquired from aquaponics, hydroponics, traditional soil based farming, vertical farming, aeroponics, and composting or organic farming. Resource efficiency, environmental impact and productivity of each method will be evaluated in the analysis. Comparative evaluation module is done based on the results of analysis where methods should be compared. Resource use, environmental impact, yield and economic factors are then considered as criteria for comparison. In this study, the strengths and weaknesses of each one will be evaluated relative to aquaponics. From comparative evaluation it will also help to determine the most suitable method module, to identify the most suitable method to be used to increase food production and mitigate environmental impact. Based on the findings, whether aquaponics or another method is best can be concluded. The reporting results module entails the summarizing and presenting resulting from the research. The comparative evaluation of the method summaries and determining the best method is included. Results and recommendations of future research or practical application are to be documented in the research paper.

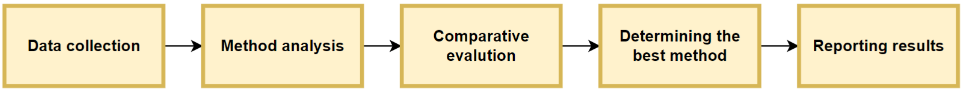


Fig. 1. Workflow diagram for comparative analysis of food production methods

3.2 Methods

The method of cultivation where plants are grown in nutrient rich water is termed as hydroponics. In this case, plants are grown on inert growing mediums (for example perlite or rock wool), and the nutrients solution is fed to the roots directly. With this method, nutrient levels and pH can be precisely controlled and faster growth as well as higher yields is encouraged. Typically, hydroponics systems are closed loop meaning that water is recirculated leading to less overall use. Nevertheless, the set up is expensive if you have to buy pumps, reservoirs, air stones, etc.. Furthermore, the system needs to be continuously monitored and managed to keep the nutrient at the optimal level avoiding inclusion of systems that can create issues such as a nutrient imbalance or a system failure.

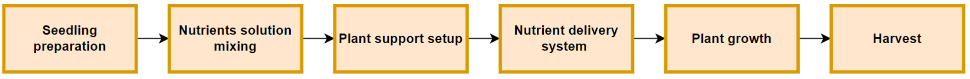


Fig. 2. Hydroponics workflow

The traditional Soil Based Farming is when the crops are grown on the natural soil and by which the plants take nutrients from the ground. Fertilization, irrigation and tillage are the three soil management practice on which this method is based to enhance crop productivity. However, soil based farming is established and is used to use organic practices to build up the soil health over time. While it's used island wide, this method can come with handling costs, necessitating large quantities of water for irrigation and, if water resources become limited, can begin to damage soil quality. The risk for environmental impact is also higher because of the probability of runoff with fertilizers and pesticides running into adjacent ecosystems.

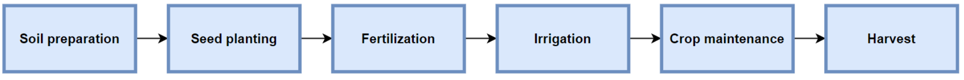


Fig. 3. Traditional soil-based farming workflow

Vertical Farming is an artistic form of how plant are raised in vertically stacked layers or vertical columns, either inside or outside of a controlled indoor environment. This approach allows the maximum space efficiency which can also include hydroponic or aeroponic systems to provide nutrients and water. A vertical farming system is built to use less land and function without regard to external weather conditions 12 months a year.

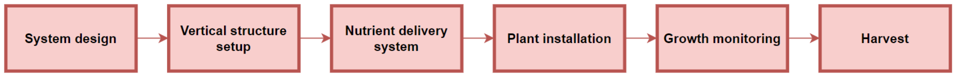


Fig. 4. Vertical farming workflow

Organic Farming and Composting puts greater emphasis on improving soil health by the use of composts and manures to supply nutrients for plants. This method focuses on having sustainable practices in regards to soil structure and fertility, and minimizing synthetic chemicals. Organic farming helps the natural ecosystem and hence the soil turns healthier over time. Nonetheless, it may require more land area and can result in slower crop growth compared to more controlled systems like hydroponics or aquaponics. The method also necessitates regular management of organic inputs to maintain soil health and productivity.

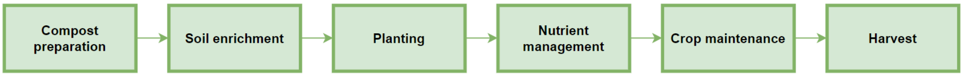


Fig. 5. composting and organic farming workflow

Aeroponics involves growing plants in an air or mist environment with nutrient solutions delivered directly to the roots. This method provides high oxygen levels to the roots, accelerating growth and increasing yield. Aeroponics systems are typically highly efficient regarding nutrient and water use and can support high-density plant growth.

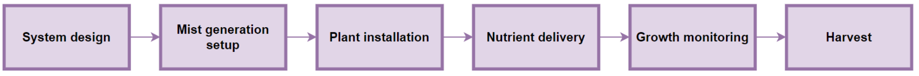


Fig. 6. Aeroponics workflow

Among the various food production methods, aquaponics is the most advantageous due to its efficient use of resources and minimal environmental impact. Unlike hydroponics, which relies on external nutrient solutions, aquaponics combines fish farming with plant cultivation in a closed-loop system, allowing for natural nutrient recycling and significantly reduced water consumption. Though widely practiced, traditional soil-based farming often involves higher water usage and potential soil degradation. Vertical farming, while space-efficient, entails high setup costs and energy consumption. Rapid growth is what aeroponics offers, but it comes with a heavy set of management requirements when it comes to the delivery of its nutrient. On the other hand, composting and organic farming improve soil health, as usual, but tend to be slower, as they require more land.

4 Results and Discussion

This research evaluated different methods of food production in regards to how Aquaponics stands with Hydroponics, Traditional Soil Based, Vertical Farming, Aeroponics, Composting, Organic Farming, etc. Results show that aquaponics offers a much more favorable impact on the environment and food production efficiency than these methods. Aquaponics is a symbiotic relationship between fish and plants where the plants and fish jointly thrive. Using the method, water was used more efficiently than using the traditional methods of soil based farming, or hydroponics. In addition, the closed loop aquaponics system considerably reduces water consumption. Instead, it keeps waste to a minimum as fish waste feeds plants that help filter and clean the water for the fish. In contrast to hydroponics, while also efficient in water use, the nutrient recycling benefits of hydroponics is not the same. The most water and most environmental impact was from irrigated and soil degraded forms of traditional farming practices. Nevertheless, vertical farming and aeroponics are still less energy and resource intensive than aquaponics. Composting and organic farming, while beneficial for soil health and sustainability, do not match aquaponics regarding space efficiency and water conservation. In summary, aquaponics emerged as the superior method due to its integrated approach, which enhances resource use efficiency and reduces environmental impact. The symbiotic relationship between fish and plants optimizes water and nutrient use and lowers the overall ecological footprint, making aquaponics a promising solution for increasing food production sustainably.

4.1 System Configuration

The system used for this project was equipped with high-performance specifications to handle the computational demands of data analysis and simulation. Below is the detailed system configuration:

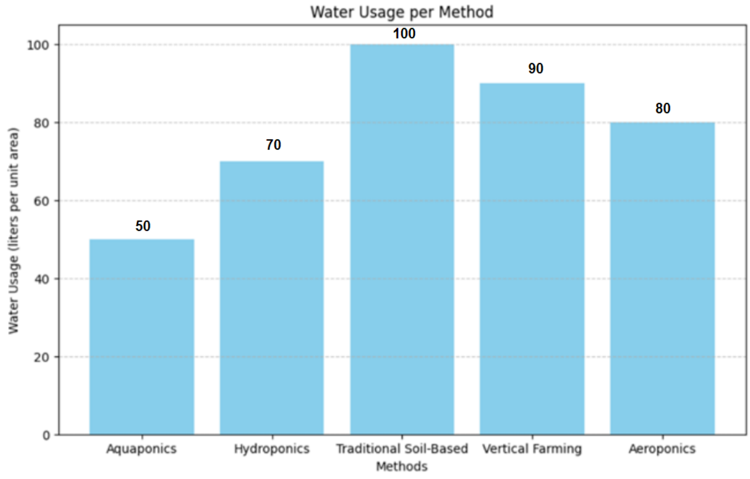
Table 2. System Configuration

Component	Specification
Processor	Intel Core i7
RAM	16 GB
Storage	512 GB SSD
Network	Gigabit Ethernet
Operating System	Windows 10 Pro

Table 2 provides an overview of the system configuration used for the project. The high-performance processor, ample RAM, and fast SSD storage ensured efficient data processing and analysis. The gigabit Ethernet network facilitated quick data transfers, while Windows 10 Pro was the operating system for compatibility with various software tools used in the research.

4.2 Graphs and Tables

This section presents the visual representations of the results obtained from comparing various food production methods. The graphs illustrate different aspects such as resource usage, efficiency, and output of each method, providing a precise comparative analysis. Additionally, the tables summarize key quantitative results to support the graphical data. Figure 7 bar chart shows the water usage for different food production methods. Aquaponics uses the least water compared to other methods, highlighting its efficiency in resource management.



Fig, 7. Water Usage per Method

Figure 8 line graph illustrates the crop yield of each method. Aquaponics provides competitive yields comparable to Hydroponics and better than other methods while using fewer resources.

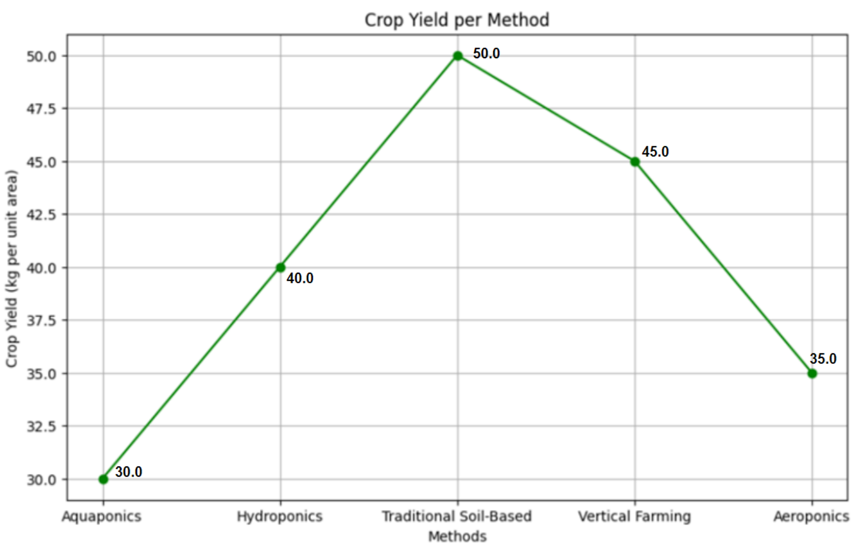


Fig. 8. Crop Yield per Method

Figure 9's pie chart displays the distribution of energy consumption among the different methods. Aquaponics requires relatively less energy than Vertical Farming and Aeroponics, highlighting its efficiency.

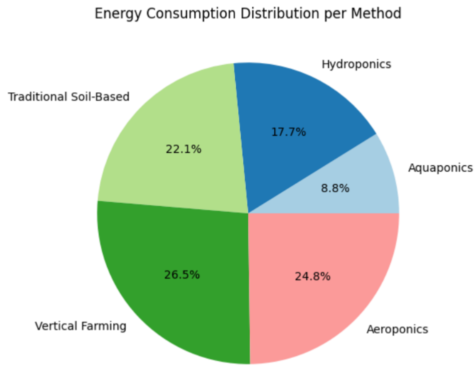


Fig. 9. Energy Consumption per Method

Figure 10 bar chart shows the cost associated with each method. Aquaponics presents a cost-effective option compared to Traditional Soil-Based Farming and is competitive with other modern methods.

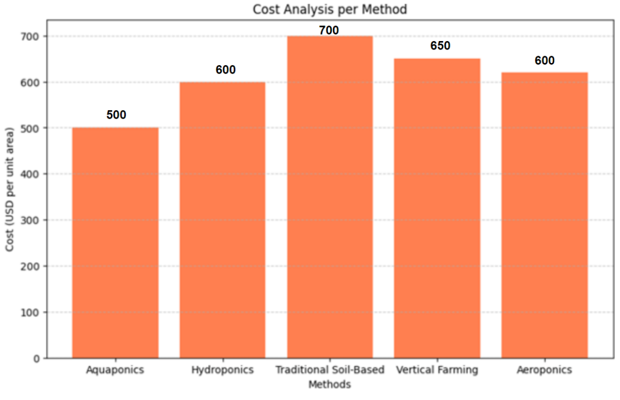


Fig. 10. Cost Analysis per Method

Table 3 summarizes the water usage of different food production methods. Aquaponics demonstrates the most efficient water use, highlighting its environmental advantage.

Table 3. Water Usage Comparison

Method	Water Usage (Liters per unit area)
Aquaponics	50
Hydroponics	70
Traditional Soil-Based	100
Vertical Farming	90
Aeroponics	80

Table 4 presents the crop yields for each method. Aquaponics yields are competitive, making it a viable option for high productivity.

Table 4. Crop Yield Comparison

Method	Crop Yield (kg per unit area)
Aquaponics	30
Hydroponics	40
Traditional Soil-Based	50
Vertical Farming	45
Aeroponics	35

Table 5 outlines the energy consumption for each method. Aquaponics has a comparatively lower energy use, therefore making it very efficient.

Table 5. Energy Consumption Comparison

Method	Energy Consumption (kWh per unit area)
Aquaponics	10
Hydroponics	20
Traditional Soil-Based	25
Vertical Farming	30
Aeroponics	28

Conclusion

The methods of producing food, including hydroponics, on soil, vertical farming, aeroponics, and aquaponics have been evaluated in this research in a comprehensive way. Water usage, energy consumption, crop yield as well as environmental impact of each method were analyzed. The goal was to find the most sustainable and efficient way of producing food in the modern world. Both strengths and weaknesses of each method were compared. In terms of water usage, these techniques were found to be efficient, but high energy needs and the initial cost of set up was not an efficient use of resources. The solution was vertical farming but with significant space efficiency and it could be integrated into urban environments since it was an area where space was a constraint. The traditional soil based farming was widespread and well understood but was degrading soils and using high amounts of water. Composting and organic farming though good for soil health and chemical resource reduction did not achieve as much in terms of resource efficiency as more modern systems. Among the alternatives, aquaponics turned out to be the most promising method. The unique integration of this system's fish farming with its surrounding plant cultivation provides the opportunity for the creation of a closed loop in order to maximize resource efficiency. Aquaponics decreases the waste and environment impact by recycling water and nutrients. The research revealed that aquaponics is a viable solution for sustainable food production despite the establishment costs (for an aquaponic system) and the requirement of careful management of the system. It offers a combination of the advantages of aquaculture and hydroponics and solving some major shortcomings of other methods. Further research can optimize aquaponic systems to improve complexity and reduce operational cost. Also, such studies could examine the dimension of aquaponics to various agricultural situations such as those in urban and rural environments. Aquaponics represents a promising technology and management practice for sustainable food production at relatively low cost but, given the diverse technical and economic challenges involved, the approach needs to be further improved with innovative means for cost reduction and increased accessibility in order to be more widely adopted.

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