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Hydroponics: An intensified system of crop production

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ABSTRACT

With the pace at which the global population is rising, in that proportion the agricultural growth rate has not happened thereby affecting food production. In the era, of climate change, industrialization, the colonization of fertile land, land degradation and the cessation of expanding agricultural land, the situation has become increasingly unfavorable for meeting food demand and changing dietary patterns. There is an urgent need to increase productivity per unit area including climate-resilient alternative agriculture production systems that focus on resilience, resource efficiency and disease management. Hydroponicsis based on vertical farming can be achieved through a soilless cultivation system. Recently it has gained interest because of reduced reliance on agricultural land and pesticides. Hydroponics technique can be used in regions with poor soil quality, thereby reducing the harmful impacts of extreme weather conditions. The hydroponic feasibility is depend on minimize challenges in cultivation such as technical knowledge, initial cost of structure, the spread of water-borne diseases, the maintenance of microclimates for diverse crops, managing root exudates, and controlling algal growth due to light and nutrients. The hydroponics system enhances yield and crop productivity by conserving water, energy, and space. Therefore, it can be an ideal option for agricultural intensification and the sustainable growth of crop production.

Keywords: *Food production, climate-resilient, Hydroponics, productivity, yield, conserving resources, agriculture intensification, sustainability, biofortification, PGPR, aeroponics, organic farming and IoT.*

A) Introduction

The world's population is expected to reach 9.8 billion people, while India's is predicted to reach 1.668 billion [111]. Further agricultural intensification is needed in India to reach food security at the pace of gradual expansion of cropland and pasture [47]. India's key task is to establish solutions to sustain and improve living conditions for a growing population, while continuing to meet evolving consumer habits and limit harmful environmental impacts [108]. Additionally, urban agriculture should be included in the 2050 drive to provide high-quality, affordable, and sustainably produced food, as urbanization continues. UA involves producing crops and livestock products in urban and peri-urban areas, integrating into the local economy and ecology where space is limited, and land use is challenging [65]. Soil fertility in most parts of the country has reached saturation, with productivity not increasing in proportion to input use. Over 6 million hectares are affected by salinity and alkalinity, along with other factors degrading soil health.

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This makes it challenging to provide quality food for the growing population. Meanwhile, the demand for fresh horticultural produce, especially vegetables, fruits, and flowers, is rapidly rising in peri-urban and urban areas [45a]. According to the Directorate of Economics and Statistics, DAC and FW, 2020, the area used for permanent pastures and other grazing land is 10.34 M ha. This area has been declining over time and the trend is projected to continue [21]. Dairy farmers feed cows excessively concentrate to maintain milk production due to limited green forage, especially in summer. While this boosts milk output, it leads to rumen acidosis and health issues. Green fodder is crucial for cow health and long-term milk production, providing essential nutrients and improving digestion [46]. Under such a scenario, hydroponics system is emerging as a potentially alternate technology for growing quality vegetables and flowers and fodder in various soil- less media under limited space throughout the year [116]. The major advantage of soilless cultivation is the uncoupling plant growth from problems associated with soil, such as soil borne pests and diseases, non-arable soil, soil salinity, and poor soil quality e.g., The increased interest in the commercial application of soilless cultivation in the last decades has encouraged intensive research activity focusing on the development of new growing systems and a better understanding of the crop physiology and its impact on quality aspects [114].

The term Hydroponics was derived from the Greek word hydro' means water ponos' means labour and means water work. At the beginning of the 1930s, Professor William Gericke coined the term "hydroponics" to refer to the practice of growing plants with their roots suspended in water with mineral nutrients [97]. Hydroponics system is scientifically possible because, in the photosynthetic process, soil is not mentioned. Photosynthesis process: (Carbon Dioxide + Water = Glucose + Oxygen) ($6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$)[44b]. It is known as Controlled Environment Agriculture (CEA), which controls factors like light, temperature, humidity, pH, and nutrients. It addresses climate change challenges, optimizes resource use, and helps combat malnutrition[16].

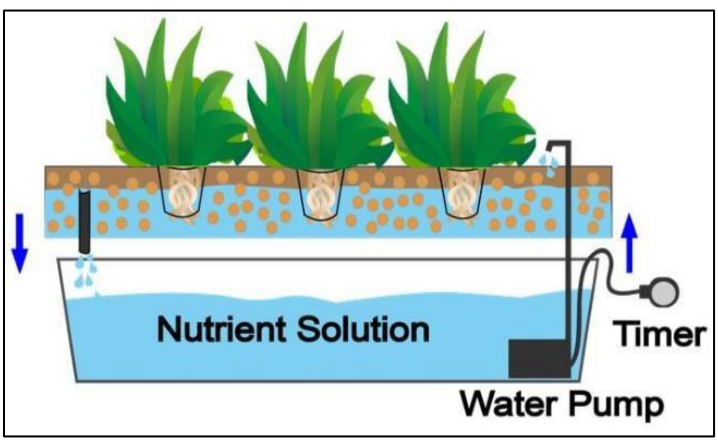
Table 1. The comparison between Hydroponics and Traditional Farming

Feature	Traditionalfarming	Hydroponic farming	References
Growing Medium	Soil	Soilless culture	[28] and [12]
Growth Efficiency	Slowerplantgrowth, dependent on seasons	Faster plant growth (year-round production	[91a]
Labor Requirements	High,labor shortages can complicate	Elimination of labor-intensive tasks, reduced labor costs (automation possible)	[49]
Space Requirements	Largeopen fields	Can be implemente smaller, controlled environments (e.g., indoors, vertical farms)	[93]
Maturity	112days in tomato	78days in tomato	[08]
Water use efficiencyand production / yield	Low	Higher (48 times higher water use efficiency and 2.83times more fresh green fodder compared to conventional methods)	[16]

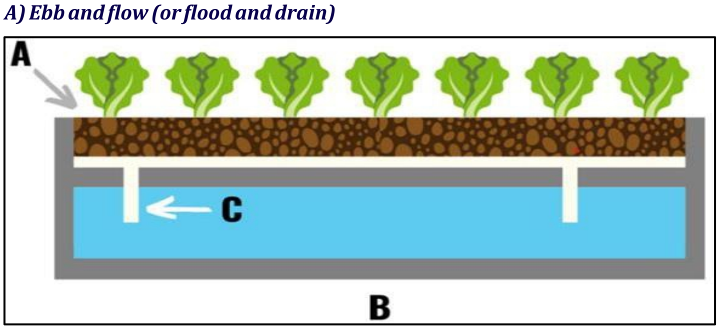
The comparison shows that hydroponic farming not only enhances output, is more effective in terms of area and water use and has animpacton crop maturity that is unlikely to be sown in traditional farming.

A) Hydroponics systems: types and operational mode

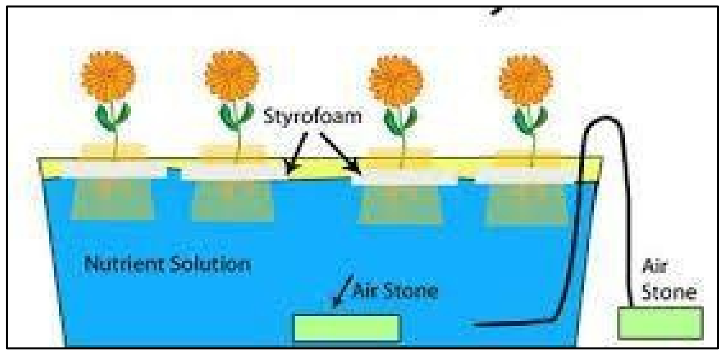
It is a typeof hydro-cultureplant cultivation. It cultivates plants with less soil and uses mineral nutrient solutioninwater [22]. The plants grow with their roots either in nutrient solution or in an inert medium (gravel, perlite, or mineral wool).There are six different types of hydroponic systems: nutrition film technique (NFT), drip system, water culture, ebb and flow, geoponics, and wick. Water/moisture, nutrients, and oxygen are common factors required by plant roots. The six types of hydroponic systems differ in how they offer the basic factors required for plant growth [61].



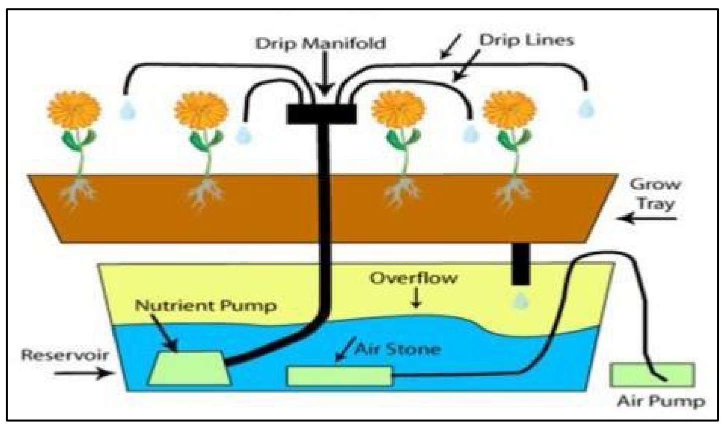
A) Ebb and flow (or flood and drain)



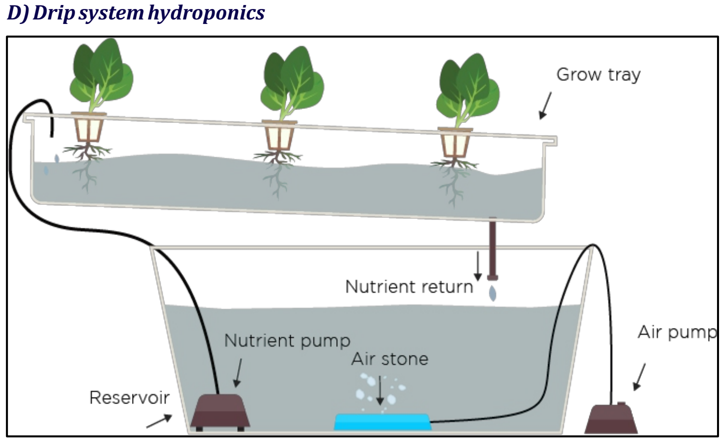
B) Wicking System



C) Water Culture



D) Drip system hydroponics



E) NutrientFilmTechnique

Source:[6]

a) Ebb and flow (or flood and drain) hydroponics system

The first commercial hydroponic system operates on a flood and drain principle, using a grow tray and a nutrient-filled reservoir. A pump periodically floods the tray, which then slowly drains. While it supports diverse crop growth, common issues include root rot, algae, and mold necessitating a filtration unit [76].The sub-irrigation systems used for potted plants, comparing wick, nutrient-flow, and nutrient-stagnant systems to the Ebb and Flow method. They found the nutrient- stagnant system maintained a steady water content of over 40%, the nutrient-flow system fluctuated between 30-40%, and the Ebb & Flow system ranged from 50-60% [100].

b) Wicking Systems

A wicking system consists of a growing tray filled with an absorbent soilless grow media, a storage tank for the nutrient solution, and an absorbent wick that transfers nutrient solution from the tank to the grow media. This system is primarily used for small plants such as leafy greens and herbs and is typically not used for commercial applications. The major advantages of this system are easy to construct, does not require the use of the pump and can be used for small setups such as offices or homes [103]. The potato seedling yield was studied inwick hydroponic system with nine growing media. These include Jeju scoria + cocopeat, Jeju scoria + perlite, perlite + cocopeat (1:1 or 1:2), perlite + peat moss, and perlite + peat moss. The results showed that perlite + peat moss (1:2) and Jeju scoria + peat moss (1:2) were the best for seed tuber development and growth [52].

c) Water Culture

The simplest version of active hydroponic systems is the water culture system. A Styrofoam platform holds the plants and floats directly on the nutrient solution, while an air pump and air stone supply oxygento the roots. This system is not suitable for long-term or large plant growth [6].Economic analysis of deep-water culture hydroponicsystem with IoT technology using Blynk and ESP32 microcontrollers for Chinese celery showedthat controlled greenhouse had the highest net profit of $750.18 per year with a 13-month payback period, while the natural conditions greenhouse had the highest ROI of 131.00% and the shortest payback period of 9 months, despite the lowest yield[26].

d) Drip system hydroponics

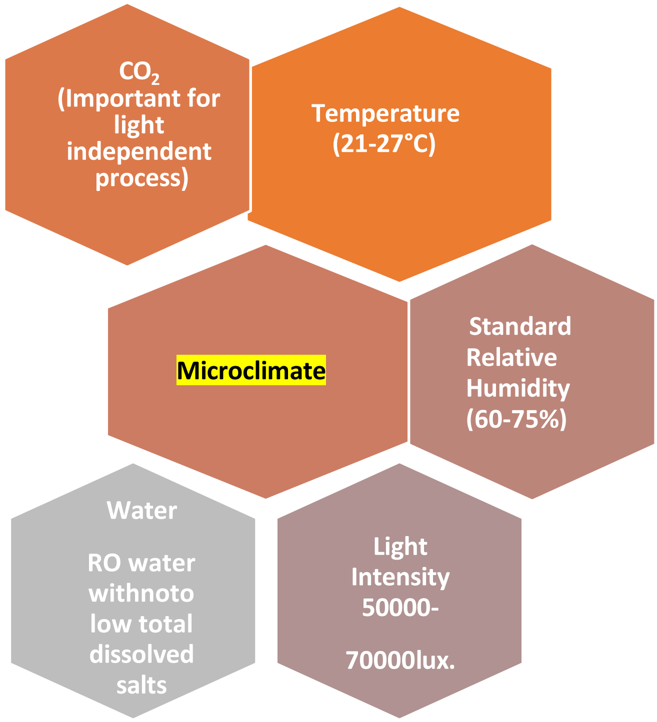
Drip system hydroponics uses pipes, hoses, and a growing media to provide regular nutrition and watering. This technology is like drip irrigation in soil gardening, gaining popularity and becoming the industry standard in hot and dry locations. Long pipes and hoses irrigate crops, save water, and decrease evaporation. Using an automated timer, a pump distributes water or fertilizer solution to individual plants or pots [68]. Presently, Big Data and IoT (Internet of Things) are employed in smart farming to modernize conventional agricultural farming to conserve nutrients and water. Sensors could help in monitoring the parameters such as temperature and soil moisture.

Drip irrigation affects water consumption efficiency, leaf area maximization, and yield in potatoes. That research evaluated the efficacy of a tangible way of repeated water delivery by the drip irrigation system [60].

e) Nutrient Film Technique

In this system the plant roots are suspended in channels called gullies where a thin film of nutrient solution passes through thus keeping the roots moist but not logged. The nutrients are mixed accordingly in a primary reservoir from which it flows through the system continuously feeding the plants at a rate of 1 litre per minute. The system can be adjusted with automation for aeration [98]. NFT hydroponic system enhances the recirculation of excess solution of nutrients and aids in the proper oxygen supply. In addition, it minimizes land usage, labor and fertilizers compared to other systems. Water consumption is also very minimal, and it is climate resistant. It is most suitable for smaller and fast-growing plants such as lettuce [113].

B) Microclimatic conditions for hydroponic grown crops



Studied carried toevaluate the growth period and water and light requirements for optimal hydroponic maize and horse gram fodder using a low-cost system. Maximum fresh biomass yield was achieved with a growth period of 9 days for maize (4.07 ± 0.04 kg) and 6 days for horse gram (5.64 ± 0.07 kg). The water required for producing 1 kg of fresh fodder was 2.00 liters for maize and 1.75 liters for horse gram. Additional night lighting was unnecessary as it did not affect biomass yield or beta carotene levels [43]. The light was not required to sprout cereal grains; however, some light in the second half of the sprouting period encouraged photosynthesis and greening of the sprouts [99].

Table 2. List of general micro elements and micro elements recommended for growing plants in hydroponics

Chemical formula	Chemicalname	Molecular weight	Elements supplied	Solubility ratio ofsolutetowater
Microelements				
$FeSO_4 \cdot 7H_2O$	Ferroussulfate	278	Fe^2, SO_4^{2-}	1:4
$FeCl_3 \cdot 6H_2O$	Ferricchloride	270.3	Fe^{3+},3Cl^-	1:2
FeDTPA	Ironchelate	468.15	Fe^{2+}	Highly soluble
FeEDTA	Ironchelate	382.1	Fe^{2+}	Highly soluble
H_3BO_3	Boricacid	61.8	B^{3+}	1:20
$Na_2B_8O_{13} \cdot 4H_2O$	Disodiumoctaborate tetrahydrate	412.52	B^{3+}	Verysoluble
$CuSO_4 \cdot 5H_2O$	Copper sulfate	249.7	Cu^2,SO_4^{2-}	1:5
$MnCl_2 \cdot 4H_2O$	Manganese chloride	197.9	Mn^{2+},2Cl^-	1:2
$ZnSO_4 \cdot 7H_2O$	Zincsulfate	287.6	Zn^{2+}, SO_4^{2-}	1:3
$ZnCl_2$	Zincchloride	136.3	Zn^{2+},2Cl	1:1.5
$(NH_4)_6Mo7O24$	Ammonium molybdate	1,163.8	$NH4^-$,Mo^{6+}	1:2.3 Highlysoluble
Na_2MoO_4	Sodiummolybdate	205.92	2Na^+,Mo^{6+}	Highly soluble
ZnEDTA	Zincchelate	431.6	Zn^{2+}	Highly soluble
Macroelements				
KNO_3	Potassiumnitrate–	101.1	K^+, NO_3	1:4
$Ca(NO_3)2$	Calciumnitrate	164.1	Ca^{2+},2(NO_3^-)	1:1
$(NH4)_2SO_4$	Ammonium sulfate	132.2	2NH4+,SO_4^{2-}	1:2
$NH_4H_2PO_4$	Ammonium dihydrogenphosphate	115	$NH4^+$,$H_2PO_4^-$	1:4
NH_4NO_3	Ammonium nitrate	80.05	$NH4^+NO_3$	1:1
$(NH_4)2HPO_4$	Ammonium monohydrogenphosphate	132.1	2($NH4^+$),HPO_4^{2-}	1:2
KCl	Potassiumchloride	74.55	K^+, Cl^-	1:3
K_2SO_4	Potassiumsulfate	174.3	2K^+,$SO4^{2-}$	1:15
$Ca(H_2PO_4)2$	Monocalciumphosphate	252.1	Ca^{2+},2($H_2PO_4^-$)	1:60
$MgSO_4 \cdot 7H_2O$	Magnesiumsulfate	246.5	Mg^{2+},SO_4^{2-}	1:2
$CaCl_2 \cdot 2H_2O$	Calciumchloride	147	Ca^{2+},2Cl^-	1:1
$CaSO_4 \cdot 2H_2O$	Calciumsulfate	172.2	$Ca2^+$,SO_4^{2-}	1:500

Source:[86]

Among the different nutrient formulation, Formulation F3 vegetative (205 ppm NO_3^-,25 ppm NH_4^+, 60 ppm P and 288ppm K), generative 1b (218 ppm NO_3^-,12 ppm NH_4^+, 172 ppm P and 380 ppm K) and generative 2b (220 ppm NO_3^-, 40 ppm NH_4^+, 149 ppm P and 402 ppm K) produces melons with high production and quality [105]. The application of K240 (240 mg/l), the concentrations of sugars, soluble solids, amino acids, and volatile acetate components significantly increased, enhancing the taste and aroma of the muskmelon [27]. In hydroponic systems, plant height, number of leaves, and stem diameter were 2-3 times greater than in open field conditions. Regarding the effect of shade net color on spinach yield, the green hydroponic structure produced yields ranging from 150-210 q/ha, while the white hydroponic structure yielded 120-200 q/ha. Both hydroponic systems significantly outperformed the open field, which yielded 50-80 q/ha [53]. Productivity of vegetables was influenced by design and nutrient solutions. To existence into a development of cost effective automatic domestic hydroponic unit for Spinach and Fenugreek with the sub-experiment of four treatments of nutrient solutions i.e. Hogland and Arnon (1938), Hewit (1966), Cooper (1979) and Furlani (1999) and three concentrations of 75%, 100% and 125% were used. Of the 36 containers, the usable surface area of each growing container is 0.0432 m^2. The highest yield of 8125.00 and 8123.92 grams in Spinach and Fenugreek was obtained by applying a 75 percentage of Cooper nutrient solution [79]. The response of tomato plants grown hydroponically to Hoagland solutions at 100%, 75%, and 50% concentrations are studied. The 100% concentration of Hoagland solutions resulted in greater plant height, number of fruits, total soluble solids, and acidity compared to the other solutions[55].

C) Hydroponics cultivation through an intensive crop production technique

Hydroponics has become a standard method in plant biology research, employing various systems, automation, and operation control methods. Beyond promoting healthy plant growth, hydroponics offers advantages such as year-round production, enhanced yields, improved quality, and environmental benefits. Extensive research using hydroponics has investigated plant responses to biotic and abiotic stressors. This agricultural system supports technological advancement, aiming to create a self-sustaining model for future generations and addressing global food security challenges [90]. Hydroponics is a farming technique that eliminates the need for soil, making it superior to soil-based farming in terms of water use, space utilization, and time management[15]. Hydroponics provides plants with the exact amount of water and nutrients that they require, ensuring optimizing plant growth [118]. In hydroponics, root exudates refer to the substancesreleased by plant roots into the nutrient solution. These exudates play a role in nutrient uptake, microbial interactions, and overall plant health within the controlled environment of a hydroponic system. This issue of accumulation of root exudates necessitates innovative solutions to maintain optimal conditions within hydroponic systems. In hydroponics, the water and nutrients are continuously circulated and reused within the system, resulting in a sustainable and efficient method of growing plants without the need for soil [36a]. The importance of nutrient recycling in hydroponics for sustainable crop production is the need for efficient management strategies to ensure optimal nutrient utilization[10].

The following technique has been implemented in hydroponics, an intensified system designed to optimize food production with minimal environmental impact.

1.Hydroponic systems are employed to study plant responses to stress and to screen suitable genotypes:

Hydroponic systems provide a controlled environment for studying plant responses to salt stress, allowing precise manipulation of salt levels and observation of root and shoot growth. By utilizing a hydroponic system, researchers can impose varying levels of salt stress on wheat genotypes while minimizing confounding factors associated with soil-based experiments, such as heterogeneity in soil properties and microbial interactions [5]. They enable systematic evaluation of salt tolerance traits across genotypes, offering insights into physiological and molecular mechanisms. Compared to soil screens, hydroponic systems are more suitable for high-throughput screening, affecting both yield and produce quality [34]. To that directionother studies wasTagetes patula response to short-term exposure to moderate (50 mM) or high (100 mM) salinity. Results indicated that salinity decreased on one hand plant biomass but on the other the induction of non-enzymatic and enzymatic antioxidant mechanisms and; short-term exposure to salinity and/or ethanol application during the flower stage resulted in higher carotenoids and anthocyanins levels of flower, which might be a new source of nutraceuticals [19]. Experiment carried out to screening two soybean varieties for salinity tolerance under hydroponic culture during the early vegetative growth stage. Two soybean varieties, i.e.,'Gepak Kuning and Dering 1', were tested at three NaCl levels, i.e., 0, 60, and 120 mM. and result shows that Gepak Kuning variety was tolerant to 60 mM salinity stress, while the Dering 1 variety showed 60 mM and 120 mM salinity tolerance[35]. Titanium dioxide nanoparticles (TiO_2) are implicated under hydroponic grown medium in Moldavian balm (*Dracocephalummoldavica* L.) plants grown underdifferent salinity levels (0, 50 and 100 mM NaCl) for the role in plant growth tolerance against abiotic stress, Results demonstrated that all agronomic traits were negatively affected under all salinity levels, but application of 100 mg L^{-1} t TiO_2 NPs mitigated these negative effects. The application of TiO_2 NPs significantly lowered H_2O_2 concentration [39]. A study was done in tomato's ten genotypes for this hydroponic culturewas usedto select promising genotypes with strong abiotic stress tolerance capabilities and organic hydroponic cultivationbased on yield and postharvest quality, including firmness, Brix level, acidity, and color. On overallperformance,'Velocity' and 'Sigma' emerged as a superior genotype in stressful environments[24]. The research conductsto reduce salinity stress in spinach and courgette grown hydroponically under drip and mist irrigation systems. The highest yields (4.657 kg m^{-2} for spinach, 5.153 kg m^{-2} for courgette) were achieved with Drip Proline 500, while the lowest yields (0.348 kg m^{-2} for spinach, 0.634 kg m^{-2} for courgette) were observed with Mist Without solution 4000 [1].

2.Biofortification is achieved through the provision of an optimized nutrient solution.

Biofortification can be achieved through mineral fertilization, breeding or biotechnological approaches [75]. However, each of these solutions has limitations. Hydroponic cultivation systems mitigate nutrient phyto-availability issues. They addres the urgent need to produce food for a growing global population by enabling precise management of plant nutritional status during growth through effective control of water and nutrient supply. The work shows how nutrient solution management in soilless culture could serve as effective cultural practices for producing Fe-enriched lettuce of premium quality, notwithstanding cultivar selection being a critical underlying factor for obtaining high quality products [37]. The exposition of the nutrient solution to magnetism, electromagnetism and conventional cultivation (control) monitored during four periods (7, 14, 21 and 28 days after transplanting), with four replicates for each treatment and it observed the increasing the concentrations of magnesium, manganese and iron in the development of the arugula crop under hydroponic cultivation [109a]. Agronomic biofortification is possible in Astro and Roka cultivars of arugula and observed that a concentration of 3.6 mg $1000L^{-1}$ of iron (iron content 9.70% above control) in winter is suitable for Astro. In the case of cv. Roka, indicated a concentration of 7.2 mg 1000 L^{-1} of iron (iron content 47.9% higher than the control), in summer. Both are recommended for consuming iron from plants for human nutrition [18].To achieve biofortification in rice three concentrations of Fe^{2+} (0, 125 and 250 mg L^{-1}) were used for greenhouse cultivationin hydroponic system. The intermediate dose of 125 mg L^{-1} produced the maximum fresh and dry weights, whereas at the higher dose of 250 mg L^{-1} a significant reduction in both fresh and dry plant weights was incurred, as well as in water content [25].

3.Hydroponics is efficient farming method that can significantly reduce carbon food footprint

The practices followed in hydroponics, optimized the use of nutrients and water and more efficient land use, i.e., better performance in terms of land surface area, less consumption, and improved water management and reduction of methane. These advantages contribute to a lower environmental impact and make hydroponics an attractive crop cultivation method in a controlled environment [80]. Malate, a precursor in the ruminal propionate production pathway, competes with methanogenesis for metabolic hydrogen, offering a way to reduce ruminal methane production in ruminants. A negative relationship between dietary malate content and CH_4 production was observed, whereas dietary NDF and starch content were positively correlated with CH_4 production. In conclusion, malate within the hydroponic fodder could potentially reduce CH_4 emissions in ruminants[64].

Solar panels and wind turbines are increasingly used to power vertical farming operations as renewable energy to reduce the carbon footprint of hydroponics systems [115]. The co-cultivation treatments with microalgae yield lower lettuce yields, the system. The co-cultivation of microalgae and actinomycete-inoculated lettuce in hydroponic systems facilitates the production of high-value microalgal biomass with superior biodiesel fuel properties that could greatly contribute to the sustainable development of the food–agriculture energy nexus [76].

4. A novel technique in hydroponics differs from conventional systems to enhance overall efficiency in plant protection.

A primary contributor to food scarcity is the continuous reduction in crop yields due to pests and pathogens. They cause up to 40% loss in annual yield worldwide[33]. UV-C radiation on bacterial inactivation in hydroponic nutrient solutions under both static and dynamic conditions are studied. Under static conditions, a reduction of 1.7 log CFU/mL was observed at 20.37 mJ/cm², with no significant additional reduction at higher doses. However, under dynamic conditions, greater bacterial inactivation was achieved, with reductions of 4.2 and 5.2 log CFU/mL at 20.37 and489.02 mJ/cm², respectively [20]. Comparing YOLOv8 and other AI based algorithm models for disease detection. Their results suggested that YOLOv8 has the ability to99 % accuracydetect the target areas accurately and precisely [57]. The results from the prototype testing demonstrated that the system performed well, achieving a wilting recognition accuracy of 90.90%, as tested on samples of vertically grown mustard plants in a hydroponicgreenhouse[106]. Implementing magnetism in hydroponic arugula cultivation enhances its development and yield, besides reducing the presence of algae on roots [109b]. To study the effects of weak electric fields on the interaction between P. palmivora's zoospores and roots of *Arabidopsis thaliana* and *Medicago truncatula*. In the first configuration, a global artificial electric field is set up to induce ionic currents engulfing the plant roots while, in the second configuration, ionic currents are induced only locally and at a distance from the roots. In both cases, we found that weak ionic currents (250–550 μA) are sufficient to reduce zoospore attachment to Arabidopsis and Medicago roots, without affecting plant health. Moreover, we show that the same configurations decrease P. palmivora mycelial growth in Medicago roots after 24 hours and concluded that ionic currents can reduce more than one stage of P. palmivora root infection in hydroponics [74].

5. Hydroponics as a new avenue of organic food production

The benefits of consuming organic food are becoming more widely recognized these days, yet the amount of arable land is still decreasing. One possible benefit of organic hydroponics is that leaf tissue accumulates nitrate (NO_3), which poses a health risk to humans when ingested in excess. It tends to decrease when organic nutrition sources are utilized instead of traditional nitrate-rich fertilizers [54].Organic hydroponics, especially in terrace gardening, offers a promising alternative. It uses organic nutrients in hydroponic systems and is also called biophonic when microorganisms are added to aid nutrient release [32]. To investigated the yield of Romaine lettuce and red Russian kale different extracts from chicken, cow, and turkey manures are studied.

Romaine lettuce and red Russian kale (*Brassica napus* var. pabularia) yield are modified at concentrations of 10–50 g/L of extract of chicken, cow, and turkey manures are used compared to full-strength Hoagland solution in an ebb and flow hydroponic system[112]. When 0.28% and 0.56% vermicompost were added to the 50% nutrient solution,with low concentration of macro nutrients (1.3 N, 1 NO_3 , 0.3 NH_4 , 0.3 P, 204 K, 45.4 Ca, and 449 Mg in mg/L), contained humic acid (485.12 mg/L), GA 24 (156 ng/L), N-(indole-3-yl-acetyl)-leucine (IAA-leu, an IAA) (198 ng/L), and iso pentenyl adenine (iP, a cytokinin) (189 ng/L). These plant hormones, along with humic acids present in vermicompost, are likely the contributing factors that improved tomato growth in static hydroponic systems with lower concentrations of nutrient solutions [9]. To study the effects of inoculating *Azospirillumbrasilense* and*Rhizophagusintraradices* and organic fertilizers on growing lettuce (*Lactuca sativa* 'Cherokee') and tomato (*Solanum lycopersicum* 'Red Robin') young plants in an indoor vertical farm. Seedlings received chemical fertilizer, organic fertilizer derived from corn steep liquor and fermented fish by-products, and food waste-derived organic fertilizer at 100 ppm total nitrogen every 2 or 3 days. Lettuce under organic fertilizers had 75% lower shoot fresh mass and 64% less shoot dry mass compared with lettuce under chemical fertilizer. Similarly, tomato seedlings with organic fertilizers had fewer leaves, 75% less shoot fresh mass, and 67% less shoot dry mass. The inoculation of *A. brasilense* or *R. intraradices* showed limited effects on plant nutrient uptake, nutrient concentrations, and seedling growth in both lettuce and tomato [69].The results of analysis on green mustard in this study showed that the organic source-based nutrient solutions provided a good range of dry matter content (8.27 – 8.95%), higher than that of the control formula (7.89%). The vitamin C content of the vegetables using the Hoagland solution was 106.84 mg/100 g, lower than those of the human urine, fish heads & bones, and soybeans meal formulas and only higher than that of the biogas wastewater formula (104.37 mg/100 g) [82].

6. Aeroponics: a modified version of hydroponics to grow mini tubers

Aeroponics is an advanced hydroponic method where plants are suspended with roots exposed to air. Nutrients and moisture are delivered as a fine mist through a timer-controlled pump, ensuring optimal supply to the roots[13]. Aeroponics represents the future of soil-free agriculture, offering a potentially more profitable alternative for cultivating tubers and rhizomes compared to traditional hydroponic or soil-based systems. Mini tubers grown in aeroponic systems are harvested using distinct methods that differ from conventional cultivation techniques. This innovation may enhance both the efficiency and yield of tuber production [84]. Aeroponic cultivation has potential to yielded more micro tubers per plant than traditional cultivation for three distinct cultivars. As plant density increasing in an aeroponic system resulted in a decrease in the number of tubers per plant. The 200 plants/m² plant density showed a mean tuber number ranging from 9.6 to 16.8 in three cultivars over two separate plant growth cycles, but the 25-50 plants/m² density showed a mean tuber number of 14.0 to 25.7 [17].

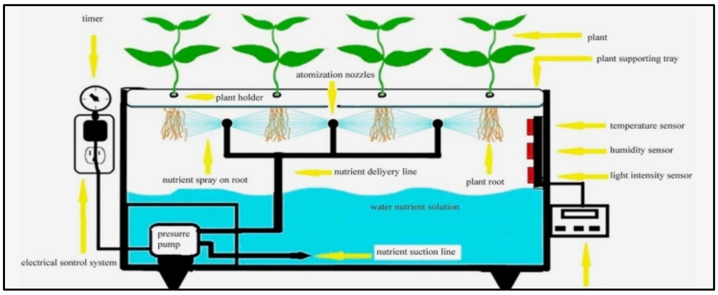


Figure 3. Aeroponics plants a growing system with computer-controlled techniques [62].

7. Technological advancements in hydroponics

The integration of hydroponic systems with advanced smart technologies represents an innovative and promising approach to sustainable crop production. This method obviates the necessity for soil, while simultaneously minimizing water consumption by delivering nutrients directly to the plant roots through a controlled, efficient system [83].

a) Hydroponic system combined with IoT and machine learning

Smart farming leverages IoT, sensors, and automation to continuously monitor soil, nutrients, and plant health, enabling precise management and optimization. This tech-driven approach boosts crop yields, accelerates growth, and maintains optimal conditions year-round. Blynk streamlines creating user- friendly interfaces for managing IoT devices and collecting data via web and mobile dashboards[71]. The Raspberry Pi hosts the Domoticz web interface to visualize data from humidity and electrical conductivity sensors, controlling lights based on input. A preprogrammed algorithm processes the data and sends results to a cloud server for logging and user access. An attached LCDs analyzed data, including pH, TDS, and temperature. The microprocessor uses PID control for automation, adjusting growth parameters, while a microcontroller collects data on TDS, pH, and other variables, transmitting it to the microcomputer via serial connection [96]. Hydroponic system that utilizes IoT and Deep Neural Networks to control plant growth haveaccuracy rate of 88% in regulating tomato plant growth, utilizing data obtained from sensors monitoring pH, temperature, humidity, water level, and light intensity. These sensors, coupled with data analysis tools, facilitate continuous, real-time monitoring of plant growth throughout the cultivation process [70]. The integration of robots employing position-based visual feedback could enhance the efficiency and precision of smart hydroponic farming systems [66]. Utilizing IoT IoT-based hydroponic system, where pH level of water solution, electrical conductivity and luminosity can be captured by sensors. After collecting the data, the ARM 7 microcontroller will automatically determine whether the value exceeds the threshold and make corresponding control [40].

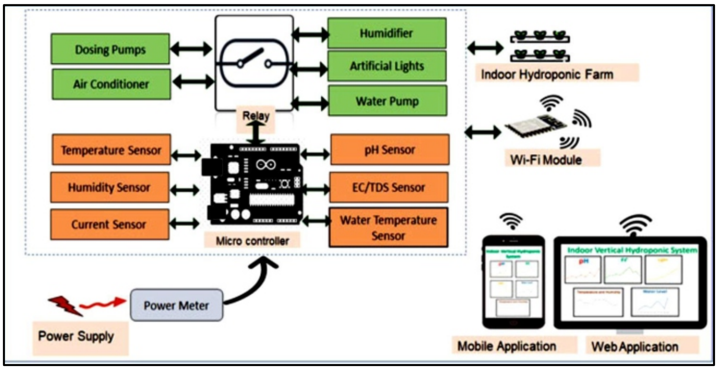


Fig. 2. Block diagram of IoT system for weather and light automation [51].

AI-SHES tool includes Prediction-DLCNN and Classification-DLCNN models that predict nutrient levels and identify plant diseases, respectively. The AI-based IoT cloud server accurately classified various plant diseases and predicted appropriate nutrientsusing the NUOnet and Plant Village datasets, outperforming traditional methods. The proposed solution aims to address the challenges faced by farmers and improve the performance of hydroponic farming operations[85]. Complete replacement of maize silage with hydroponic barley fodder resulted in a slight increase in milk yield without significant impact on milk components and the resource footprint analysis showed potential benefits associated with HBF in terms of water consumption. However, the energy footprint assessment showed that the energy ratio of HBF was less than 1 (0.88) compared with11.89 for maize silage [67]. Examine plant phenotyping technology can be applied to measure physiological and growth conditions and predict plant productivity non-destructively by using camera image analysis. For these studyPakcoy mustard and romaine lettuce are grown hydroponically in a greenhouse. Plant images were taken using a digital web camera installed on a photo box set with dimensions of 90cm×60cm×90cm (l×w×h). The result shows that the plant growth estimation model built has a high level of accuracy[104]. The application of vector regression to manage data from an Internet of Things system, which is responsible for automating the lettuce environment without human intervention. The proposed model achieved a higher prediction accuracy of 82.07%, enhancing yield prediction [42]. In comparative analysis, machine learning algorithms, indicating that among all the models, the decision tree and gradient boosting classifier achieved an accuracy of 99.42% in the dataset by making stage-wise decisions for nutrient management of crops.[41]. Conducting experiments in four separate hydroponic houses, each with different factor controls: House 1 (light and temperature), House 2 (temperature only), House 3 (light only), and House 4 (natural conditions). The IoT-based system maintained optimal water conductivity and pH levels, monitored through the Blynk application and regulated by an ESP32 microcontroller. Sensor data, including water conductivity, pH, internal temperature, humidity, and water temperature, were collected throughout the study.

Results revealed significant differences in weight and final yield among the houses, with House 1 achieving the highestyield, 13.91% higher than House 4. An economic analysis demonstrated the cost-effectiveness of investing in the automated control system, with House 1 being 14% more profitable than House 4 [26].

b)Nano-elicitation and hydroponics: a synergism to enhance plant productivity and secondary metabolism

Nano-elicitation stimulates metabolic processes in plants using nanoparticles (NPs) as elicitors. The stimulation of these biochemical processes can enhance plant yield and productivity, along with the production of secondary metabolites. Nanoparticles have garnered the attention of scientific community because of their unique characteristics, such as incredibly small size and large surface-to-volume ratio, which make them effective elicitors. Hydroponic systems, which optimize growing conditions to increase plant production, are typically used to study the effect of elicitors. By integrating these two approaches, the qualitative and quantitative output of plants can be increased while employing minimal resources. As the global demand for high-quality crops and bioactive compounds surges, embracing this synergistic approach alongside sustainable farming practices can pave the way for resilient agricultural systems, ensuring food security and fostering an eco-friendly environment [48]. Nano-elicitation represents an approach of nanotechnology aimed at enhancing plant yield and secondary metabolite content. This technique involves triggering the natural defense system of plants using nanoparticles as an elicitor that can induce the molecular machinery of plants. The biochemical pathways that are stimulated in response to elicitation promote the production of beneficial metabolites, which aid in addressing environmental stressors. This is coupled with improved nutrient uptake, thereby enhancing plant vigour [63]. Nanoparticles were utilized in hydroponics systems to accelerate the development of various plants such as spinach and tomato [29].Thesynthesized silica NPs from rice husk and applied them to maize seeds to improve seed coat resistance and nutritional availability of maize plants[107]. Application of ZnO NPs to hydroponic cultivated rice plants can mitigate the detrimental effects of chilling stress, leading to enhanced photosynthesis and improved growth [101]. It has been observed that copper oxide (CuO) NPs were translocated to every organ in both soil and hydroponically grown tomato plants, though there was less absorption in soil-raised plants [2]. The experiment was conducted at faculty o fAgriculture UniversityofAl-Qadisiyah, to investigate the influence of Nano siliconfertilizer(NS), Nano complete fertilizer(NC) and Atonik (A) in maximizing of hydroponically growth barley fodder, applied at 2ml L^{-1} water of hydroponicsolution, all nano fertilizer types and Atonik. There results showed that (NS+A+NC) hydroponic solution treatment was significantly higher followed by the diandsingle hydroponics combinations, in dry matter content crude protein, crude fat, crude fiber, acid detergent fiber, neutral detergent fiber (18.597, 22.500, 5.007, 18.40, 15.697 and 35.597%) respectively, compared with the control (14.597, 15.197, 3.197, 13.64, 11.197 and 26.403%). The highest barley fodder yield and water use efficiency 10.433 barley fodder yield per 1kg seeds and 3.467 Kg L^{-1} were with tri hydroponic solution (NS+A+NC) than other treatments [7].

c) Renewable energy/solar based hydroponics

Hydroponic Crop Cultivation (HCC) has multiple environmental benefits, such as significantly lower land and water use, than conventional crop cultivation (CCC). However, most HCC systems are energy intensive, relative to CCC and are powered by electricity, either from the electric grid or generators. Both of these power sources are widely dependent on fossil fuels, which detracts from the environmental benefit of HCC. Comparing the energy requirements of lettuce grown by hydroponic and conventional methods in Arizona and showed that the total energy use for the hydroponic production of lettuce was 90,000 ± 11,000 (kJ/kg/y), which is much more than that for conventional production 1,100± 75 (kJ/kg/y) [11]. To reduce the energy/environmental footprint of HCC, as well as to reduce its energy cost, research is now underway into the use of renewable energy in HCC systems[14]. Solar based hydroponics monitoring system using Arduino is proposed to control and monitor the plants growth. In this system we use solar panels for power supply and Wi-Fi for communication purpose. The system automatically detects and controls the temperature, humidity, pH level and light using different sensors. It also saves wastage of water and fertilizers, gives better yield as compared to soil system. The sensor results are sent to Arduino Uno microcontroller and communication with an Android smartphone [89]. The study conducted to economic viability of using renewables instead of conventional power sources. The results showed that this application is a success because the initial investment can be recovered in approximately 6 years [88].

d) Microbes' intervention in Hydroponics crops

One method to increase hydroponic plant yields involves adding plant growth-promoting bacteria (PGPB) into these systems. PGPB are organisms that can significantly increase crop yields via a wide range of mechanisms, including stress reduction, increases in nutrient uptake, plant hormone modulation, and biocontrol [101]. PGPR are bacteria that may enter plant roots after being injected into the seed and stimulate plant development. They inhabit rhizospheres and rhizoplanes in nature.PGPR enhance the bioavailability of mineral nutrients in the rhizosphere by stimulating a variety of processes such as atmospheric N_2fixation, P solubilization, and siderophores production for Fe chelation [38]. Nitrogen fixing bacteria includes Rhizobia, Azospirillum, Azotobacter, Bacillus, and Beijerinckia. When added to a nitrogen-free hydroponic system, Azospirillum and Bacillus increased nitrogen yield in bananas by up to 144%, shoot growth by 200%, and biomass by 140% [72]. A lettuce trial using *Gluconacetobacterdiazotrophicus* observed up to 16%increases in yield using an organism that produces both the hormones IAA and gibberellin [92]. Setiawati et al reported that the 50% inorganic fertilizer and 100% biofertilizer combination amplified the weight of the tomato by 36% compared to the control in hydroponic system. The application of biofertilizers in the hydroponic system for tomato plants is not only beneficial in minimizing the dosage of inorganic fertilizers but also enhancing the fruit quality [95]. Inoculation of biological agents (PGPR and AMF) in a hydroponic system of substrate culture augments the growth and yield of cherry tomato plants. Tomatoes fruit per plant with treatment of biological agents weigh higher than the one without their application [3].

Hibiscus sabdariffa, inoculation with AMF species such as *Glomus sp., Gigasporasp.* and *Scutellospora sp*. under soilless culture resulted in the proliferation of fungal spores in the growing medium, ranging from 55 to 61 spores/10 g substrate. Root colonization levels ranged from 59% to 64%, and root volume doubled compared to the control [94]. Meta-analysis of AMF application in hydroponics had a higher (compared to none-inoculated) positive effect on crop biomass and yield than fruit and leaf quality (antioxidants, phenols, and sugars) as well as leaf nutrients [77]. Application of Plant Growth-Promoting Bacteria (PGPB) to lettuce resulted in a 388.2% increase in chlorophyll a, 439.8% increase in chlorophyll b, 398.3% increase in total chlorophyll, 246.3% increase in carotenoids content, 42.6% increase in plant fresh weight, and 22.2% increase in the number of leaves compared to control plants[73]. Azospirillumenhance the natural levels of indoleacetic acid (IAA) and improves nutrient absorption in plants. These modifications positively affect vegetative growth and the production of female reproductive organs in pumpkin plants, potentially increasing crop yield, as observed in melon cultivation[87].

D) Hydroponics: Scope or Future issue

Hydroponics, which separates plant cultivation from soil, can be integrated into advanced systems like vertical farming. Current consumption patterns, favoring resource-intensive diets, are increasingly impacting the environment negatively. Soilless culture as home hydroponics presents a viable alternative to mitigate these effects [102].

The co-cultivation of microalgae and plants to enhance the growth of hydroponically cultivated plants while concurrently producing microalgal biomass characterized by an elevated lipid content and favorable properties for renewable biodiesel [78].

Reusing partially treated water for hydroponic plants reduces costs, conserves water, and supports sustainable development goals like zero hunger, no poverty, clean water, and sanitation [4].

Hydroponics allows year-round cultivation anywhere, enhancing urban agriculture. This can improve the food supply chain's efficiency and cleanliness, boosting food security amid climate change [117].

New agronomic strategies, such as the application of biostimulants or plant growth regulators, meet the food demands of a burgeoning population by enhancing crop yields with reduced environmental impacts [23].

The aquaponic solution is a junction between hydroponics and aquaculture to generate both fish and plants and produce organic food. Implementing the artificial intelligence presented by machine learning technology, to converge the optimal environment, reduce human intervention, and improve real-time data exchange [31].

Utilizing the potential of hydroponics and aeroponics to satisfy the rising demand for premium decorative plants while reducing resource consumption and environmental effects is key to the future of floriculture [56].

E) Challenges and Solution for betterment of hydroponics.

Challenges of technology gave the chance to modify existing technologies and contribute to system build-up. The progresss of hydroponics technology is rely on technical knowledge and initial cost of structure. Water borne diseases can easily spread from one plant to the next in a hydroponics system since the plants share similar nutrient [59]. If pulses, cereals and vegetables are grown in similar hydroponic structures, then microclimate maintenance becomes a problem. In hydroponics, root exudates refer to the substances released by plant roots into the nutrient solution affects the nutrient uptake, microbial interactions, and overall plant health within the controlled environment of a hydroponic system [36b]. Hot climate and a lack of oxygen can reduce production and lead to crop loss. The necessity of maintaining the EC, pH, and optimum concentration of the nutritional solution cannot be overstated (Sharma et al., 2018). Normal process of plant is affected by plant disease that leads to reduced growth and yield and hydroponic crops also suffer from this disease thats whys need study to disease controlled in hydroponics. Certain crops can quickly accumulate large levels of nitrate-N (NO3± -N) from the system [44] Algal growth in a hydroponics system is noticed mainly due to light and nutrient availability regulate the water supply, competitors for nutrient absorption with plants, and certain algae produce toxins that can inhibit crop growth [81].

Solutions Achieved Through Advancements in Hydroponic Systems

The adoption of any technology depends on the benefits and drawbacks of its use by end users. It is essential to design low-cost hydroponic structures that reduce reliance on human workers and lower overall set-up and operation expenses in order to encourage commercial hydroponic farms (Sharma et al., 2018]. After each crop cycle, reused plastic system components should be sanitized, common sanitizers include chlorine bleach solution, Hydrogen peroxide (H_2O_2), quaternary ammonium chloride, phenolic materials, and cryptocidal soaps are used to control a algal growth [91b]. UV-C radiation has scope to reduction of colony or bacterial inactivation in hydroponic nutrient solutions [20]. Modern LED systems pr microclimate modification can be programmed to deliver precise light cycles, adjusting intensity and spectral output to match the needs of different crops and growth phases. This flexibility enhances photosynthesis and promotes healthier, faster-growing plants [110].

F) Conclusion

The benefits of hydroponics, i.e., higher yields, high produce quality and the potential of control over the emission of nutrients and plant protection products are greatly achieved in high-tech greenhouses which enable year-round production. In India, many farmers are adopting hydroponics for fodder production. To address changing consumption patterns, reutilize wastewater, and enable cultivation in diverse locations, hydroponics can contribute significantly if its adoption is increased. Furthermore, the state of the art in hydroponics may undergo significant changes as a result of PGPR and nanotechnology and IoT making it more sophisticated and sustainable. The whole concept of farming is evolving. Thetechnological advancements in hydroponics will present countless opportunities to increase food security, particularly important for farmers who usually farm less than 2 ha of land. Developing such sophisticated soil-less farming has, therefore, allowed for a wide variety of research, raising expectations that can help nourish the next generations. It should be no surprise that the hydroponics/aeroponic system is the most promising method for mass-producing crops in any environment that humans can access, i.e., land, water, or space.

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