Names
Abdelhamid Ahmed
Abdelrahman Ayman
Mohamed Ihab
Youssef Mostafa

Sandponics Automated Plantation

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Abstract

Following the aims of sustainability and well-being, Egypt has faced several grand challenges obstructing these goals, including mitigating climate change and improving the scientific and technological environment. Subsequently, much effort has been made toward applying integrated solutions. Further, resource unsustainability is linked to these issues, and hence, is the problem to be solved in this project. The purpose of this study is to illustrate the potential of a low-cost aquaponics system for recycling waste and providing accessible nutrition. The proposed solution is a sandponic system equipped with an automatic feedback mechanism to facilitate autonomous operation. A prototype was made and tested according to the design requirements of pH, temperature, water loss, and water pollution potential to ensure sustainability. The prototype maintained suitable environmental conditions for the growth of Tilapia fish and lettuce through a closed nutritional system. Further, several enhancements were implemented, including the addition of red wiggler worms and the usage of a bell siphon to improve test performance. Consequently, testing the prototype yielded promising results, and the observed growth was highly improved with significantly lower resource consumption. In conclusion, the project outcomes deemed modified aquaponics as a potential solution for sustainable farming and nutrition supplies. Additionally, the project could be further improved to be readily applied in real life with better performance as will be further shown.

Introduction

Egypt grand challenges, the summary of Egypt's problems, are the main hindrances of development in Egypt. Accordingly, this study is conducted to approach a problem concerning two grand challenges: Improving industrial and agricultural bases, and scientific and technological environment. The impacts of these two grand challenges have been regularly observed.

Figure (1), for example, shows the GDP contribution percentage of agriculture in Egypt, which has drastically regressed in the recent years. This can be largely blamed on the downfall of industrial and agricultural bases since they contribute about 11.3% and 30.7%, respectively, to the country's total GDP. On the other hand, the low investment in the research and development (R&D) in Egypt slowly dissipates the scientific environment in Egypt. Egypt has merely allocated 0.9% of its already suffering GDP to the R&D which is less than the world's average: 1.7%.

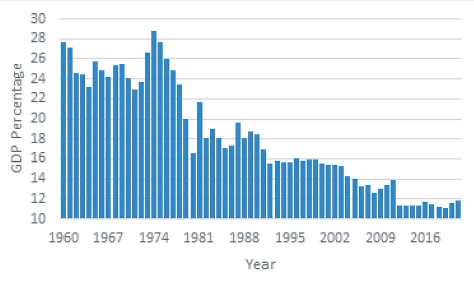

Figure 1: GDP contribution of agriculture (1960-2021) (World Bank)

Unfortunately, these are only the major observed impacts. There are several underlying small problems that fall under these two challenges. Soil degradation, resource unsustainability in agriculture, and water and soil pollution are examples of such problems. These problems all share in the resources misuse in agriculture in Egypt, which is the problem to be solved of this study. Among the projects proposed to solve this problem is an EU-funded project called SmartFish which focuses on data collection and analysis of each process in fish farming. This project introduces dramatic increase of productivity in fisheries as a point of strength. However, it has one weakness: the project is too complicated and disturbs the ecosystem in which the system is implemented (Özbilgin H, 2018). Another project, called AquaMaof, utilized a recirculatory aquacultural system that recycles water in the aquaculture using mechanical and biological filters. The project's main point of strength is that it applies closed loops to maintain the water level and the environment steady all the time. Still, such a project exposes the organisms to risk disease outbreaks that include all organisms at once.

Learning from these prior solutions, a new mechanism is proposed to solve the nutritional deficiency in agriculture. A media-based aquaponic system where Internet of Things (IoT) is involved. Media-based aquaponic systems are systems where plants and fish are cultivated together, and plants feed on the fish waste produced. To provide suitable environmental conditions, technology is used to control pH, water loss, and temperature levels, while keeping the sustainability factor, water pollution potential, at the lowest level, marking four design requirements. On the practical level, the materials used in such a project should be compatible for careful environmental considerations as applied in the prototype.

Materials & Methods

Name	Description	Quantity	Image
Tilapia fish	Freshwater fish.	290 grams	
Lettuce seedlings	A fast-growing crop.	3 seedlings	
Analog pH sensor	Electronic device used to accurately measure acidity and alkalinity in water.	1 piece	
Waterproof temperature sensor	Electronic device that measures the temperature of water.	1 piece	
PTC heater	Electrical resistance heater used to maintain warm temperature for fish.	1 piece	
Arduino Uno	Arduino UNO is a microcontroller board with 14 digital input/output pins and 6 analog inputs.	1 piece	
Red wiggler worms	Composting worms for breaking down organic matter.	0.5 kg	
Mini water pump	An Electronic device used to circulate water in the system.	3 pieces	

Table 1: Materials list

Methods:

With the materials for the prototype assembled, the next step was to develop a clear methodology for testing and evaluating its effectiveness. The prototype construction passed through two phases: fish tank and hydroponic bed. A fish tank filled with 48 liters of dechlorinated water serves as a home for 290 grams stocking density of fish.

Constructing Fish tank

The lid of the fish tank serves as the "brain" of this prototype, as shown in Figure (2), where a microcontroller (Arduino Uno) was connected to breadboard that acts as a bridge to control all the following components:

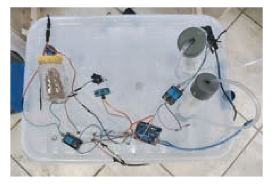
Figure 2: Lid of the fish tank

First, Pump-based pH control system:

An analog pH sensor was inserted into the fish tank, with three pins connected to the Arduino (VCC to 5V, GND to GND, and analog pin to A0). From signal to action, two pH tubes of volume 0.5 liter, one for calcium hydroxide ($Ca(OH)_2$) solution and the other for phosphoric acid (H_3PO_4) solution, were installed with two submersible mini water pumps. The pumps were controlled by a 3- channel relay module which was responsible for switching on and off them based on the pH sensor data. The acid and base pumps were connected to digital pins 7 and 12, respectively.

Second, Temperature control system:

A waterproof temperature sensor was submerged in the fish tank and connected to the Arduino's 5V pin for VDD, GND for GND, and digital pin 2 for signal (with a 4.7k pull-up resistor between signal and power). To control the temperature, a PTC heater is submerged in water and connected to relay module with external power supply of 12V and connected to Arduino via digital pin 4.

Third, A small-perforated plastic can, attached to a servo motor at its cap, as illustrated in Figure (3), was installed on the top layer of the fish tank to control fish feeding rate. An ultrasonic sensor was also embedded in the layer and connected to the Arduino via digital pins 9 and 10 (trig and echo pins, respectively) as well as to the 5V and ground pins.


Figure 3: Automatic feeder

Constructing Hydroponic bed:

First, a plastic container with dimensions of 70 cm length, 30 cm width, and 34 cm height was established above a wooden stand with a hole at its center. Through this hole, the water is drained through a constructed bell siphon. This bell siphon consists of 3 components including media guard (36 cm height and 7.5 cm diameter), bell (30 cm height and 5cm diameter), and standpipe (24 cm height and 2.5cm diameter) shown in Figure (4).

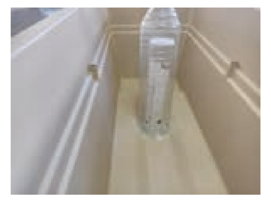
Figure 4: Bell Siphon

Second, a three-layer grow bed medium was installed, with a height of 5 cm for gravel, 25 cm for sand, and moderately spread expanded clay on the surface. Finally, 0.5 kg of red wiggler worms were placed at the top layer of medium.

Test plan

1- The Arduino was connected to Laptop via cable. The heater was connected to an External power supply of 12 volts, and the codes were uploaded through Arduino IDE.

2- Two water cycles were selected to calculate water loss percentage using the ultrasonic sensor. One at the beginning of each day while one at the end.

3- Over 24 hours, the temperature values were measured and recorded every 1 hour using the temperature sensor and observed through the serial monitor of Arduino IDE. Also, pH readings were measured using the pH sensor every 1 minute, starting with controlled change of pH at 7.5.

4- After the pH of the water was changed, fish was transported into the tank.

5- To achieve the design requirement of sustainability, Estimated Water Pollution Potential (EWPP) value was determined by substituting in Equation (1):

$$\bar{\sigma} = \sum_{i=1}^{n} \frac{\sigma_i}{n}, \qquad \sigma = \frac{30 r_t}{Q} \times S$$

Equation 1: Estimated Water Pollution Potential Equation.

Where $\bar{\sigma}$ is the EWPP. σ is the pollution potential coefficient for a specific polluting substance, r_t is the waste mass of the substance produced during one day of operation, Q is the permissible concentration of the substance multiplied by a volume of 1 m^3, S is a scale factor dependent on the substance toxicity and danger.

Results

By following the test plan steps, the following results were obtained, positive and negative.

Negative Results:

The PTC heater was not effective since the aluminum plate covered a relatively small surface area. Thus, due to the high heat capacity of water, the controller took a long time for the heating effects to take place, which was not fast enough to combat fluctuating day-night temperatures.

Positive Results:

The results for the water pH, temperature, and height loss are shown in Figures (5 – 7), respectively.

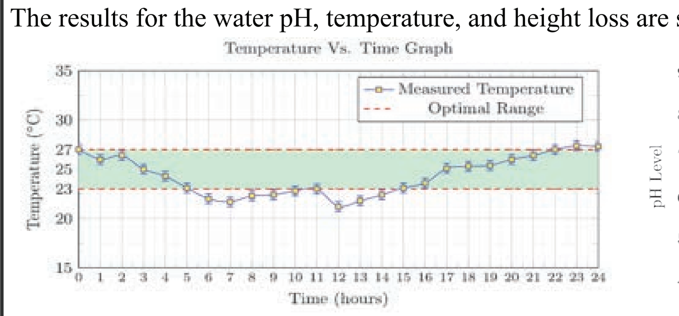

Figure 5: Temperature Vs. Time graph

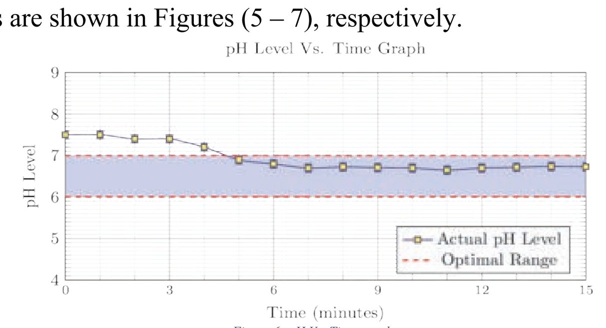

Figure 6: pH Vs. Time graph.

The EWPP value was calculated by substituting σ_i values for the following possible pollutants in an aquaponic system, which are present in high concentrations in fish waste: ammonia ($\sigma 1$), phosphorus (σ_2), and iron (σ_3). In Equation (1), the (Q, r_t, S) triplet values for each pollutant were determined based on the available data on water quality standards from WHO and aquaponics calculated performance (Recycling Efficiency ~ 96%) and prior research data. Substituting in Equation (1), the EWPP value is 0.485 ± 0.2, which is considerably below the design requirement value of 2. Error value was based on different application methods for sandponics and deviation in elements concentration due to diet differences.

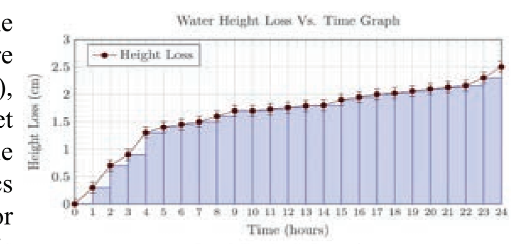

Figure 7: Water Loss Vs. Time graph.

$$\frac{\frac{30(2.264\times10^{-3})}{0.25}\times 3+\frac{30(2.032\times10^{-3})}{0.1}\times 1+\frac{30(1.553\times10^{-4})}{0.3}\times 2}{3}=\frac{0.815+0.610+0.031}{3}=0.485\pm0.2$$

Analysis

Nitrogen Cycle:

The nitrogen cycle in aquaponics, performed in the grow bed, achieves sustainability through filtering the water from the ammonia and making it usable for another cycle, as shown in Figure (8). Different types of nitrifying bacteria turn fish feces, urine and uneaten food, which are diffused in the form of ammonia and ammonium, into nitrates which act as nitrogen sources for the plants. The nitrification process is done through two steps and two different types of nitrifying bacteria: ammonia-oxidizing bacteria, and nitrite – oxidizing bacteria. The ammonia-oxidizing bacteria, Nitrosomonas and Nitrosococcus, change the ammonia in the water to nitrites. These nitrites are then oxidized by the nitrite-oxidizing bacteria, Nitrobacter and Nitrococcus, into nitrates that's an accessible form of nitrogen to the plants. Equations (2.a & 2.b) illustrate these processes.

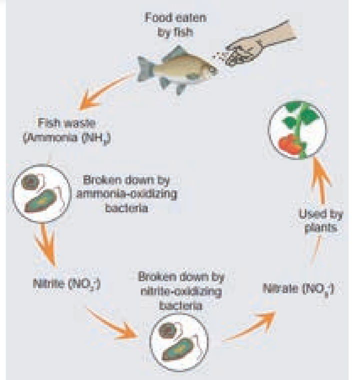

Figure 8: Nitrogen cycle in aquaponics system

$$2NH_3 + 3O_2 \Leftrightarrow 2NO_2^- + 2H_2O + 2H^+ \quad (2.a) \quad | \quad 2NO_2^- + O_2 \Leftrightarrow 2NO_3^- \quad (2.b)$$

Equation 2: The nitrification process of nitrogen

Feed-rate ratio:

When concerning the fish feed provided for the fish, it is essential to effectively determine the amount of nutrients supplied since it affects directly both fish and plant growth; when fish is nourished, waste is produced and then converted from harmful ammonia into nitrates usable by plants and makes a cycle shown in Figure (8). Hence, selecting the proper feed ratio is essential for optimal growth. For green vegetables with plenty of leaves, the feed-rate ratio is calculated based on equation (3):

$$N_r = A \cdot \frac{(45 \pm 5)}{Q}$$

Equation 3: Feed-rate ratio equation

Where N_r is the feed-rate ratio in grams of feed per day, A is the plant growth area in square meter, and Q is the effective consumption percentage for fish.

For leafy green plants, like lettuce, one plant takes approximately 0.05 m^2 of area. 3 lettuce heads were planted hoarding an area of 0.15 m2. Not to mention that since the width of the container equals 30 cm, a free distance of 17 cm is given to each plant, as shown in Figure (9). On the other side, a minimum of 40 g of fish feed is required per square meter, meaning that about 6 g of fish feed are needed for the 3 lettuce heads daily. Further, adult fish often consume about 1 – 2 % of their biomass daily (Somerville, 2015). Hence, a maximum of 300 g of fish biomass is to be grown in the hydroponic part of the prototype. Thus, the automatic feeder is designed so that the servo motor rotates 2 times a day, with each rotation giving out 3 g of fish feed. As learned in MA 2.09, it is possible to integrate N_r as a function of time to calculate the required quantity of stored feed for a given time interval, denoted K. Hence, $K = \int_0^t A \cdot \frac{(45 \pm 5)}{Q)} dt = At \cdot \frac{(45 \pm 5)}{Q}$ where t is the time in days.

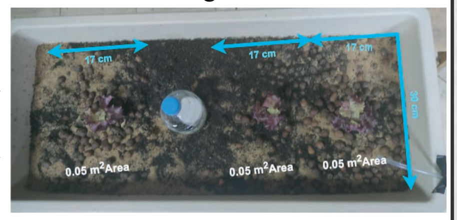

Figure 9: Growing area for lettuce crop

Water flow dynamics:

As the prototype contains 290 g of fish biomass, a constant water volume of 29 liters is essential to maintain suitable DO levels beside the aeration process. So, better circulation is achieved by cycling the water thrice per hour. For a water volume of 48L in the fish tank, 16L will go into the grow bed within 8 minutes and about 14.2 L return to the fish tank in just 10 minutes while 1.8 liters will remain because of bell siphon mechanism.

As learned in ME 2.05, the concept of power illustrated in Equation (4) can be used to find the power required to pump 16 liters of water with a flow rate of 2 Lwhere P is the delivered power (kW), F is the flow rate (liters/hour), H is the pump head in feet of water column, and η is the efficiency.

$$P = \left(\frac{F_{l/h} \times H_{ft.w.c.}}{9 \cdot 10^5 \times \eta_{Pump} \times \eta_{motor} \times \eta_{VSD}}\right) \times 0.746$$

Equation 4: Formula for required power supply to a water pump.

Grow bed:

Aquaponics systems have come in three main designs. Grow Media Bed (GMB) is the most popular and a relatively inexpensive technique, allowing its application in developing countries. GMBs are based on media for plant growth that satisfy essential criteria, including a sufficient surface area for plant growth, good drainage properties, and neutral pH.

Light Expanded Clay Aggregates (LECA) have excellent performance due to its porosity and large surface area but become quite expensive when used in large amounts. In the project, LECA is used in modest amounts to maintain bacteria growth in biofilter sites inserted in a mixture of sand and river rock, which has the required properties, including availability and wide spacing.

In a grow bed that follows the flood-and-drain circulation method, three zones are created based on their distinguishable water and air content: Dry Zone, Wet-Dry Zone, and Wet Zone. The Dry Zone acts as a shield for micro-organisms from direct sunlight, preventing algal and harmful bacteria growth. Most filtration and biochemical processes occur in the Wet-Dry Zone. Further, red wigglers, which are efficient decomposing worms, are present in this zone. The worms are introduced into the grow beds, where they can break down the organic waste, converting them into humus, Nitrogen, Phosphorus, and Potassium (NPK), micronutrients, and growth hormones, as illustrated in Table (2).

Characteristics	Value
Organic carbon, %	9.15 to 17.88
Total Nitrogen, %	0.5 to 0.9
Phosphorus, %	0.1 to 0.26
Potassium, %	0.15 to 0.256
Sodium, %	0.0055 to 0.3
Calcium & magnesium (Meq/100 g)	22.67 to 47.6
Copper; mg kg^{-1}	2.0 to 9.5
Iron, mg kg^{-1}	2.0 to 9.3
Zinc, mg kg^{-1}	5.7 to 9.3
Sulphur, mg kg^{-1}	128.0 to 548.0

Table 2: Chemical composition of vermicompost (Garg, Gupta, 2009)

In addition, the tunnels made by the worms aerate the growing media, providing better conditions for plant growth and bacteria reproduction. Lastly, the Wet Zone represents the mineralization site, which supplies broken-down waste to plants.

To optimize water flow and maximize Wet-Dry Zones, which are essential for growth, a bell siphon is used to apply flood-and-drain irrigation. Bell-siphons let water accumulate in the grow bed up to a specific height, then drain the water into the fish tank. One strength of bell-siphons is the absence of complex technologies as the siphon is composed only of a bell, a standpipe, and a media guard to prevent clogging of bed as shown in Figure (10).

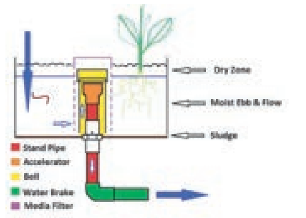

Figure 10: Bell siphon structure and placement in a grow bed.

Pump-based pH controller system:

As studied in CH.2.02, pH is a measure of how acidic or basic a solution is on a scale ranging from 0 to 14 (Zumdahl et al., 2016). It can also be calculated using Equation (5):

$$pH = -\log([H^+])$$

Equation 5: pH equation for an aqueous solution.

The pH of water is an especially important parameter for lettuce, and the nitrifying bacteria. For plants, the pH controls the availability of micro- and macronutrients in the soil. The ideal pH range for lettuce is 6-7, and a deviation outside this range causes a nutrient lock-out. For the nitrifying bacteria, literature suggests their optimal working pH range to be 7.2-8.1. To conclude, the optimum pH range for aquaponic systems is 6-7. Not to mention that Tilapia fish and the red wriggler worms tolerate pH from 6 to 8.

There are two processes that change the pH in water over time: nitrification process and fish stocking density. During the nitrification process, small amounts of nitric acid are produced as the bacteria liberates hydrogen ions during the conversion of ammonia to nitrate. Additionally, the breathing of fish produces carbon dioxide (CO_2) that reacts with water forming carbonic acid (H_2CO_3) lowering the overall pH level.

Accordingly, a feedback system, as shown in the flowchart in Figure (11), is initiated for this parameter. A pH meter is used to sense the pH and give value to the Arduino Uno, while the Arduino gives orders, based on the water pH, for two mini water pumps in two tubes. The two tubes contain phosphoric acid (H_3PO_4) and calcium hydroxide ($Ca(OH)_2$). Equations (6.a & 6.b) present the chemical processes that occur during the addition of both the acid and base.

$$H_3PO_4 \rightarrow 3H^+ + PO_4^- \quad (6.a) \quad | \quad Ca(OH)_2 \rightarrow Ca^{+2} + 2OH^- \quad (6.b)$$

Equation 6: pH neutralization reactions by (a): addition of acid, (b): addition of base

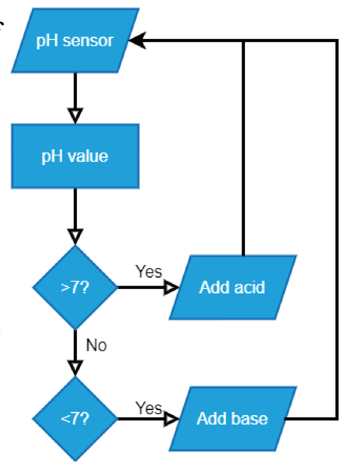

Figure 11: Water pH feedback flowchart

Heating feedback mechanism:

Temperature has a variety of effects on DO level, ammonia toxicity, and biofilter performance. In fact, as the water temperature rises, the solubility of oxygen decreases. Further, an increase in water temperature and pH will lead to an increase in the concentration of toxic NH_3. For example, at a water temperature of 20 °C, 1.24% of the total ammonia is non-ionized at constant pH value. At 25 °C, these values increase to 1.77% (Krastanova et al., 2022). In addition, although Tilapia fish tolerate water temperature ranging between 14 and 36 °C, their ideal temperature is 27-30 °C.

So, temperature is also another water quality parameter that needs to be monitored using a closed feedback mechanism illustrated through Figure (12). The system works by taking a reference input (desired temperature range) and comparing it to the temperature sensor reading.

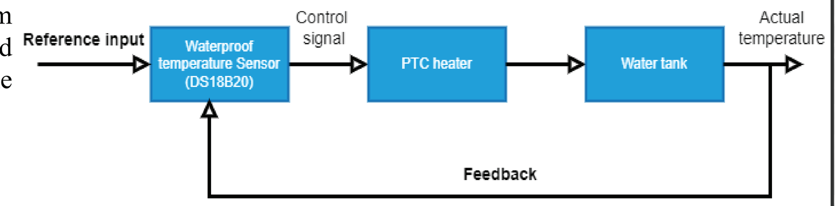

Figure 12: Closed feedback loop for temperature

Based on this comparison, a relay module controls switching on and off the heater. If the temperature falls below the desired range, the heater is on; otherwise, the heater is off. The aluminum shell PTC heater was selected to be actuator because of its ability to rapidly increase temperature. PTC heater simply consists of a ceramic thermistor covered with an outer aluminum shell. This thermistor depends on the Positive Temperature Coefficient (PTC) effect. When the electricity passes through the material, its temperature increases. As the temperature of the material rises, its resistance to the flow of electricity increases rapidly, which in turn causes the heat output to increase rapidly as well. This means that the PTC heater can generate a significant amount of heat quickly and efficiently, without wasting energy or overheating. The outer aluminum shell acts as a heatsink that dissipates the heat generated by the thermistor.

$$\frac{Q}{t} = \frac{K \cdot A \cdot \Delta T}{L}$$

Equation 7: Heat conduction equation.

As mentioned earlier in negative results, The PTC heater was not able to effectively heat a large amount of water due to its small surface area. So, based on the heat conduction equation that is illustrated in Equation (7), the heat transfer rate of the PTC heater was increased by attaching aluminum fins to increase the surface area in contact with water (Halliday et al., 2020).

Water loss percentage calculation:

Regarding water loss daily calculation, Ultrasonic sensor is used which emits soundwaves and then receives the reflected waves. So, it can calculate the distance by measuring the travel time and speed of sound from its base to the object. Through the lines of codes written in Arduino IDE, it will calculate the difference between two measurements at the start and end of the day from the water surface. Then, the difference Δh will be inserted through Equation (8) to print the water loss volume percentage:

$$V_L\% = \frac{\Delta h}{h_0} \cdot 100\%$$

Equation 8: waterloss volume percentage

Conclusion

The project performance, illustrated in the test plan, provided several compelling results. This study aimed to illustrate enhanced sandponics as a sustainable solution for farming and low-cost nutritional plantations. Subsequently, the continuous recycling cycle of minerals in the prototype provided a productive mechanism to sustain Tilapia and lettuce growth. Further, the application of relatively low-cost control mechanisms enabled the project to operate automatically and maintain near-optimal environmental conditions. The prototype satisfied the design requirements by stabilizing pH and temperature levels as well as maintaining the water level with negligible waste accumulation. Implementation of several modifications, including the bell siphon, helped improve the project performance without the need for advanced technological equipment. Moreover, the project treats issues found in other prior solutions by improving cost-effectiveness and maximizing the usage of waste resources. Subsequently, investing in the project's possible applications represents a potential step toward better access to nutrition and waste management, which further contributes to solving Egypt's grand challenges.

Recommendations

- Alternative Sources of Protein

Among promising, sustainable, and cost-effective alternatives are the green macroalga Ulva lactuca and the red Pterocladia capillacea. These types of seaweed are widespread along Egypt's Mediterranean coasts. Since they are available all year round and have rich amino acid and fatty acid profiles, they can act effectively as a low-cost protein supplement in fish feed.

Freshwater microalgae have a protein content of 30-50% dry matter and a lipid content of up to 40%. Further, experiments in the Egyptian environment have shown a 50% increase in fish weight and feed conversion ratio compared with traditional crude protein meals (Abd elaziz M, 2015). The price of microalgae reaches 15 EGP/kg, compared with high-quality fish feed, which can have prices exceeding 40 EGP/kg.

- Real-life Application:

A place suitable for aquaponics systems should have essential characteristics, including direct access to sunlight, the availability of a freshwater source in proximity, and climate stability. Subsequently, it is recommended to apply the project in Kafr El-Sheikh governorate, El-Hamool Markaz, shown in Figure (13), because it is a rural area with high population density and has limited access to local nutrition. Further, El-Hamool is close to the Egyptian Mediterranean coasts, which have abundant growth microalgae. This helps decrease transportation costs for fish feed.

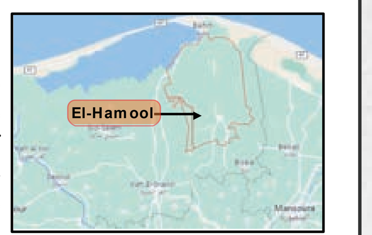

Figure 13: Application of sandponics design in Markaz El-Hamool (red dashes represent El-Hamool

- Intercropping and Vertical Farming

Since supplying large grow beds for plant growth can be expensive, it is essential to be space efficient when using aquaponics. One important method to ensure so is intercropping; since different crops often have varying needs and nutritional requirements, it is recommended to select pairs of crops so that the nutrients left by one crop are utilized by the other. An example is garlic and tomatoes, which combine perennial and annual crops. Intercropping could also be based on other requirements. For instance, a tall crop could be planted with a short crop requiring partial shading. On the other hand, vertical farming by stacking crop layers can handle mass production efficiently.

Different implementation techniques are available, including green hydroponics. Through vertical farming, 1/6 land farming and 98% less water compared to traditional farming are consumed to produce the same crop quantity. Vertical farming outperforms traditional farming in different aspects as shown in Figure (14).

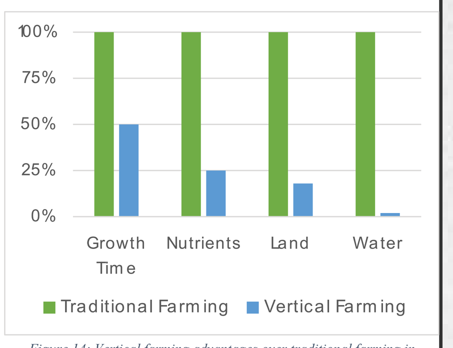

Figure 14: Vertical farming advantages over traditional farming in different aspects.

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