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Monitoring Root and Shoot Characteristics for the Sustainable Growth of Barley Using an IoT-Enabled Hydroponic System and AquaCrop Simulator

Monica Dutta [1,†], Deepali Gupta [1], Yasir Javed [2,*], Khalid Mohiuddin [3], Sapna Juneja [4,*], Zafar Iqbal Khan [2] and Ali Nauman [5,†]

1 Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura 140401, India
2 College of Computer and Information Sciences, Prince Sultan University, Riyadh 12435, Saudi Arabia
3 Department of Management Information System, College of Business, King Khalid University, Abha 62529, Saudi Arabia
4 Department of Computer and Information Sciences, International Islamic University, Kuala Lumpur 53100, Malaysia
5 Department of Information and Communication Engineering, Yeungnam University, Gyeongsan-si 712-010, Republic of Korea
* Correspondence: yjaved@psu.edu.sa (Y.J.); sapnajuneja1983@gmail.com (S.J.)
† These authors contributed equally to this work.

Abstract: Vertical farming methods are gaining importance in the current era of urbanization and industrialization 5.0. These methods of farming enhance sustainability by consuming less space and reducing carbon emissions and greenhouse gas emissions. The Green Internet of Things (G-IoT) offers greater environmental sustainability by switching to a dormant mode while not in use, thereby consuming less energy. Each farming method has a different effect on the shoot and root growth of the plants. Thus, dedicated farming methods must be identified for each crop according to the type of crop under consideration. This leads to a need to compare and analyze the root as well as shoot growth trends of crops in different cultivation mediums, using different cultivation methods, thereby identifying the most suitable method for the cultivation of the crop. A comparative analysis of barley shoot and root growth in green IoT-embedded hydroponics and substrate cultivation methods has shown that hydroponics exhibits two times more shoot growth than substrate cultivation. Furthermore, the results were verified against the results obtained from the simulator, which confirmed that the hydroponic method of cultivation produced a year-round qualitative product with 17.112 tons of biomass and 8.556 tons of dry yield.

Keywords: vertical farming; hydroponic system; sustainability; simulation; barley; green IoT

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1. Introduction

Farming has been an integral part of many nations throughout the world. It is a more productive version of vegetation which is crucial in maintaining life on earth. On the other hand, urbanization, an inevitable change in modern society, has been growing exponentially in recent decades. With the advent of the Internet of Things, the pretext is to make everything smarter and smarter. However, its advent has had a profound effect on urban lifestyles. Consequently, large numbers of habitats have been displaced from rural areas into urban areas, leading to the eradication of farming lands and greenery in urban areas. As urbanization brings many opportunities and innovations, there is a growing need to develop greener areas in urbanized areas.

All these factors have led to the concept of soilless farming in vertically stacked layers, which has proved to be a boon wherein the dependency on land for cultivation is abolished. This type of farming technique has proved it is feasible, efficacious, and efficient in farming on rooftops, terraces, or other such places of urban habitation.

Vertical farming is a concept that involves cultivating crops in vertically arranged stacks. It is an advancement over artificial methods of cultivation wherein the dependency upon soil for cultivation is eliminated [1–3]. There are three basic categories in which vertical farming can be classified, namely, aeroponics, hydroponics, and aquaponics as depicted in Figure 1.

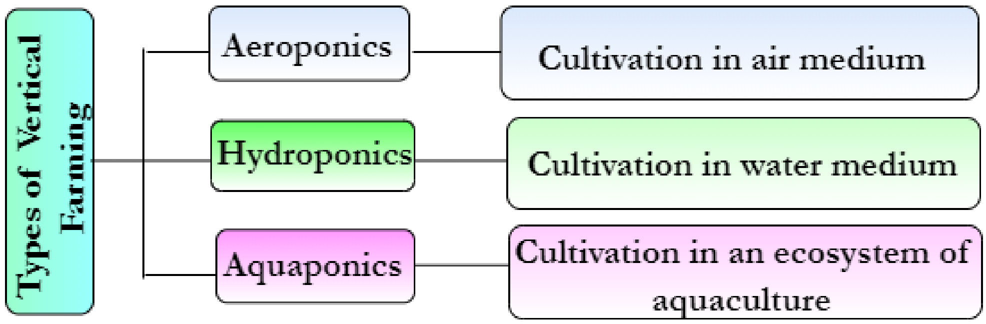

Figure 1. Types of vertical farming.

The concept of growing crops in an indoor environment in controlled growing conditions for temperature, pH, light, water, etc., is another concept developed, namely, CEA. This helps in providing the optimal environmental conditions required by the vegetation to ensure quality yield all through the year. CEA also aims at better crop quality in a sustainable manner using minimal resources, like energy, area, manpower, investment, and water. The automatic feature that is introduced and implemented in smart agriculture can be implemented using green IoT, wherein environmental conservation and cost reduction are taken into consideration. Along with a green environment, the green IoT also caters to systematic solutions for enabling sustainability in society [4–6].

In this experiment, barley (*Hordeum vulgare* L.) is considered the subject crop. Barley is one of the most important cereal grains apart from maize, rice, and wheat. It is a crop for both food and feed in the ratio of 3:7. It is grown as a summer crop in temperate regions as well as a winter crop in tropical regions. The growth cycle of barley is short, and it also has good tolerance to drought. The consumption of barley is not only as a livestock feed but also as barley malt, a coarse cereal used with oats, millet, corn, etc., for human consumption. Barley is full of carbohydrates and proteins, thus proving itself to be an ideal livestock feed. Apart from that, the inedible parts of barley can also be used for animal bedding, making hats, etc. Barley is also not far behind in terms of industrial consumption.

The various factors that act as motives towards adapting and working towards smart agriculture may be listed as sustainability, year-round production, less time use, better yield, food security, minimum resource use, and limited cultivation area needed. These factors undoubtedly provide an added advantage over the traditional substrate cultivation method.

There are several health benefits of the green shoot part of barley that has not started making seeds. It has several health benefits which can be listed, such as that it is rich in minerals, vitamins, and antioxidants; prevents breast and colon cancer; improves bone health, immunity, and digestive disorders; etc. Barley grains, on the other hand, are rich in many beneficial nutrients, and its fiber content helps in weight reduction, reduces the risk of heart disease, prevents gallstones, controls blood sugar, etc. The enhanced length and volume of barley roots help in their better intake of water and nutrients and increase the survival of chances of the plant.

To formulate some research questions to be analyzed and answered after the process of the research, the identified research questions are as stated:

RQ1: Which cultivation medium is the most suitable for barley?
RQ2: Compare the shoot and root growth trends of barley in different cultivation mediums.
RQ3: How can water conservation be further enhanced in the hydroponic setup?

The research questions formulated have significant relevance to the research work carried out. The best cultivation medium for barley crops has to be identified for its efficient mass production, and the different growth trends of the shoot and the root have to be identified for barley so that we can develop a clearer knowledge of the outcomes of various cultivation methods. Energy conservation can be ensured by implementing the use of green IoT in the system. Green IoT goes off into an inactive or sleep mode when not in use. Thus, this ensures environmental conservation, cost reduction, and a green environment, and cater to systematic solutions for enabling sustainability in society. Water conservation can be enhanced in the implemented system by including an electrocoagulation plant for recycling wastewater. Thus, incorporating all these sustainability measures into a novel work is the aim of the experiment. The novelty of this experiment is that a comparative analysis of barley shoots as well as root growth trends was lacking in the literature studied. This was identified by experiments in two trials and validated with the outcomes of the 'AquaCrop' simulator. The best cultivation method was further made more sustainable with the use of green IoT and wastewater recycling methods.

The hydroponic mode of cultivation is multiple times more productive, better in qualitative and quantitative comparisons, and economically beneficial to farmers, but this does not give a general or exact answer for all the crops. Every crop thrives best in a particular setup, depending upon its requirements to grow fruitfully [7], and the exact setup for the best cultivation method for each crop has to be identified in terms of shoot and root growth trends to enhance the qualitative and quantitative yield. This in turn has led to the quest of ensuring enhanced sustainability in terms of global sustainability and water conservation. For the experiment, barley was cultivated in the soil as well as in a deep-water culture (DWC) hydroponics setup wherein growth quality and quantity were checked and analyzed. The hydroponic setup was further embedded using green IoT to ensure environmental sustainability by reducing greenhouse emissions. It was also equipped with a wastewater treatment setup using an electrocoagulation method that helps the contaminated, muddy water to get clarified and recycled in the setup. Finally, the results for the growth characteristics show that the DWC method of hydroponics is best suited for barley cultivation and that energy and water usage efficiency can be enhanced in a hydroponic setup which further adds tremendous value to it.

In the case of hydroponics, the cultivation medium is water, which is mixed with nutrients in the required proportion. Hydroponics setups can further be of five basic types: drip, ebb and flow, deep water, nutrient film, and wick technologies [8,9]. A detailed background study regarding vertical farming types and the technologies used in these processes is presented in this section. A smart hydroponic system based on the IoT using deep neural networks is proposed in this work. The sprinkler and the water flow are controlled intelligently based on parameters like temperature, water flow, pH, and humidity. The nutrient solution to be applied is controlled by the trained RNN–LSTM based on future predictions of light, temperature, and humidity [10–13]. Various combinations of temperature, light, humidity, and water are used in several random forest algorithms for their performances to verify the sensor fusion concept [14–17]. The concept of sensor fusion enhances the performance of random forest classification with an accuracy of 90.62% [18]. The best technologies, like IoT, computer vision, and edge computing, are put together into a hydroponic system to create a cultivation estimation system dependent on image processing with an accuracy of 95% for corn [19–22]. Automatic cooling down of the roots of IoT-based aeroponically grown lettuce and retrieving of the temperature and humidity data has been studied [23–25]. A cooling fan was attached to an Arduino board for real-time recording of data and cost-effectiveness. A mobile application was used to obtain the data, and an excel sheet was maintained to be sent to the user weekly. This significantly increased the growth of the lettuce and its absorbance of inorganic nutrients. Plants grown in controlled conditions are seen to grow better than plants grown in uncontrolled conditions [26–28]. The growth of the plants is depicted in pictorial forms on a web application, and out-of-range values can be easily detected; the farmers are subsequently alerted, and control measures are activated, ensuring minimal damage to the plants. Automatic control of electrical conductivity, TDS, pH, and the level of liquids is proposed to improve hydroponic farming [29]. A system developed for automatically adjusting the pH value and nutrients in lettuce cultivation using a neural network was developed to facilitate continuous data collection from multiple sensors in urban farm conditions [30].

The various types of hydroponic setups are classified in Figure 2. The five types of hydroponic setups are the nutrient film technique (NFT), ebb and flow, deep water culture (DWC), wick system, and drip system. NFT is a setup where a reservoir containing nutrient-infused water is supplied at regular intervals to the plant roots. Ebb and flow is another type of setup where the plant roots are flooded with nutrient-infused water for a particular period and then it is drained out. In the DWC setup, the roots are completely immersed in water and the water is changed after several days for nutrient infusion and oxygenation. The wick system is a hydroponic setup where there are cotton wicks that supply nutrients to the plants through capillary action. A trickle system is another name for a drip system where the nutritional water is sprayed or trickled to the plant roots with the help of emitter pumps. Each setup is suited for different plant types which depend on the plant types and characteristics. Three features combined in the form of leaf, color, shape, and texture for chili are proposed to enhance precision agriculture, which also aims at estimating five types of plant conditions: calcium, magnesium, sulfur, and potassium deficiency and healthy [31,32].

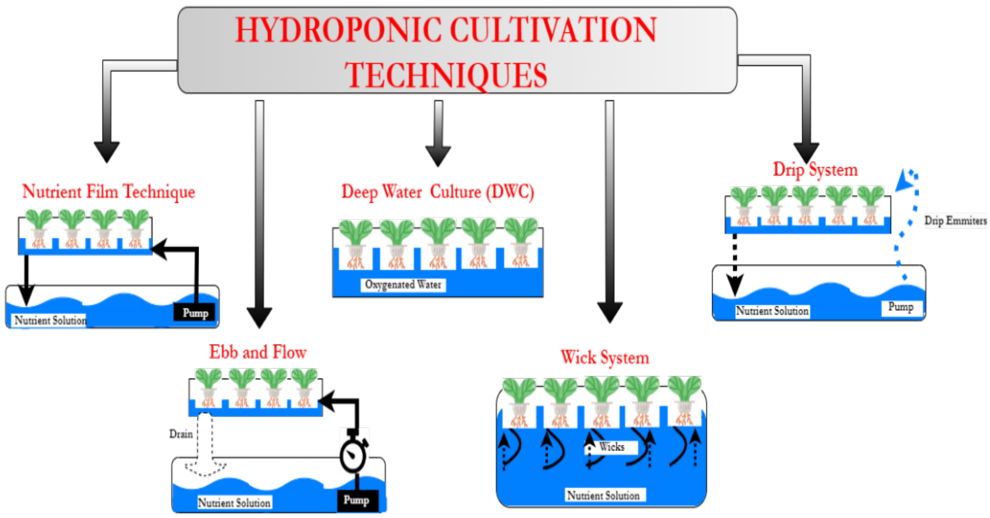

Figure 2. Classification of hydroponic setups.

To analyze and perform a comparative study of barley growth in hydroponics and substrate cultivation methods, and to improve energy efficiency and water conservation in hydroponic systems, this research put forth the contributions listed: (1) Barley is cultivated with all the nutrients needed for its growth and its growth is monitored in the soil in specific weather conditions. (2) A DWC setup is used to grow barley while providing it with all the necessary environmental conditions and nutritional requirements. (3) The DWC setup of the experiment is equipped with a wastewater treatment setup that further ensures almost zero water wastage during the entire cultivation process. (4) The qualitative and quantitative growth of barley shoots and roots are compared in both mediums. (5) Qualitative and quantitative analysis is performed from outputs of the 'AquaCrop' simulator. (6) The growth trends of the actual cultivation methods are compared with those of the simulator results.

2. Materials and Methods

The methodology carried out in this study is a comparative analysis of the growth of barley (*Hordeum vulgare* L.) in water, i.e., in a deep-water culture (DWC) setup of hydroponics, and soil, and the results are compared and analyzed with the outputs obtained from a simulator [33].

The cultivation of barley was carried out in the Punjab state of India towards the end of September 2022, when the temperature ranged between 14 °C and 31 °C, humidity ranged between 62% and 67%, and average rainfall was in the range of 100 mm to 300 mm. The optimal pH required in the soil for the best growth of barley is neutral to alkaline. An acidic pH is not suitable for barley cultivation. Heavy loam and sandy soils are the most suitable for the growth of the same. The percentage contents of nitrogen, potassium, and phosphorous in the growing medium must lie in the ratios of 7%, 9%, and 5% of the total nutrient content [34].

A DWC hydroponic setup was used for the cultivation of barley and the growth comparison was performed with barley cultivated in a substrate medium. Healthy barley seeds were soaked in water for 24 h and then left to germinate for a couple of days [35,36]. Half of the seeds were then planted in soil and the other half were put in the DWC setup simultaneously. It has been noticed that barley grown hydroponically outperforms that grown in the traditional substrate medium in various ways. Two trials of soil and hydroponic cultivation were conducted, and the best samples out of those two were analyzed for comparison [37]. The agronomical variables affecting barley growth were inputted to a simulator called 'AquaCrop', and a comparative analysis was obtained between hydroponic and substrate cultivation [38]. The results of the simulation were then compared with the actual output obtained.

A pictorial representation of the pathway of the methodology followed is presented in Figure 3. The experiment started with the aims of comparing and analyzing the growth responses, root analysis [39], and shoot analysis, and the results were confirmed by comparing them with the results obtained from the simulator. The initial phase was cleaning and soaking the barley seeds overnight and then sowing the seeds in the substrate and DWC hydroponic setup separately [40,41]. The DWC setup was monitored using the green IoT, which helped in ensuring environmental sustainability by keeping a check on carbon and other greenhouse emissions. Though the hydroponic setup uses multiple times less water compared with the substrate cultivation method, the water consumption was further reduced by employing a water purification setup using the electrocoagulation method [42]. This further ensures sustainability by conserving and reusing soiled water. The clean water is again infused with nutrients and recycled to the hydroponic setup and the silt is disposed of. The growth time and the root and shoot analysis of the barley are compared for both methods of cultivation, where hydroponics outperformed the substrate method of cultivation [43,44].

To cross-verify the obtained results from the actual cultivation method, similar growth conditions and cultivation media [45,46] were applied in the 'AquaCrop' simulator to verify and validate the results. The results of both methods were found to be the same, thus verifying the results of the experiment performed [47]. To ensure water conservation in this experiment, the contaminated water was purified using the electrocoagulation method and recycled in the setup by adding nutrients to it.

A DWC setup in hydroponics is a setup wherein nutrient-infused water is supplied to the roots of the plant, the water is kept at the roots for a specific time, and then the water is drained out. The drained-out water is muddy and contaminated [48]. A detailed diagram of the workings of the DWC hydroponic setup is shown in Figure 4. Two ways of ensuring sustainability in the process of the hydroponic cultivation of barley were applied in this experiment. Firstly, the green IoT was employed in the setup, whereby greenhouse emissions were reduced considerably, thereby ensuring less hazard to the environment as compared with the normal IoT [49].

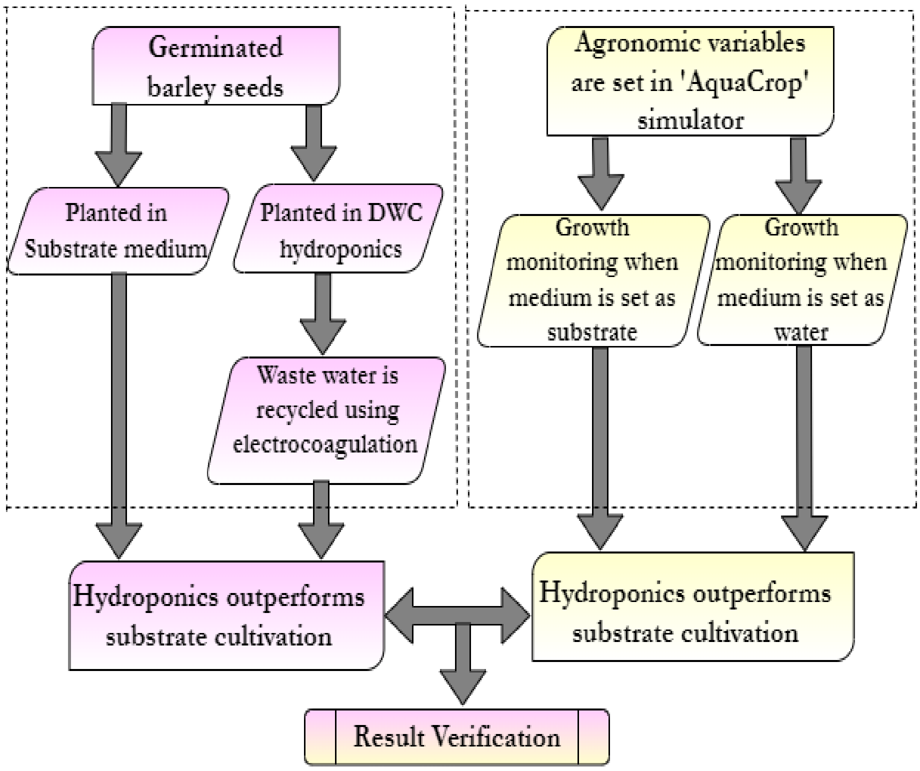

Figure 3. Workflow of the smart DWC setup used in the experiment.

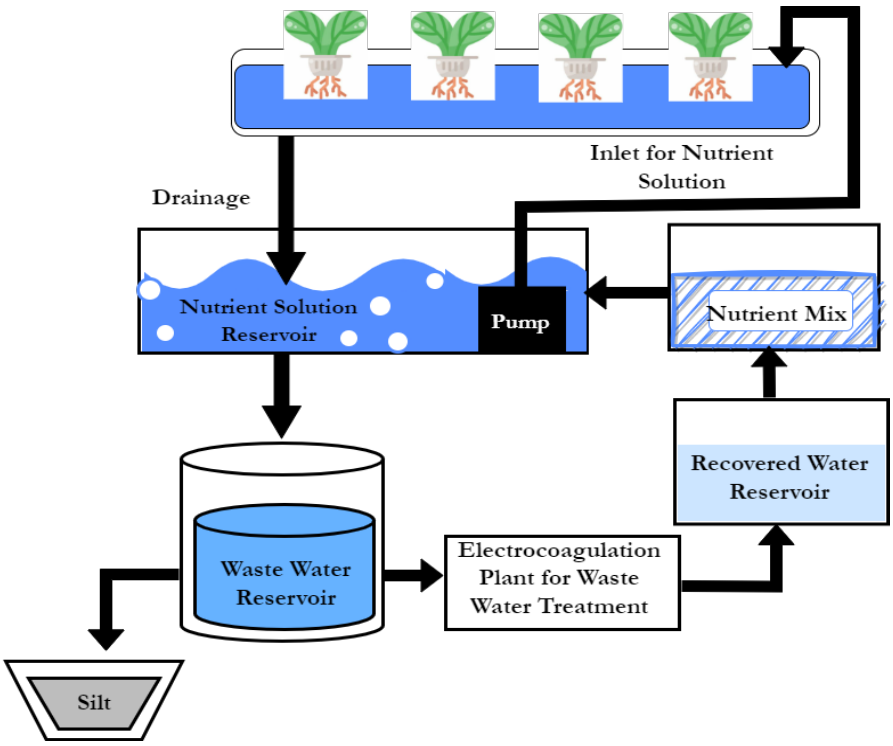

Figure 4. Block diagram of a DWC setup using recycled wastewater.

Secondly, a wastewater treatment plant was set up in the DWC system, which uses an electrocoagulation method to cleanse the wastewater collected from the outlet of the DWC setup. Although hydroponics is a method of cultivation in the water medium, it uses much less water than the traditional substrate method. The minimal water that is wasted in the case of cultivation in a DWC setup was also conserved and reused in the setup used in this experiment. This also imparts novelty to this experiment.

The DWC setup was equipped with several sensors, namely, a pH sensor, water level sensor, temperature sensor, and humidity sensor. All the sensors were attached to the microcontroller through a dedicated port. All the sensors were also set with a permissible range for the respective parametric values according to the agronomic variable ranges specified in Table 1. While the system is powered on and functioning, the microcontroller reads and interprets the values from each of the sensors. The microcontroller reads and interprets all the values and sends the data to the cloud for analysis, via gateways.

Table 1. Ranges of agronomic variables for barley cultivation in the substrate medium.

Parameters		Values
The temperature in the sowing and growing period		12–15
The temperature in the maturity and harvest period		30–32
Average rainfall		146.48 mm
Humidity		64%
pH		7.8
Growth cycle		Up to 20 days
Nitrogen (N)	Percentage of each component in the mixture	7%
Phosphorous (P)		9%
Potassium (K)		5%

The DWC setup used in the experiment was embedded with the IoT. Figure 5 depicts the sensors, actuators, and other components used in the setup. The DWC setup equipped with a water purification setup was further made smart. The entire setup was monitored using the green IoT, which continuously keeps a check on the sensor values obtained by the microcontroller. The various sensors used in the setup were temperature, humidity, pH, water level, and nutrient sensors. The complete sensor module relates to the actuator module via a microcontroller and relay. All the sensors were set with pre-defined ranges suiting the growth conditions of barley. The microcontroller continuously checked the sensor values and sent those values to the cloud for analysis.

If the read values are found to be lying within the range, no action is taken. If the values fall from or cross the range, the actuators are activated through the relay. The entire unit is powered by a power supply for its proper functioning.

The actuator module consists of a fan, water pump, nutrient pump, and mist spray. The actuators in the system act accordingly whenever there is a breach in the parametric range of the sensor values. For example, the microcontroller checks the temperature from the temperature sensor; if it detects that the temperature is exceeding 32 °C, it instructs the relay to make the actuator activate the fan, automatically. The values of the temperature sensor are monitored continuously, and whenever the temperature reaches the permissible range the microcontroller again directs the actuators to stop the fan.

Similarly, in the case of the humidity sensor, the microcontroller reads the humidity sensor values; it analyses whether the value lies in the range or not. If the humidity is in the permissible range, no action is taken; otherwise, if the humidity is found to be below the specified range, mist sprays are automatically activated to increase the humidity of the setup until the humidity level reaches the range. In the case of the pH sensor, again, the microcontroller works similarly to read the pH value and analyze whether it lies within the pre-defined range. Any variation in the range of pH, when detected, leads the microcontroller to glow the alert LED and the buzzer to beep. The pH level is maintained by manually adding pH up or down solutions and checking for the pH value simultaneously.

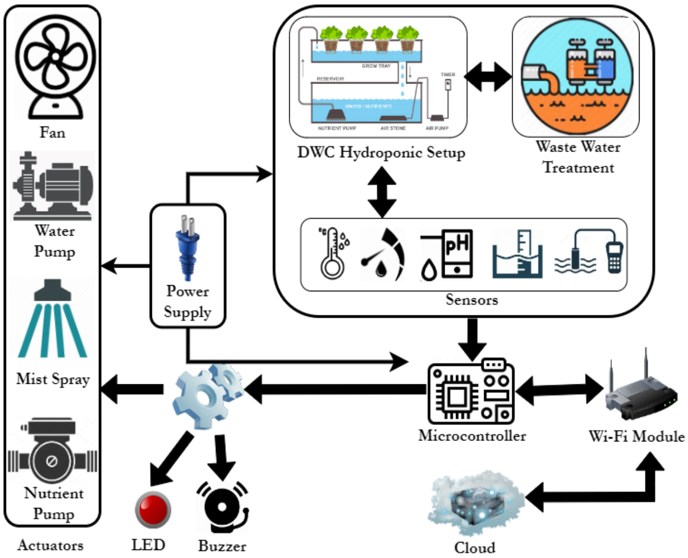

Figure 5. The smart hydroponic experimental setup used in the experiment.

A water level sensor is used to check whether the level of water is maintained in the DWC setup. If the microcontroller analyses that the water level is below the limit, the actuators are directed to power on the water pumps, and the water level is increased to a level where the roots of the plants are dipped in the water completely. The nutrient pump pumps the nutrients as and when needed to the water reservoir, and, subsequently, the nutrient-infused water is sent to the hydroponic setup. Two other hardware devices attached to the relay are an alert LED and a buzzer. These are activated when the nutrient level is found to drop below the range. The user is alerted of the issue, and nutrients are added in appropriate proportions to the nutrient tank manually. All the communications by the microcontroller are made with the cloud via a Wi-Fi module.

Two of the components of the smart DWC setup are depicted in Figure 6a,b. The first figure shows the controlling unit used in the smart DWC setup and the second figure depicts the temperature sensor used in the setup.

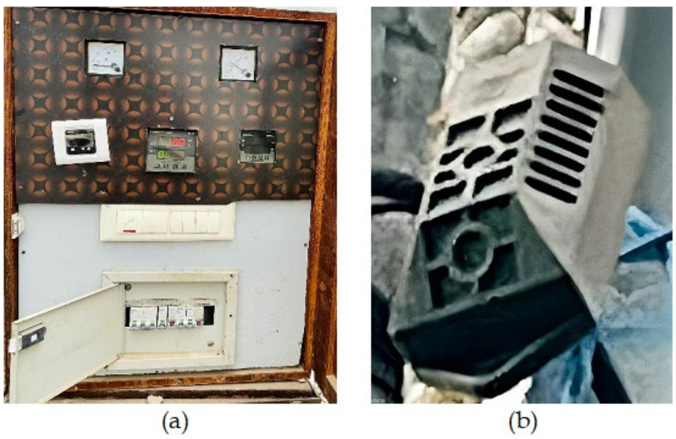

Figure 6. The actual hardware components used in the experiment: (**a**) the controlling unit used in the experimental setup; (**b**) the temperature sensor used in the setup.

The materials needed for the experiment are discussed in this section along with the methods to do it. Cultivation of barley was carried out in soil as well as in the DWC hydroponic setup. The cultivation was carried out in two trials. The results obtained were plotted and compared to identify the best-suited method for the cultivation of barley. The results obtained were verified from the outcomes of both trials. The result was then finally compared with the results obtained from the 'AquaCrop' simulator.

2.1. Cultivation in Substrate Medium

Propagation in the cultivation of barley is done through seeds. Table 1 is a tabular representation of the ranges of various environmental conditions that are required for barley production to thrive. The land must also be plowed repeatedly and made weed-free to prevent damage caused by soil-borne diseases and pests. Table 1 includes the ranges of agronomic variables best suited for barley cultivation in a substrate medium.

2.2. Cultivation in the DWC Hydroponic Setup

The germinated barley seeds were placed in a DWC hydroponic setup wherein the roots were kept dipped in the water medium and the roots extracted all their nutrient requirements directly from the water. Table 2 includes the ranges of agronomic variables best suited for barley cultivation in the DWC hydroponic method.

Table 2. Ranges of agronomic variables for barley cultivation in DWC hydroponics.

	Parameters	Values
	Temperature (°C)	15–35
	Average rainfall	150 mm
	Humidity	68%
	pH	6.9
	Growth cycle	Up to 12 days
Nitrogen (N)	Percentage of each component in the mixture	7%
Phosphorous (P)	Percentage of each component in the mixture	9%
Potassium (K)	Percentage of each component in the mixture	5%

2.3. Growth Comparison in Substrate vs. the DWC Hydroponic Setup

The various stages of the cultivation of barley were captured and recorded for experimental purposes. The cultivation was done in two trials each, in the soil as well as for hydroponics. The cultivation of barley eventually proved to give the best results in the DWC hydroponic setup compared with cultivation in soil.

Figure 7a–e shows the growth of barley in the substrate medium of cultivation. The substrate method of cultivation is also susceptible to fungal infection, along with the risks of weeds and rodents, which further impose a risk of crop damage. Figure 7 depicted the growth of barley in the DWC hydroponic setup.

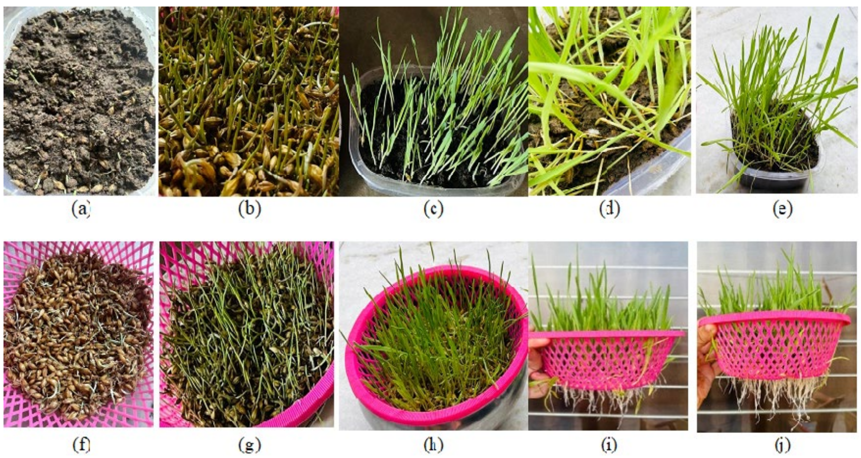

Figure 7. The pictures showing the growth of barley in soil and hydroponics: (**a**) Day 1 of barley in the substrate; (**b**) Day 3 of barley in the substrate; (**c**) Day 7 of barley in the substrate; (**d**) Day 9 of barley in the substrate; (**e**) Day 12 of barley in the substrate; (**f**) Day 1 of barley in the hydroponics; (**g**) Day 3 of barley in the hydroponics; (**h**) Day 7 of barley in the hydroponics; (**i**) Day 9 of barley in the hydroponics; (**j**) Day 12 of barley in the hydroponics.

3. Results and Discussions

The results on the barley growth are calculated and analyzed in this section. The growth trends of barley leaves and roots are analyzed, taking into consideration the two best samples of barley crops cultivated in two different trials. The crop was cultivated in a substrate medium as well as with the DWC hydroponic method. The results of the yield were analyzed qualitatively as well as quantitatively. Leaf length and perimeter were analyzed and plotted as the shoot analysis, and root length was analyzed for the same samples. The results were finally analyzed and compared with the outputs of the simulator. The roots and shoots were seen to grow much better with the hydroponic method of cultivation.

3.1. Growth Comparisons of Barley Shoots and Roots in the Two Trials (Soil and Hydroponics)

The best samples from each of the two trials of cultivation of barley are considered for this plot. In both trials, the best growth of the leaf was found to be in the DWC setup of the hydroponic cultivation method. It was seen that the maximum shoot length of barley in hydroponics reached 19 cm whereas that attained in the substrate cultivation method was a maximum of 11 cm. Thus, hydroponic cultivation was seen to give almost two times better shoots than those obtained in the substrate medium.

The root growth can also be analyzed as being the best in DWC hydroponics, where the maximum root length attained in hydroponics reached 9.7 cm, and that in the substrate medium reached only 7.4 cm.

The graph in Figure 8 is plotted to provide a comparative vision of the maximum shoot and root lengths of the barley. Therefore, it can be analyzed that, in both trials, the shoot and root lengths of the best samples are similar, thus proving that the two trials are giving consistent shoot and root growth trends.

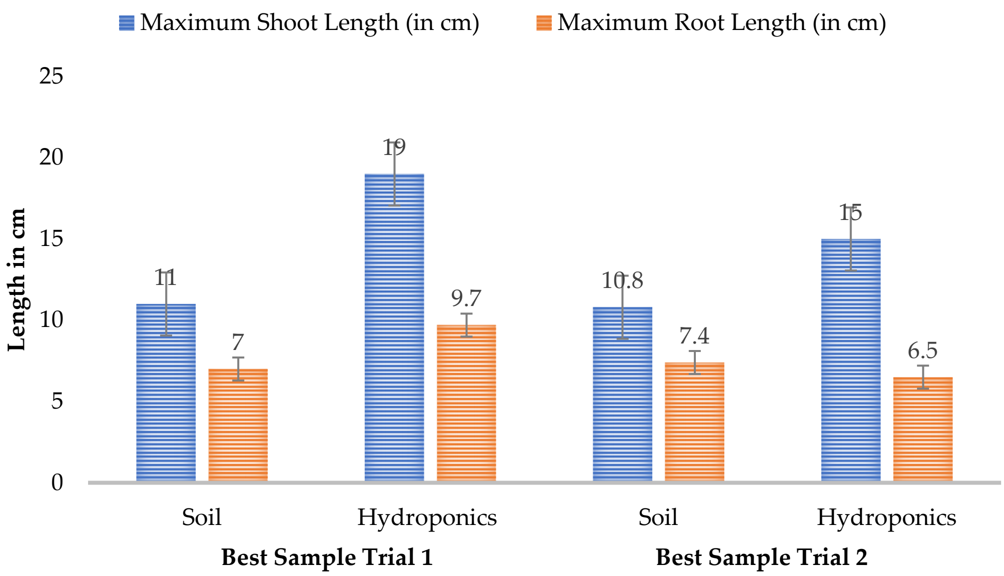

Figure 8. Shoot and root growth analysis for the barley samples for the substrate and hydroponic methods of cultivation.

3.2. Growth Comparisons of the Maximum Length of Barley Shoots in the Two Trials (Hydroponics and Soil)

Figure 9 shows a leaf length comparison for the best samples of barley in both mediums. In the DWC hydroponic setup, growth was seen to prove better than in the substrate medium.

Figure 9. Day 12 shoot growth comparison of barley: DWC vs. soil.

The plot in Figure 10 is a depiction of the length of barley leaves in the substrate as well as in the hydroponic medium. The lengths of the best samples out of both trials were plotted and were found to be approximately 11 cm in the substrate medium, whereas the shoot length was in the range of 15 to 19 cm in the case of the hydroponic setup. Therefore, as a response to RQ. 1, it is found that the hydroponic cultivation method is seen to be more efficient and suitable for the cultivation of barley than the substrate cultivation method.

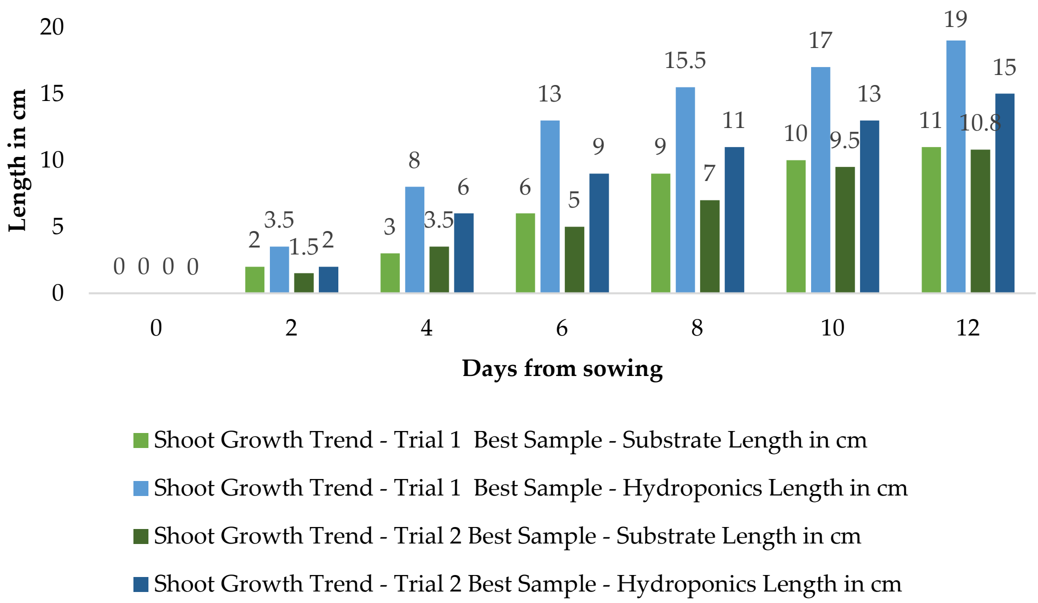

Figure 10. Shoot length growth trend in substrate vs. hydroponics as found in the two trials.

The shoot growth trend analysis in terms of the leaf perimeter in the hydroponic setup is shown in Figure 11. The leaf perimeters in both trials were measured and analyzed. Leaf perimeter analysis for the best samples of barley in both trials shows that the leaf perimeter measures approximately 23 cm in the case of the substrate medium of cultivation, whereas its range lies between 30 and 40 cm in the case of the hydroponic setup.

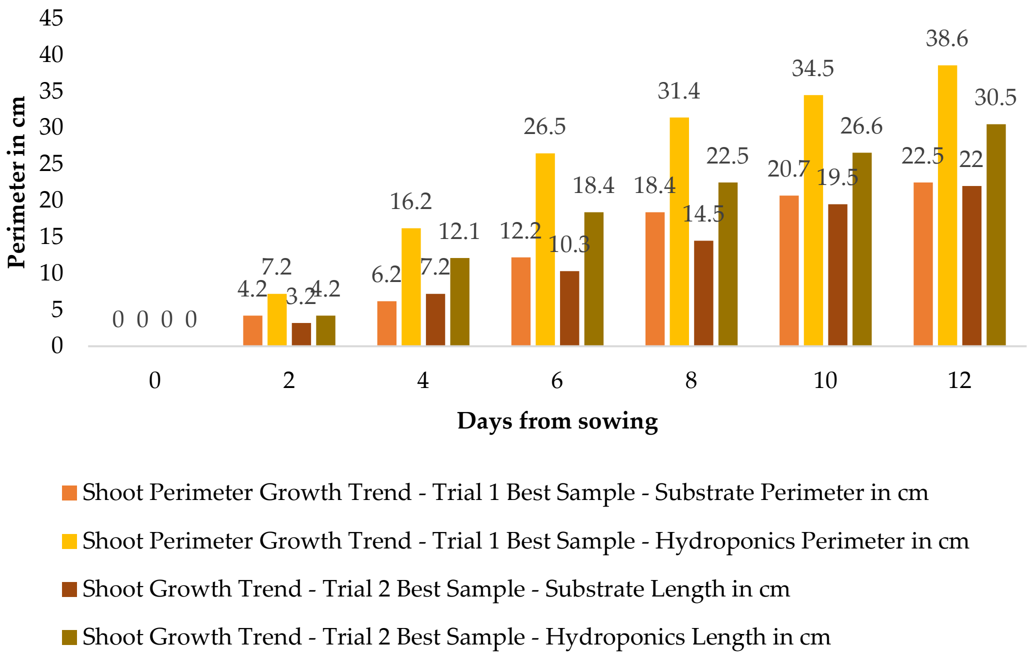

Figure 11. Shoot perimeter growth trend in substrate vs. hydroponics as carried out in two trials.

3.3. Growth Comparisons of the Maximum Length of Barley Roots in the Two Trials (Hydroponics and Soil)

Figure 12 shows the measurement of the roots of the best samples of both the trials of the hydroponics and substrate mediums. It clearly shows that the hydroponic roots grew better than those grown in the substrate medium, with a maximum root length of 9.9 cm attained in hydroponics compared with that grown in the substrate medium, with a maximum length of 7.5 cm.

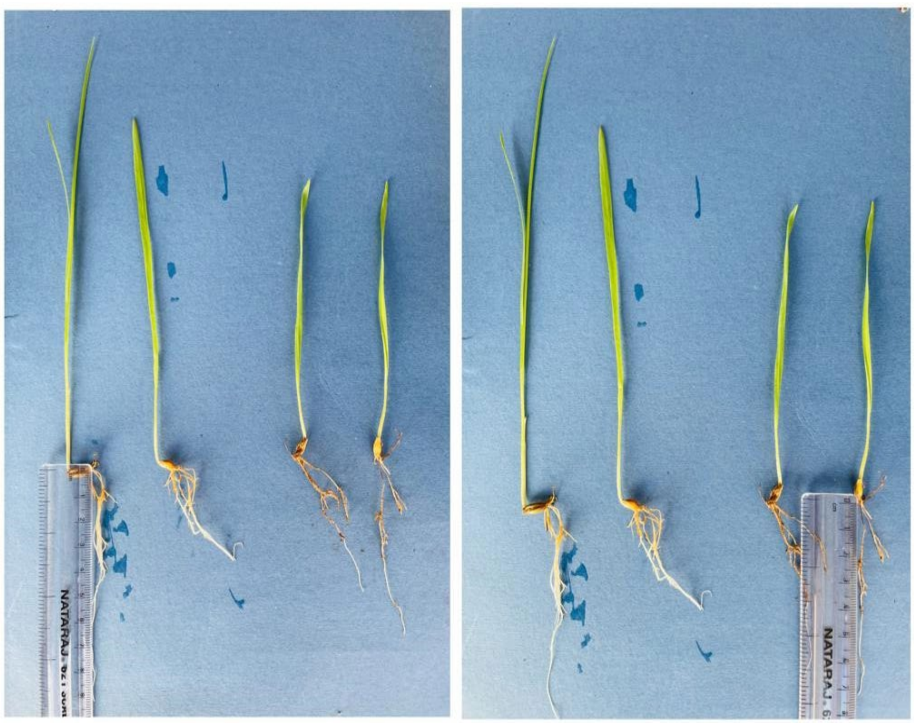

Figure 12. Day 12 root growth comparison of barley: DWC vs. soil.

Table 3 shows the root lengths of the best samples of barley root out of the two trials of cultivation in hydroponics as well as substrate medium. The maximum root length of the best sample of barley grown in a hydroponic medium was found to reach 9.9 cm and the maximum root length of the best sample of barley grown in a substrate medium was found to reach 7.5 cm. Therefore, in response to RQ. 2, it can be answered that the shoot and root growth trends of barley in different cultivation mediums are not very different. Both the shoot as well as the root are found to show better growth responses in the DWC hydroponic setup compared with soil.

Table 3. Root growth analysis: DWC hydroponics vs. substrate.

Growing Technique	Best Samples of Two Trials	Root Length in cm
DWC Hydroponics	Best sample trial 1	9.9
	Best sample trial 2	6.2
Soil cultivation	Best sample trial 1	7.5
	Best sample trial 2	7.1

The comparison of the root and shoot characteristics of barley grown in the substrate and smart hydroponic mediums and the energy and water conservation methods included in the experiment sum up to prove the novelty of this research work.

3.4. Growth Comparison Using the Aquacrop Simulator: DWC vs. Soil

The results obtained in the previous sections were then verified with the growth responses from the AquaCrop simulator. The input parameters for the actual cultivation of barley in the substrate medium and water are mentioned in Tables 1 and 2, respectively. The same growing conditions were given as an input to the AquaCrop simulator one at a time. The results from the AquaCrop simulator gave the same output as the results obtained from actual cultivation; i.e., the DWC hydroponic method was the best-suited method for the shoot and root growth of barley.

Figure 13a shows the simulation results in the 'AquaCrop' simulator when the growing conditions were set to be like a DWC hydroponic system. The growing medium is nutrient-mixed water, and the roots of the plants are submerged in the solution. The solution is drained out at regular intervals.

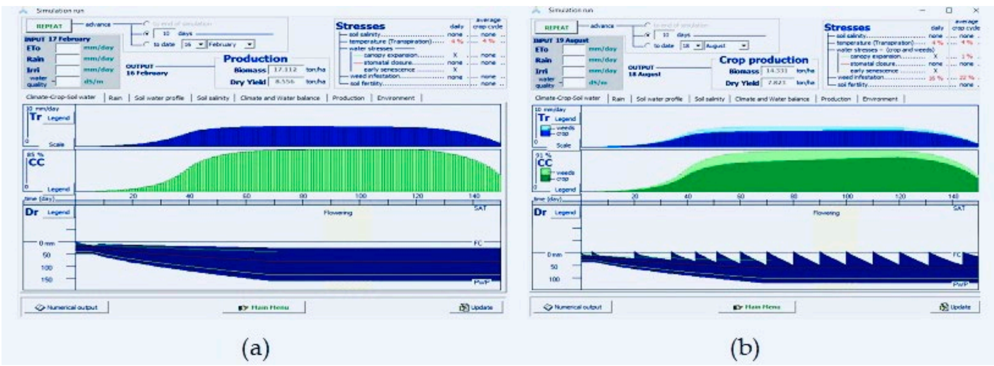

Figure 13. 'AquaCrop' simulator results: (**a**) in the DWC hydroponic setup; (**b**) in the substrate cultivation method.

Figure 13b depicts the 'AquaCrop' simulation results for barley grown in a substrate medium. The soil condition was set to be sandy and loamy. The maximum and minimum temperature and rainfall quantity per day were set as the input environmental conditions, like those provided to the barley grown in the substrate medium. Soil cultivation is always susceptible to damage by the presence of weeds and rodents. The simulation results also show the reduced growth trend for barley in a soil medium. The light green portion of the growth plot of canopy cover (CC) shows the maximum growth possible in the ideal condition and the dark green portion of the plot shows the growth obtained in the given conditions.

Figure 13a shows the screenshot of the output obtained from the 'AquaCrop' simulator when the growing medium, temperature, humidity, and pH were set according to the inputs used during the actual cultivation process in the DWC hydroponic setup. Similarly, Figure 13b shows the result of the barley cultivation when the growing conditions are set similarly to the actual growing conditions in the soil. Transpiration in the case of hydroponic cultivation is completely from the crop, but, in the case of the substrate, cultivation is affected by weed transpiration too. Most importantly, the canopy cover of the crop in the case of hydroponic cultivation is seen to be the maximum, whereas that in the case of soil cultivation is affected by weeds, thus reducing the canopy cover of barley. It is also evident that, apart from the qualitative yield, the DWC system of hydroponic setup also improves the quantitative yield of the produce. Table 4 depicts the quantitative growth analysis of barley in DWC hydroponics and in substrate cultivation.

Table 4. Quantitative growth analysis: DWC hydroponics vs. substrate.

Cultivation Medium	Quantitative Parameters	Values in ton/ha
DWC hydroponics	Biomass	17.112
	Dry yield	8.556
Substrate medium	Biomass	14.331
	Dry yield	7.823

Therefore, it is clear from the experiment as well as the simulator results that sustainability in hydroponics can be ensured by year-round production and better yield: that it is ensured irrespective of dependency on natural resources and weather conditions. The possibility of damage caused to growth due to weeds and rodents is also eliminated in hydroponics. Water and energy conservation are further ensured using G-IoTs and a water purification setup.

4. Conclusions and Future Scope

In terms of cultivation methods, hydroponics is the best choice for barley. It is found to consume 5 ± 15 times less water than that consumed in the substrate method of cultivation and give almost 1 ± 2 times more yield, and that, moreover, throughout the year. To ensure lesser water consumption, the DWC hydroponic setup is equipped with a wastewater treatment plant. For the best results to be obtained in DWC hydroponic cultivation, shoot and root growth analyses were conducted, both practically and in a simulator. Besides producing a higher qualitative yield, hydroponics also proved to produce a higher quantitative yield than substrate cultivation.

Several authors have worked on various vertical farming methods for various crops. The authors of [3,34] have concluded that hydroponics is the best method to cultivate herbaceous plants, and the authors of [2,7] have concluded that lettuce leaves thrive best in a hydroponic medium. The crop considered by the authors in this research work is barley. Previous works have focused specifically on the shoot growth responses of the plant, whereas the authors of this research have used barley to verify the shoot as well as the root growth responses. Barley cultivation was carried out twice in a substrate medium and it was also cultivated in a water medium to analyze and verify the shoot and root growth responses. The authors of this research have obtained the result that hydroponics is the best cultivation medium for barley as well. Not only the shoot growth responses, but also the root growth responses, of barley were found to be better in a hydroponic medium as compared to a substrate medium. In previous works, researchers have analyzed the growth responses of herbaceous plants with the help of simulators. The results from the simulator have also proved hydroponics to be the best cultivation medium for herbaceous shoots. The authors of this research have also cross-validated their actual growth response with the help of the 'AquaCrop' simulator. The results obtained from the simulator validated the results obtained from the actual cultivation and showed that the hydroponic medium is the best-suited cultivation medium for barley to obtain a better qualitative as well as quantitative yield for the crop.

By comparing crop growth in other methods of vertical farming, the scope of the experiment can be further expanded in the future. Aquaponics, aeroponics, and hydroponics can all be used to grow the crop, and growth analyses can be conducted to determine which method of cultivation is most suitable for this particular crop. The grain yield of barley can also be analyzed, along with the root and shoot growth responses.

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