Implementation Procedures of Greenhouse Modernisation

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***Abstract*— The primary objective of this paper is to address the design and implementation of automated soil and hydroponic farming systems, utilizing experimental data and a customized autonomous control system. The study also encompasses the monitoring of soil quality and plant selection, which are crucial factors in optimizing crop yields and quality while minimizing environmental impact and manual labor. This study presents an implementation procedure for modernizing privately-owned, old-style greenhouses. The primary aim is to optimize crop yields and quality through real-time monitoring of critical environmental factors. The study also discusses the economic and practical outcomes of implementing aquaponic systems while highlighting potential issues that require attention. Overall, this implementation procedure offers a promising solution for private greenhouse owners seeking to enhance their crop production while minimizing environmental impact. The final autonomous control system regulates the irrigation quantity, the indoor temperature and controls the lighting in the greenhouse. The proposed innovative design provides not only functional features, but also modularity attractive in terms of design and aesthetics at the same time. The constructed prototype is used for growing crops and helping research in real life conditions. Furthermore, the proposed solution aims to contribute knowledge to the emerging field of vertical agriculture by mimicking the vertical farming system.**

***Keywords*— control system, greenhouse, irrigation, automation, hydroponic, vertical farming, mathematics, soft computing, sensors, artificial intelligence, sustainable development goals**

I. Introduction

The utilization of digitization and smart farming technologies is crucial in realizing sustainable agriculture and mitigating challenges encountered by the global food system [1-4]. By optimizing resource utilization and minimizing waste, these technologies facilitate improved crop yields and quality. Moreover, they enable farmers to monitor environmental variables such as soil moisture, temperature, and nutrient levels in real-time, empowering them to make informed decisions and adjust farming practices accordingly [5]. Smart farming methods, including precision agriculture and vertical farming, promote crop diversity and decrease reliance on monocultural practices, ultimately resulting in enhanced soil biodiversity and reduced soil degradation. Furthermore, digitization and smart farming reduce dependence on chemical fertilizers, thereby mitigating environmental degradation and contributing to food security for future generations [6]. Furthermore, the lack of water is becoming a progressively common phenomenon with continuously increasing importance and impact for the growing of crops [2,3]. These main factors cause difficulties for growing crops by turning the previously fertile soil into inhospitable environments. Fertilizer runoff causes algae overspread in lakes and oceans [4]. These chemicals often seep into underground and contaminate the diminishing supplies of drinking water. In addition to immense application of fertilizers by concurrent intensive agricultural practices, it also places high demands on water resources [12]. This paper deals with the aim to create a functioning irrigation system in connection with hydroponic cultivation. For this purpose, a design and construction of a greenhouse in size of a privately owned farming unit has been developed. For the convenience of the owner of such a greenhouse as well as to ensure the correct functioning of such interconnected complex system conjunction, the designed greenhouse includes autonomous control system to continuously monitor and self-control its functioning [9-11]. For this innovative solution the hardware part of the greenhouse system with all necessary actuators and sensors and an algorithm to control the growth of plants cultivated in the greenhouse have been proposed. The whole proposed solution was implemented in real conditions and tested on the functionality of the greenhouse. There is currently a research gap in advancing a reliable control system which is also efficient in advance data collection for building foundation of IoT compatible control system. The current study proposes the implementation of such system also elaborated in several studies, e.g., [12-15]. The rest of this article is organized as follows. The implementation procedures of these systems are showed in chapter IV. Using a real example in private ownership, it also shows all the usual steps in such modernization of old-style greenhouses. It also briefly mentions the analysis of the suitability of the soil used and the selection of cultivated plants. After final economical and practical results of chapter VI, it also addresses in chapter V.

II. Methodology

The greenhouse, provided for research purposes by the owner, was analyzed and turned into a smart greenhouse. The procedure included not only the analysis of the greenhouse`s structure, but also a quality check of used soil. The soil had neutral PH. And by the Jar test [16] we identified the texture of used soil as Sandy-loam. Secondly, the forms of cultivating crops were studied in order to acquire enough knowledge about aquapony and hydropony for identifying necessary hardware components in order to provide suitable conditions for plant growth. Species of growing plants have been chosen according to the season, soil attributes and according to actual offer. The chosen list of species for cultivation in soil comprise species: *Raphanus sativus, Brassica oleracea var. gongylodes, Viola cornuta, Fragaria vesca,* and for cultivation in hydropony comprise species: *Lactuca sativa, Raphanus sativus, Solanum lycopersicum.* Plants were cultivated from late February to late May. The theoretical system has been developed as a conjugation of aquaponic tubes with possible plant cultivation, area for cultivating plants in soil irrigated by water from aquaponic cultivation and a reservoir with fish to produce water enriched to naturally fertilize the planned plants without additional artificial fertilizing chemicals. However, as the water from the fish reservoir in pure unchanged form directly from the tank would represent a poisonous substance in contrast to the desired fertilizing natural fluid, an additional tank for fermentation of the fluid was added to the design. After the fermentation procedure is finished, the fluid contains nutrients for the plant fertilization to support the growth and speed of growing of planted plants. The given building object is described in subsequent chapter 3. The individual tasks as described as follows. 1) Reconstruction of the greenhouse which concerned with the modification of the greenhouse - sealing the surfaces of the walls of the greenhouse and the aquarium, reconstruction of the door, elimination of pests. 2) Study and construction of the hardware part for the irrigation system, i.e., choosing a suitable microcontroller platform, sensors, actuators, and their construction, in addition to irrigation system construction. 3) Study and construction of software part for irrigation control system, i.e., design of suboptimal parameters for the greenhouse, which included temperature (air, soil, water), humidity (air, soil), light, etc. Also the design of simple control algorithms, which, based on this parameterized information, controls all actions. 4) the study and software implementation of alarms and other security elements [17], i.e., the design of a series of alarms that will notify the user of various types of emergency situations that could occur. 5) Study and software implementation of Human Machine Interface [18], i.e., The design of a user interface that connects the user with the smart greenhouse and provides him with full control over the system.

III. Description of the Green House

A. Dimensions

The dimensions of provided greenhouse were 3.2 m in width, 4 m in length and 3.6 m in height. See Fig. 1. The walls, as well as the ceiling, were made of thick double-walled polycarbonate panels.

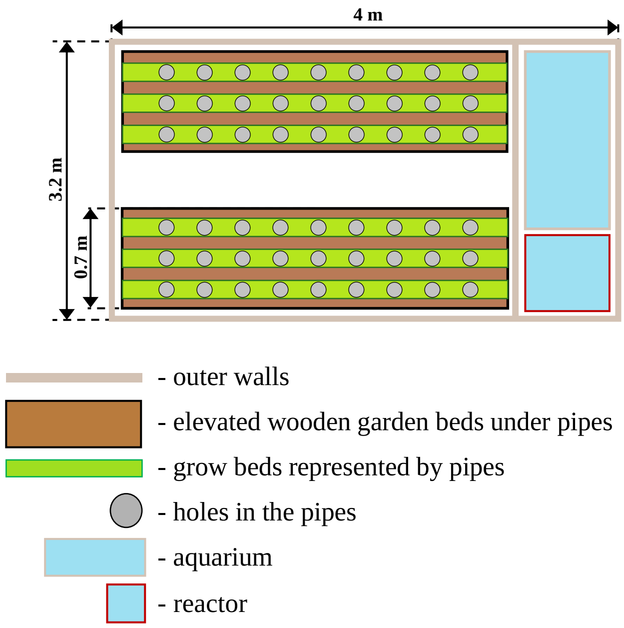

Fig. 1. Green House dimensions

The tank section consisted of two reservoirs: one for fish cultivation and one for fermentation of the wastewater from fish reservoir in order to turn the poisonous fluid into a nutrient fertilizer. The first tank for fish breeding, an aquarium, was constructed with dimensions of 1.7 m in width, 0.5 m in length and 0.7 m in height. In the real implementation the small reactor with the pump for irrigation was added to the aquarium in second step. The reactor was connected to the aquarium by another siphon. The role of the reactor was the production of nutrients for plants in cooperation with microorganisms and fermentation. The water levels, temperature as well as other characteristics of the tank reservoirs are planned to be equipped with various sensors for monitoring the actual conditions. The right and left side of the greenhouse can be used for plant cultivation in soil with micro-irrigation. These two areas for cultivating plants in soil were constructed in forms of raised wooden garden beds filled with soil. These garden beds were used for the initial experiment with soil irrigation. The dimensions of each raised garden bed is 0.7 m in width and 2 m in length. The soil in these 80 cm high wooden garden containers reaches a height of 60 cm. Furthermore, the area above the soil level can be divided into multiple sections filled with pipes for aquaponic cultivation of plants. Altogether, there are six 2 m long pipes installed in the greenhouse. Three per side.

During the implementation of the solution, the partial installation phase itself, the main focus was given to ensure watering only the left side of the greenhouse. This was conducted based on the assumption that the procedure would be analogue for the right side for a complete implementation. The pipes were used as grow beds for aquaponic cultivation. These pipes were connected in series through siphons at both ends. To create one aquaponic cultivation bed, nine holes with a radius of 5 cm were evenly spaced along the upper part of each tube. Each hole was reserved for a flowerpot that would enable the root system of the plant planted in the particular pot to absorb enough of the nutrient fluid flowing through the pipe. The type of the flowerpot was chosen accordingly to the measurements of the pipe's holes. It was designed to be adjustable and applicable to different crops. Any flowerpot with planted plant can be anytime individually replaced.

IV. Implementation

Diverse irrigation approaches were implemented when assembling the prototype of the proposed smart autonomous greenhouse solution. After each test, changes, improvements, or modifications were made to the greenhouse in order to improve the operating of the conjunction of the complex systems. Ideally, the system will reach a point where we can automatically adjust the controllable growth variables to optimize plant growth.

A. Soil Irrigation

During the initial part of the project, we made a classical soil irrigation. This way, we got to know the control unit, sensors, and actuators. Fig. 2 shows the distribution of sensors and actuators within the greenhouse.

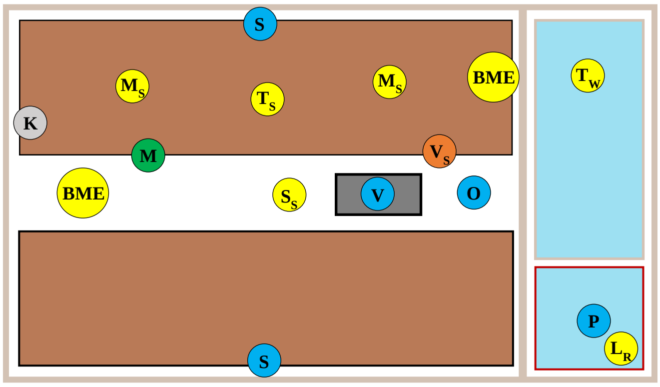

Fig. 2. Schematic diagram of the soil irrigation project (Project 1)

Designations of individual elements from Fig. 2. and Fig. 3.:

- M – Microcontroller
- K – Camera
- S – Lighting
- V – Ventilation
- O – Heating
- P – Irrigation pump
- V_S – Soil irrigation valve
- T_W – Water temperature
- L_R – Low limit water level
- S_S – Light intensity sensor
- T_S – Soil temperature
- M_S – Soil moisture
- BME – Air properties
  - Temperature (T_A)
  - Moisture (M_A)
  - Quality (Q_A)
  - Pressure (P_A)

The goal of the initial part of the project was to make the system work reliably. Sensors and actuators for soil plants have been implemented. We were facing problems like Wi-Fi, and power outages, or faulty sensors malfunctions. The occurrence of harmful insects (ants and wasps) was also recorded, which were subsequently mechanically/chemically eliminated. In the third week, the greenhouse finally reached the point where it was possible to start improving the parameters of the regulators on optimizing the crop growth environment without significantly changing the greenhouse's physical design. The plants did very well in the modified conditions.

B. Aquaponics

In the next part, the growing plant`s roots are directly immersed in water and a nutrient solution. We implemented Ebb and Flow System. In this growing system, roots are regularly flooded and drained by the solution inside the pipes. Sensors and actuators were like the first project but without soil moisture sensors. Fig. 3 shows the positioning of used sensors and actuators.

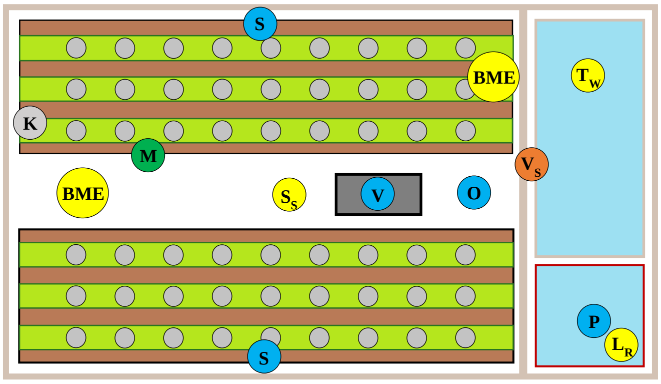

Fig. 3. Designations of individual elements of project 2

We had to create distribution lines for the system, including seals, insulations, and siphons. In addition, we added a reactor with microorganisms to the system, which we connected to the aquarium. We also prepared flowerpots, which we filled with expanded clay aggregate, which we used as a foundation for plant growth. These are shown in Fig. 10. We planted plants of different species like arugula, radishes, tomatoes, Swiss chard, and lettuce. The results after the first two weeks could have been better. Salads could have grown up better; some of them even wilted. The other plants (arugula and radishes) grew quite well, but even the best grew below 2 cm in height. Tomatoes and Swiss chard were also starting to wilt. Their roots were still very short and little branched. The problem was in the source of nutrients. The clean water from the well was not enough for them to grow; they needed a source of nutrients, including minerals. Therefore, we added a natural liquid fertilizer based on molasses and ground phosphates to the reactor, and microorganisms that would not be harmful to fish nor plants. In these conditions, the plants have already started to do much better. After the next two weeks, we noted better results. The plants have grown to larger sizes, and the roots have also grown considerably. We added additional rules for lights to the control. They started turning off from midnight to morning so that the plants had time to regenerate (formation of phytochrome) [14]. A large amount of heat accumulates in the greenhouse during the warm summer. Therefore, fan ventilation alone could not keep the system in the desired temperature range [15].

C. Combined Irrigation

In the last part of the project, we focused on combining soil and aquaponic irrigation. For the aquaponic system to work correctly, the pump must constantly supply it with water from the reactor. Nevertheless, it was possible to use only one pump. That is why we added a two-position valve to the system. The valve was built in so that the new control algorithm could divert part of the water flow from the reactor to soil irrigation if necessary. In the open valve state, the process of soil irrigation was taking place. During which the water flow to the aquaponics system slowed down. The plants in the greenhouse's soil and aquaponic parts did very well under these conditions. The system worked reliably, and there was no management problem during the last two weeks of the ongoing project. The graphs in Fig. 4 show the course of the measured quantities over two days.

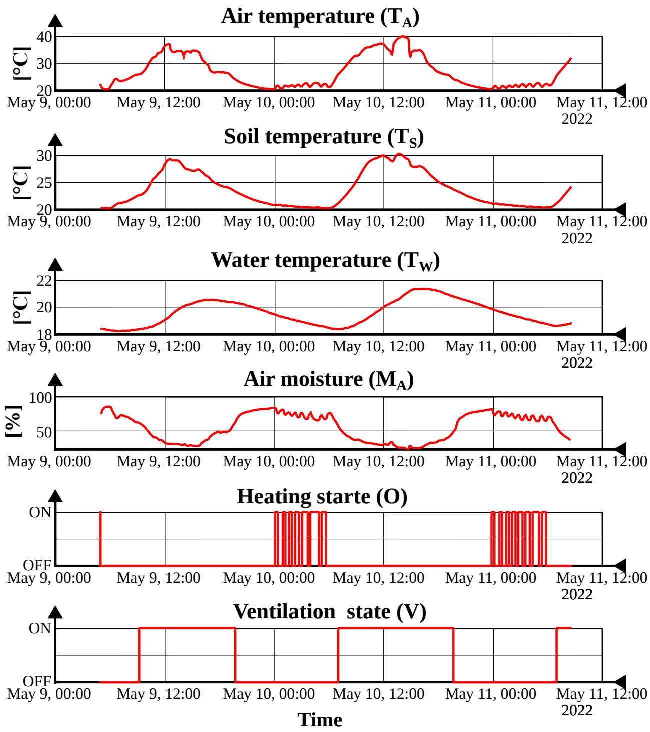

Fig. 4. Greenhouse temperature control (May 9-11, 2022)

It also shows the course of temperature control in the greenhouse during a two-day measurement period. The algorithm keeps the temperature in the desired range for the plants in the greenhouse. The temperature also affects air and humidity. The temperature under heater control was able to maintain the air temperature in the desired range even at night. The heater could also slightly influence the temperature of soil and water. During the day, the temperature of the air inside the greenhouse was regulated less successfully. The ventilation alone did not have a sufficiently large effect on the temperature in the room. The cause may be excessive heat accumulation in the greenhouse during warm summer weather. These potent effects could be compensated by adding fans or implementing other cooling methods.

In Fig. 5 can be seen that the soil moisture did not fall below the critical limit of 20%, and the valve was not opened during the two days shown. Soil moisture ranged from 63 to 68%. During this time, it fell by only 3%. Because we covered the soil with black non-woven fabric, water losses through evaporation were limited. The pump was constantly on. The pump constantly drew water from the reactor and thus kept the aquaponic system in operation. The water was always returned to the system for re-enrichment with nutrients, which also saved the water source.

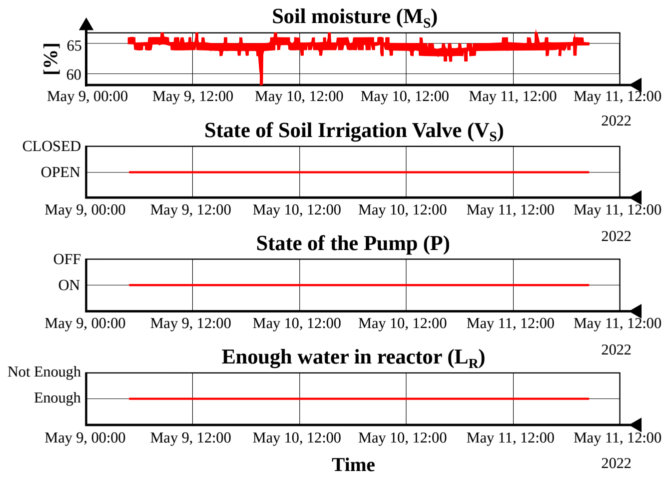

Fig. 5. Soil moisture management and hydroponics (May 9-11, 2022)

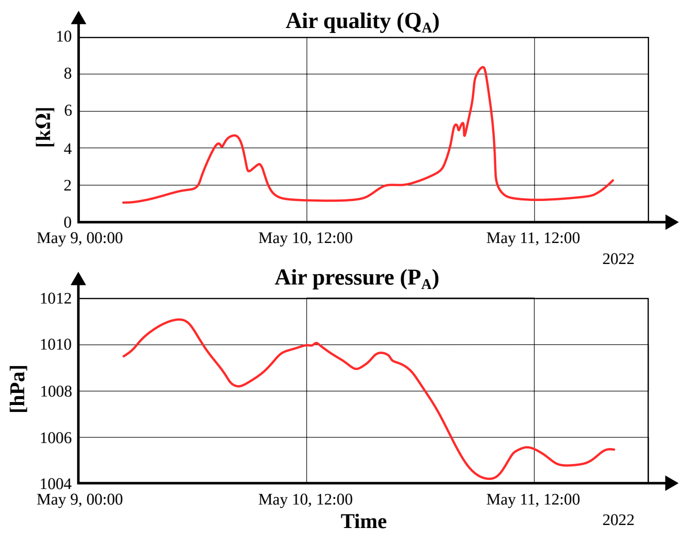

Fig. 6. Sample of measured air quality data (May 9-11, 2022)

According to the indoor air quality classification, the air quality in the greenhouse was satisfactory. The air quality data measured from May 9 to May 11 are shown in Fig. 6.

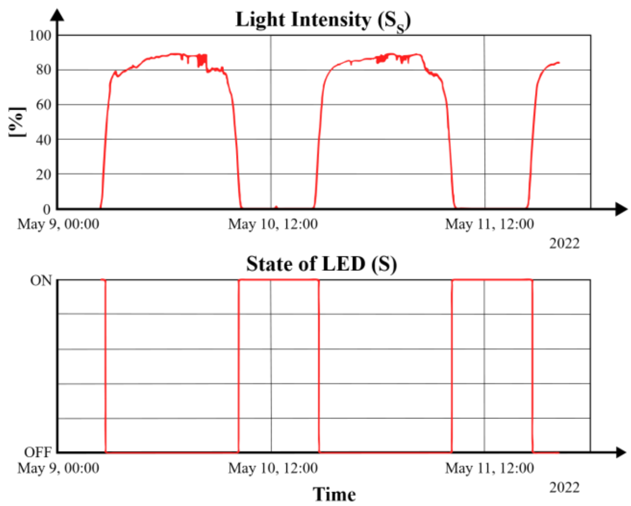

Fig. 7. Light control in the greenhouse (May 9-11, 2022)

Fig. 7 shows the control of luminosity in the greenhouse. The LED lighting [13] was active if the luminosity was lower than 15%. But at midnight they turned off so that the plants had time to regenerate [14].

V. POTENTIAL PROBLEMS OF AQUAPONIC SYSTEMS

Aquaculture represents a hybrid of agricultural and hydroponic practices. In the specific context of aquaponics culture, an interconnected system is established where water flows through both subsystems. This facilitates the utilization of metabolic waste from fish as a valuable nutrient source for plant growth. Hydroponic systems represent an alternative approach for managing water consumption, regulating nutrient input, and reducing the reliance on chemical fertilizers. The adoption of hydroponic systems not only results in higher crop yields by minimizing the adverse effects of soil-borne diseases but also poses a potential challenge for aquatic-pathogen management due to the adaptability of pathogens to aquatic environments. Therefore, it is important to monitor and manage pathogen levels to maintain a safe and healthy environment for aquaponic systems. A significant risk in cultivating hydroponic crops poses fungal diseases, especially those caused by some species such as *Fusarium* sp., *Pythium* sp. and *Phytophthora sp*., which can spread with water in the system. The recirculating fertilizer solution system has the potential to serve as a source of infection. In liquid media, zoospores may be present and can cause infections in new hosts. The dispersion of certain diseases through water media may be related to the type of substrate used in the system's design and the plant species present as drivers of microbiological activity in the hydroponic system. Recent articles have proposed an interesting hypothesis that fish water may contain antagonistic microorganisms or inhibitory compounds. Organic compounds could also play a significant role in the impacts on aquaponic and hydroponic systems. The organic matter present in the water arises from uneaten food debris, organic plant growth media, fish feces, plant residues, and root exudates. There are still knowledge gaps. The results from international activities focused on aquaponic production developed in the USA, and Europe reminds the need for more knowledge of producers about the incidence of plant diseases and plant health in the studied systems. Proposing potential improvements, especially against fungal diseases and pathogens in hydroponic and aquaponic culture production, is very desirable [1].

VI. DISCUSSION

The study proposes an automated greenhouse system that uses soil and aquaponic irrigation, artificial lighting, and temperature control to optimize crop growth in a controlled environment. The greenhouse's experimental design minimizes resource use while investigating optimal conditions for food cultivation. The system's functionality was tested in stages, with each test providing insights on how to improve the system. Results show that the greenhouse system can function reliably with minimal user intervention, enabling precise monitoring of environmental variables and reducing resource wastage. The proposed greenhouse system's automated features provide a promising solution for enhancing crop production efficiency while minimizing resource use in controlled environments. It holds immense potential for revolutionizing agriculture and ensuring food security for future generations. The workflow overview can be observed on Fig. 12. The plants did very well in the modified conditions. The growth progress is documented on Fig. 8, Fig. 9, Fig. 10 and Fig. 11.

Fig. 8. Initial status of plants grown in irrigated soil: Kohlrabi and strawberry transplants are up and yarrow plants are down

Fig. 9. Final state of grown plants in irrigated soil

The total power consumption was determined using a Solight DT27. The average annual cost for 2022 in households for electricity was €364.73, and the average annual electricity consumption is 2271 kWh. Converted, 1 kWh of electricity costs €0.16. From 01.05.2022 – 11.05.2022, the measured consumption was 29.63 kWh. It follows that the average monthly costs for the greenhouse operation in the summer would be €14.22 without VAT. Next papers will present further details of this project from several points of view more in detail. Next steps going throw further upgrades in IoT and will look in some more modular less time-consuming alternative procedures. As mentioned in chapter V, it is important to check presence of diseases or other threads also in an aquaponic system. The present study utilized BME260 and BME680 sensors for data collection. However, the solution proposed herein is designed to be flexible and capable of integrating a diverse range of sensors in response to the rapidly evolving technology in this sector. The hardware system for the solution is controlled using a 2-core, 32-bit uCPU architecture, which can be implemented on multiple uCPU platforms. The choice of double-core uCPU was driven by the need for efficient communication and data processing. As the system under consideration is non-deterministic, i.e., unpredictable in behavior, it is crucial to use asynchronous processing of tasks to minimize the risk of data loss. By adopting this approach, the system's performance can be optimized, and smooth functioning can be ensured.

As the data collection continues and builds a comprehensive data base for four seasons including numerous conditions and scenarios using machine learning, e.g., [19-22] would be further feasible. Often large databases provide opportunity for novel deep learning integrated with the proposed control system [23-27]. The proposed smart greenhouse control system is compatible with IoT systems [28-31]. Future research will elaborate on integration of IoT and learning systems for further advancement.

Fig. 10. Plants grown from seeds were ready to be placed in the aquaponic project

Testing the system's feasibility in urban settings, where space is limited, is also important, as it can address growing demands for fresh, locally grown produce and reduce transportation-related carbon footprints. Future studies can focus on reducing design, construction, and operational costs while addressing potential scalability issues. Overall, integrating machine learning, renewable energy, and urban adaptability can improve crop production sustainability and efficiency.

Fig. 11. Final state of grown plants in aquaponic project

Fig. 12. Installation works

VII. CONCLUTIONS

The present study reports promising results regarding the overall functionality of the greenhouse using the proposed control system. The control system was found to be efficient in measuring and applying automated improvements accordingly. Notably, the greenhouse was fully functional without any user intervention, and the plants grew well in the modified conditions. The average annual cost of monitoring soil quality and plant selection was accurately calculated, which further validates the efficacy of the proposed control system. The proposed innovative design not only provides functional features but also modularity attractive in terms of design and aesthetics simultaneously. The constructed prototype serves the purpose of growing crops and facilitating research in real-life conditions. Moreover, the proposed solution aims to contribute knowledge to the emerging field of vertical agriculture by mimicking the vertical farming system. Therefore, the study presents a fully automated greenhouse system for crop production in a controlled environment, which employs soil and aquaponics irrigation, artificial lighting, and temperature control. The system facilitates experiments to ensure optimal conditions for crops and efficient food cultivation. Integrating advanced machine learning algorithms into greenhouse control systems can improve resource utilization and optimize crop growth by using historical data and current observations to adjust environmental variables. For example, the system can learn to adjust water and nutrient levels based on the plant's growth stage, leading to increased yields and reduced waste. Incorporating renewable energy sources, like solar panels and wind turbines, can enhance the greenhouse's sustainability and decrease reliance on traditional energy sources while offsetting high energy consumption.

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