Hydroponics: A Review of Modern Growing Techniques

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Abstract

An increase in land distress, food requirements, and greenhouse emissions, are some of the innumerable problems dealt with by conventional farming. The use of pesticides and chemical fertilizers often leaves consumers looking for organic and safer produce. Hydroponics can be the solution to these problems with its potential to enhance and maximize the use of water, nutrients, and space. Furthermore, it also provides superior control over the environment and plant protection aspects. Hydroponics technology is arguably the most diverse technique for producing crops currently. Hydroponic is an effective way to grow crops in ecosystems with harsh natural conditions, such as deserts, mountainous areas, or arctic settlements. Hydroponics cultivation improves crop quality and productivity, leading to a higher economic outcome. This paper reviews hydroponics as a whole. The types of systems that can be implemented, are based on factors like structure and techniques, and the factors affecting them. This paper further analyses the production of various crops and compares it to conventional farming methods. Hydroponic systems produce a yield much better than traditional methods. With a wide variety of techniques available, hydroponics can be customized based on the type of crop grown.

Keywords: Automation, hydroponics, nutrients, review, soilless cultivation, techniques.

1. Introduction

In The significance of soil in sustaining life on earth cannot be more accurate. They act as a base for plants, providing them with essential nutrients and minerals necessary for growth. Moreover, soils support an intricate ecosystem of microorganisms and invertebrates that help maintain soil fertility and contribute to the cycling of nutrients [12]. Soils also serve as a critical reservoir for carbon, playing a significant role in regulating the earth's climate. In essence, soils are a valuable and irreplaceable resource that must be managed sustainably to ensure their continued ability to support life on our planet [75]. Even though soil plays a pivotal role in the growth of natural vegetation, it imposes several limitations. This includes the presence of disease-causing organisms and nematodes, undesirable soil compaction, poor drainage, erosion, lack of land fertility, and so on [18]. Apart from this, open-field agriculture uses a lot of land, intensive labour, and massive capital costs. Agriculture is not at all a feasible option in metropolitan areas as there is no availability of soil in such regions [79]. The global population is estimated to increase by 2 billion by 2050 [30]. Meeting the food-related demands of the vast population would be one of the most challenging tasks in the future. Increased crop production is needed to satisfy the ever-increasing food and crop demands. Increased land degradation, lesser availability of farming land due to urbanization, and irreversible climate changes are some factors that might impose a setback in agricultural activities [72].

Under such circumstances, it is practical and crucial to introduce new principles for sustainable farming to meet the nutritional needs of the growing crops. Soilless farming or “Hydroponics” is one of the sustainable technologies which could be a better alternative to traditional farming. The word Hydroponics comes from the Greek language. "Hydro" means water and “Ponos” means labour. Hence, “Working Water” is the true meaning behind the word, Hydroponics [54]. With the help of this technique, one can eliminate the need for soil by supplying the nutrients as a nutrient-rich solution that directly to the roots of the plants and facilitates their growth. Plants may be grown with their roots immersed in the mineral nutrient-rich solution as well as in inert mediums such as perlite, gravel, and mineral wool could also be used [70]. This system would help in coping with the problems faced by traditional agriculture and would ensure the efficient utilization of available natural resources. There are many advantages of using hydroponic systems over conventional farming. One of the primary advantages of hydroponics is the efficient usage of water. Hydroponics has an edge in speaking of sustainable agriculture, including improved water efficiency, higher yields, and better control over the growing environment [32]. These benefits make hydroponics a promising option for meeting the increasing demand for food production and sustainably. Plants in the hydroponic system can achieve 20–25% higher yields than a soil-based system having productivity 2–5 times higher. Furthermore, it enables better control of agricultural water, fertilizer, climate, and pest conditions, improving productivity and economic income. Hydroponic plants are consistently good in quality, have a speedy harvest, and have a high nutrient content [24].

The review paper aims to provide a comprehensive overview of the current research on hydroponics, including its benefits and limitations, recent developments and innovations, and potential applications. The main goal is to provide a comprehensive and objective analysis of the current state of research in this field and to promote greater understanding and awareness of the potential benefits and limitations of hydroponics as a sustainable agricultural practice. By synthesizing and critically analyzing the existing literature, the paper can provide valuable insights and guidance for researchers, practitioners, and policymakers seeking to advance the field of hydroponics and promote more sustainable and equitable food systems.

2. Hydroponic System

The simplest hydroponics system requires plants, a container, water, a means of anchoring the plants, fertilizers, and a light source. A growth medium that holds the plant's root and provides support is necessary for a hydroponic system. Perlite, rockwool, pumice, coconut coir, gravel, and rock wool are a few substrates that are used often. These are soilless growth mediums that enhance water absorption, maximizing the health of plant root systems. Growing outdoors in the summer on a balcony or patio with exposure to the sun is a popular hydroponic lighting option. The most prevalent lighting options for small-scale farmers using indoor hydroponics are LED and fluorescent lamps. The plants receive nutrition through a nutrient solution. Delivery of the nutrient solution changes based on factors like weather, crop, location, etc.; some of the techniques available are drip system, wick system, NFT, aeroponics, and so on. Additionally, it's essential to maintain the pH balance of the nutrient solution, as this can have a significant impact on plant growth and health.

Overall, hydroponic systems offer many benefits, including faster growth rates, higher yields, and the ability to grow plants in areas with limited space or poor soil quality. However, it's essential to properly set up and maintain the system to achieve these benefits and ensure the health and growth of the plants.

3. Growth Medium

In conventional farming, the roots of the plants are buried in the soil to provide support and allow the plants to grow. In soilless farming many organic and inorganic materials have been used as a substitute for soil, providing similar support to the plant roots for their growth. They nourish the roots by maintaining a proper water/oxygen ratio. Growth mediums like rockwool, coco coir, perlite, etc. support the plant roots and absorb the nutrient solution like pseudo soil. Peat is an organic growth medium that was popular in hydroponic cultivation however, they are now better used as fertilizer. Rockwool is currently a popular choice amongst growth mediums followed by coco coir [8].

Rockwool:

One of the most popular growing media in hydroponics is rockwool. Rockwool is a sterile, porous, non-biodegradable material made mostly of granite or limestone heated to a high temperature, melted, and spun into tiny threads. Following this, rockwool is cut into blocks, sheets, cubes, slabs, or flocking. Because rockwool readily absorbs water, it is necessary to avoid letting it become saturated as this could suffocate the roots of your plants and cause stem and root rot. Before use, rockwool needs to be pH balanced [94].

Coco coir

The outer husk of coconuts is where coco coir/ coconut fibre is derived. One of the best-growing media was once considered rubbish. Although coco coir is an organic plant material, it decomposes very slowly, so the plants growing in it won't receive any nutrients from it, making it ideal for hydroponics. Moreover, coco coir has a neutral pH and retains moisture well, while allowing for optimum root aeration. There are two types of coco fibre: coco chips and coco coir. They are both constructed of coconut husks; the only distinction is in the size of the particles [94].

Perlite

The fundamental ingredients of perlite are minerals that are heated to extremely high temperatures, causing the particles to burst like popcorn, making the material extremely light, porous, and absorbent. Perlite is extremely porous, has a neutral pH, and has good wicking properties. Perlite can be combined with other types of growth material or used alone. But, depending on how one has planned their hydroponic system, perlite alone may not be the best option for growing media for flood and drain systems because it is so light that it floats. Any nursery has stock bags of perlite because it is frequently used in potting soils [94].

Vermiculite

Vermiculite is a silicate mineral that expands when subjected to extremely high heat. It is similar to perlite in terms of growing media, with the exception that it has a higher cation-exchange capacity and can store nutrients for later use. Vermiculite is extremely light and has the same tendency to float as perlite [94].

Oasis Cubes

Oasis cubes and Rockwool cubes are comparable in terms of their properties. Yet, oasis cubes resemble the stiff green or white floral foam that forests use to hold the stems in their floral displays more than they do in oasis cubes. Oasis cubes are made of an open-cell polymer, allowing the cells to take in both air and water. Although oasis cubes and rockwool cubes are comparable, oasis cubes resist waterlogging more readily [94].

Sand

Sand is a highly popular growing medium in hydroponics. Sand is similar to rocks but smaller. The smaller particle size than typical rock means that moisture doesn't drain out as quickly. Furthermore, vermiculite, perlite, and coco coir are frequently used with sand to preserve the moisture content and aerate the root mix [94].

Rice Hulls

Rice hulls are a by-product of the production of rice. Although an organic plant material, they decompose very slowly, much like coco coir, which makes them appropriate as a hydroponics growing medium. There are four types of rice hulls: fresh, aged, composted and parboiled, and carbonized. As a hydroponic growing medium, fresh rice hulls are usually avoided because of the high likelihood of pollutants which include rice, bacteria, fungal spores, decomposing bugs, and weed seeds. When the rice has been milled from the hulls, they are steamed and dried to produce parboiled rice hulls (PRH). After eliminating all spores, bacteria, and pathogens, a clean and sterile product is obtained [94].

4. Factors Affecting Growth of Plants in System

Hydroponics is a rising technique for growing plants like lettuce, cherry tomatoes, berries, etc. Unlike conventional agriculture, this process does not involve any soil. However, the factors affecting the growth of plants remain similar to growing plants traditionally. Climate change, water crises, and thousands of acres of land vitiated makes it hard for traditional farming. It is easy to control factors like light, EC, pH, irrigation, etc., growing plants hydroponically [81]. Hydroponics further makes it possible to grow plants without the effect of pesticides and fertilizers [81]. Although the factors do not have a proven direct influence on the growth of the plants, they affect other parameters leading to improved growth in the plants. The growth of the plants can change based on the type of crop grown.

Light

Light is one of the key energy forms required by plants to photosynthesize. Lighting in hydroponics can differ based on the type of hydroponics (indoor or outdoor). Three points to consider for lighting are, light intensity, spectral quality, and photoperiod, affecting root growth, water, and nutrient uptake [6]. Optimal light intensity changes concerning the plant grown [15]. For photosynthesis, plants require photosynthetically active radiation (PAR), which lies in the spectrum of visible light of 400 to 700 nm. Only 10 percent of the captured light is converted into chemical energy for photosynthesis, the rest is converted to heat [43].

Indoor hydroponic systems make use of LEDs or red and blue lights. Since the weather affects plant growth, an indoor setting with artificial lighting is preferable. Red light has radiations in the range of 600-700 nm, which is an efficient range for photosynthesis considering the quantum yield. Blue light radiation falling in the range of 400-500 nm is preferred when specific phenotypes are desired in the plants grown [8]. Though UV or red and blue lights give desirable results they appear purple to human eyes, making it difficult to detect any defects in the plants [8]. Light-emitting diodes (LEDs) also act as a light source. LEDs are cost-effective and preferable for long-term use and can be used to optimize plant yield by LEDs of different peak wavelengths [8].

Many investigations on light affecting plant growth have been conducted. Klieber *et al.*, 1993 noticed that high-intensity light improved the fruit colour and found high chlorophyll content in the peel cucumbers. Concentrations on P, S, K, Ca, and Mg in shoot tissue, were found to be increased when grown under LEDs than when grown under fluorescent light. In root tissue concentrations, the concentration of K had increased while Mg had decreased under the LED vs. fluorescent lights. On the contrary, calcium and phosphorus uptakes were unaffected regardless of the lighting used [14].

Temperature

The temperature of the environment affects plant growth by altering germination rate, root growth, the rate of photosynthesis, transpiration, and respiration [39], [41]. Optimum temperatures of about 21-27 °C are preferred by most crops grown in greenhouses [37]. In an indoor setting, the temperature of both, light and air affects plant growth, altering vegetative growth, fruit set, fruit development, fruit ripening, and quality. A large variation in day-night temperature led to taller plant growth with short leaves [39].

In hydroponics, nutrients are provided to the roots via a nutrient solution which is circulated through the system. The temperature of the nutrient solution can be optimized to control the amount of oxygen consumed by plants [33]. Every plant has its optimum temperature for growth controlled by the nutrient solution temperature. Villela, Luiz, Araujo, & Factor, 2004, investigated better production of strawberries by cooling the nutrient solution to 12 °C. several studies have been conducted investigating fruit quality affected by the temperature of the nutrient solution [33]. Rootzone temperature must also be kept in check. Low temperatures decrease the root length and affect the overall growth of the roots and their density. On the other hand, High temperatures affect the functionality of the roots [41], [64].

Oxygenation

Lack of oxygen in plants can cause adverse effects. Oxygen consumption of the plants depends on the temperature of the nutrient solution and the photosynthetic activity of the plants [58]. There is an increase in the concentration of CO_2 if the roots of plants are not well aerated [52]. Dissolved oxygen below concentrations of 3-4 mg/L proved harmful to plant roots, causing brown coloration and stunted root growth [28]. Pedersen *et al.*, reported that in adverse conditions, plants can adapt to low-oxygen soil by modifying their anatomy and architecture to maintain root functioning [59].

Plants in hydroponic systems may experience oxygen deficiencies. A drop in the oxygen level was observed when using the NFT [78]. Additionally, the flow velocity of the nutrition solution lowers when roots entwine, indicating a decreased oxygen transport rate to dense root layers [10]. To ensure water and nitrate uptake processes in situations of root hypoxia, plants may utilize the oxygen from the reduction reactions of nitrates to nitrites [51]. The amount of energy available for uptake, growth, and maintenance is drastically reduced in situations when aerobic respiration is switched to glycolytic ATP synthesis at the cost of decreased growth and output [41], [74]. Aeration encourages plant growth, leaf K, P, Mg, water intake, and plant net photosynthetic rate [61]. In soilless commercial cultivation, oxygenation is a frequent practice, and many oxygenation techniques are used [49], [56].

Electrical conductivity (EC)

EC is used to measure the electrical conductivity of the soil. It helps to keep the amount of nutrients in the soil in check. The EC of soil for cultivation must strictly be maintained under 4ds m^{-1} [39]. In hydroponics, the EC of the media changes accordingly. Organic substrates have been found to have higher electrical conductivity than inorganic substrates [39]. Abad *et al.*, and Bunt reported that Peat was found to have the highest EC value of 1.065 ds m^{-1} among all the organic substrates like coir dust, decayed animal manure, reed peat, etc [1], [13]. While Cuartero & Fernández-Muñoz and Saha *et al.*, reported that EC has a significant effect on the water uptake by the plant roots, root growth, and marketable yield of the produce grown hydroponically [17], [68]. A linear decrease in marketable yield is noticed on increasing the salinity beyond the threshold [39].

pH

pH is a parameter that is essential when it comes to soilless crops. It allows for optimum growth by considering the chemical composition of media particles, irrigation, and nutrient mixture used for that specific plant [39]. pH ranges of the media vary according to the plant species being grown and depend heavily on the fertilizer concentration used [55]. A media having a pH ranging between 5.5 and 6.5 is preferable [95]. (Brown & F. A.) investigated that upon the addition of sand, certain media have reduced acidity as the pH of sand is 7 [88]. (Baskaran & Saravanan) recorded that the incorporation of coco coir helped reduce the pH of a medium [87]. Coir pith helps to lower the EC from 3.2 to 0.7 dS m^{-1} when mixed with saline-alkali soil [39].

Rootzone pH is monitored to ensure healthy plant growth. Rootzone pH influences microbial activity and root growth and influences root water and nutrient uptake [85]. Most plants have a rootzone pH between 5.5 and 6.5. Anything lower is considered toxic due to the high concentration of Mn while, a high pH level can lead to a lack of nutrients like P, Fe, and Mn for the plants [6]. Dyśko *et al.*, conducted study effect of different values of pH on tomatoes. The concentration of available phosphorus was found to be dependent on the pH level of the nutrient solution and any increase in the pH resulted in a drop in phosphorus levels [21]. Different species of plants have been tried and tested for on a range of pH solutions. However, there is a need for a proper investigation of how the rootzone pH affects root growth, morphology, and architecture in soilless cultivation [6].

Irrigation

Water is an essential requirement for growing plants. In hydroponics, it further carries the nutrients right to the plant roots. The timing and amount of water are crucial factors for the efficient management of resources, while ensuring better growth in plants [6]. The frequency of irrigation promotes growth and improves yield. The method of irrigation is chosen, considering the root initiation, elongation, branching, development, and dry matter partitioning between roots and shoots [46].

CO2

CO_2 is essential for plants for carbon fixation as a source of energy and nutrition. Elevated CO_2 (eCO_2) is known to trap the earth's heat. The growth, architecture, and nutrient content in the roots of a plant depend on elevated CO_2 (eCO_2). There is an observed increase in biomass due to eCO_2, which gets distributed to the plant roots, increasing the root-to-shoot ratio in nutrient-limited conditions [47]. The enhanced growth of the plant roots because of eCO_2 can be related to increased nutrient requirements resulting in the allocation of photosynthates to roots [47]. An increase in the concentrations of soluble sugars like glucose, fructose, and sucrose and organic acids like citric, malic, and oxalic acid was observed by Balliu *et al.*, 2021. This, tells us that eCO_2 promotes robust growth of the plants providing a better yield.

Relative humidity

Relative humidity influences the quality of plants produced. RH of a majority of the crops is 60-75 percent. However, typical plant growth occurs at a relative humidity of, 25-80 percent. Relative humidity has to be maintained carefully, as a high RH can cause pathogenic spores to germinate on or nearby the plants [39]. The first few hours after sunrise a greenhouse have dangerously high humidity levels because solar radiation speeds up plant transpiration [50]. An increase in air humidity promoted growth and photosynthesis, and high humidity levels accelerated the rate of photosynthesis [11].

Gisleroed *et al.*, 1987 investigated nutrient uptake in plants affected by humidity. Nine different species of young plants were grown for 24 to 100 days at relative humidity (RH) levels of 55-60, 70-75, and 90-95 percent. Twice a week, they received a nutritional solution [29]. S. Khan *et al.*, 2020, reported a decrease in the transpiration rate with the increase in RH.

5. Techniques For Hydroponics

Nutrient solution management is of utmost importance in soilless production [35]. The right balance of nutrients ensures healthy growth in plants. There are different techniques for supplying nutrition to plants in Hydroponics. Techniques are chosen based on the type of plant, climate, environment, cost, etc. The difference in each method is the structural setup [39]. Plants need nutrition to grow, and in hydroponics, the nutrient solution is provided to the plant roots by circulating the solution through the system.

Continuous Flow Solution Culture

It is a system where the nutrient solution is circulated through the plant roots, and any excess solution collected is recycled back to the storage tank. The nutrient solution is changed when the EC changes. Continuous flow systems are considered to be the excellent nutrient delivery system. In this system balancing the nutrient solution becomes a low influential factor on the plant yield as the EC is maintained at the same composition [35]. This principle can be observed in two types of systems, the nutrient film technique and the deep flow technique which are described further in the paper. [38].

Nutrient Film Technique (NFT) System

The nutrient film technique shown in Fig. 1, is one of the most popular methods in hydroponics. Plants are grown in channels where the nutrient solution is pumped continuously. The roots of the plants are nourished, by a thin film of the nutrient solution [39]. Since it is a continuous process, there is no requirement for a timer or a growing medium. The roots absorb the nutrients directly from the film. Unlike Deep water culture, the roots of the plants are not fully submerged in water but rather, kept moist [4]. Maintenance of the electricity and pump system is essential to prevent the failure or stoppage of the system [76]. Typical NFT systems circulate the nutrient solution at the rate of 1 litre per minute. This technique is preferable when growing short-term crops like lettuce, herbs, onions, etc. Increasing the channel size allows NFT systems to be used for long-term crops [39].

Deep flow technique (DFT)

This system requires an open or protected space making it favourable to grow herbs like oregano, basil, thyme, and more. The plants are potted in plastic net pots where PVC pipes are arranged to provide the nutrient solution to the roots of the plants. The pipes are assembled in a zig-zag pattern to save space and for low-growing crops. Water collected gets oxygenated in a storage tank and is recirculated through the system. Some similar techniques are Root Dipping Technique, Capillary Action Technique, Trench or Trough Technique, Pot Technique, Deep Water Culture (DWC), etc [39].

Deep Water Culture system

One of the simplest systems is where the plant roots are immersed in the nutrient solution while kept on a floating platform [93]. The roots of the plants get a constant supply of water, oxygen, and nutrients [4]. The water is oxygenated using an air pump to help the roots breathe [76]. Fruiting plants like tomatoes and cucumbers are grown using the deep-water culture system [73].

Ebb and Flow

Also known as the flood and drain process, the ebb and flow technique are not a preferable technique in hydroponics. The process works by periodically flooding the plants with nutrient solution for a few minutes and draining the solution. The nutrient solution is stored in a reserve as shown in Fig. 1. This process is not preferable for commercial soilless production. However, it is a great method for small hydroponic setups [39]. The system drains the water using gravity and recirculates it using a pump [23]. Crops like strawberries, beans, radishes, cucumber, tomatoes, etc., can be grown using this system. The process can be carried out several times a day, depending on the plant grown, the medium used, and other environmental factors [93].

Drip Systems

Drip systems are widely used for soilless production due to the ease of moisture control [23]. This system is preferable for long-term crops like tomatoes, peppers, onions, etc. Nutrient solution stored in tanks is pumped to the roots of the plants via a drip system. The growing medium is flushed by the drip cycle and holds the nutrients, water, and oxygen required for plants [39]. The drip rate of the nutrient solution is adjusted, and the solution is circulated through the system, allowing the growth of multiple kinds of plants [4]. Continuous drip systems are classified into recovery and non-recovery systems. Recovery systems reuse the nutrient solution as long as it can provide the plants' nutrition, making it a cost-effective method. On the contrary, non-recovery systems do not reuse the nutrient solution keeping its strength constant [39].

Wick System

This is an effortless yet least preferred technique. The wick system works without electricity or pumps [86] as shown in Fig. 1. The nutrient solution stored in reservoirs is provided to the root system via wicks by capillary action [4]. Perlite, Vermiculite, Pro-Mix, and Coconut Fibre are some of the preferred choices for growing mediums for this technique [93]. The Wick system is used for plants that do not require regular watering [23]. A major drawback of this system is the poor oxygenation of plant roots [4]. Hence, this system is desirable for growing small plants, herbs and spices [73].

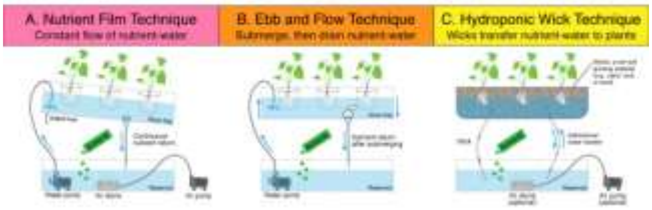

Fig. 1 Schematic of the most common techniques used in Hydroponics [32]

Aeroponic System

The aeroponic system is a specialized version of hydroponics where the plant roots extend only in the air and are sprayed directly with a nutrient solution [90]. In aeroponics, plant roots are open in the air i.e., oxygen, at all times, as seen in Fig. 2. Surplus oxygen accelerates nutrient absorption at the root surface. This is the most advanced type of hydroponic system. Different nozzle types, such as ultrasonic atomization foggers, high-pressure atomization nozzles, and pressurized airless nozzles, are utilized to mist nutritional solutions onto the plant roots. A computerized system maintains and regulates the static pressure, which ranges from 60 to 90 Psi. This frequency depends on the type of crops, the period of cultivation, the stage of the plant's growth, and the time. The duration of the spray will be between 30 and 60 seconds. Owing to its expensive investment and management costs, the aeroponics technique has not been widely adopted and is best suited for small horticultural crops. A timer controls the nutrient pump much like other types of hydroponic systems, except the aeroponic system needs a short cycle timer that runs the pump for a few seconds every couple of minutes [86]. Aeroponics, though expensive, has shown the most promising returns in crop production, making it a suitable system for space travel [45]. Hydroponics is the most efficient plant cultivation technique that can be used to grow hybrid varieties of tomatoes, potatoes, pineapple, lettuce, etc [60].

Fig. 2 Aeroponics System [45]

6. Hydroponic Systems Based on Structure and Material

U-Shaped hydroponic system

This type of construction is known as a U-shaped hydroponic system because the pipes are arranged to create a U shape. Studies show that Unplasticized polyvinyl chloride (UPVC) pipes would be preferable for the planning and development of commercial hydroponic systems. This system is used for harvesting lettuce plant [92].

Vertical and Horizontal Hydroponics

There is a direct influence of space utilization on productivity per unit area in greenhouse food production systems. Increasing the planting density is one technique to improve space use efficiently [91]. From a commercial perspective, the gradients within the Vertical farming systems (VFS) affect crop value which is determined by how the crop is going to be processed and sold [89]. By maximizing the growing space, vertical column-based VFS offers a competitive alternative to traditional horizontal growth systems by increasing crop production per unit area. Reducing the observed, Photosynthetic Photon Flux Density (PPFD) gradient using artificial lighting inside the VFS results in more yield gains [89]. Whether on a small or big scale, vertical systems can benefit from the vertical space in greenhouses or plant factories. Typically, structures built for human habitation are unsuitable for maximum-yield indoor farming however, a brand-new, transparent structure made with plants in mind would be able to get around many of the issues with existing structures [91]. While trough and grow bags hydroponic systems are suited for vast areas, A-frame, U-shaped, vertical tower, and horizontal hydroponic systems are suitable for small spaces [92]. All these systems are implemented when growing crops like strawberries, lettuce, Swiss chard, herbs, spinach, kale, broccoli, and flowering petunia [92].

7. Production of Various Crops Using Hydroponics

Urban farming can produce organic food locally, significantly reducing the miles of transportation of produce and bringing organic production closer to the consumer. Hydroponics allows us to do exactly this, with an ability to produce food 2-5 times higher than in conventional farming while saving space [25]. A wide variety of crops can be grown hydroponically. Plants require less growing time compared to conventional farming. The absence of weeds and pests (rodents, earthworms, etc.) lead to a better quality of products without hampering the taste or nutritional value. Leafy vegetables have shown excellent results when grown hydroponically [73]. Table I compares the hydroponic yield and agricultural yield for different crops.

Lettuce Production

Lettuce, a leafy green vegetable with a wide global consumption, has been the subject of numerous research papers exploring its nutritional value, cultivation techniques, and postharvest quality. One such investigation revealed that lettuce is a rich source of essential vitamins A and C, as well as vital minerals including potassium and calcium [16]. Another study compared the growth and quality of lettuce cultivated through different methods and ascertained that hydroponic cultivation yielded higher yields and superior quality than soil-based cultivation [42]. In a study, the postharvest quality of lettuce was examined, and it was discovered that storing lettuce at 5°C resulted in the optimal retention of quality attributes such as texture and colour. Taken together, these research papers underscore the significance of lettuce as a nutritious vegetable and highlight the necessity for meticulous cultivation and storage practices to uphold its quality.

Hydroponic lettuce output was found to be 11±1.7 times more productive per square foot than its traditional counterpart. The production capacity of Lettuce is seen to have increased by around 41±6.1 times with the help of Hydroponics in terms of water usage, the use of hydroponics is an overall better alternative to traditional methods. We can expect up to 13 ± 2.7 times less water for in fact a better overall yield. If we take each single crop into consideration, 250 ± 25 L/kg/y of water was used by traditional methods while hydroponically grown lettuce had a consumption of just 20 ± 3.8 L/kg/y. But in terms of energy consumption, due to use of different energy intensive equipment such as a running light source, circulating motor and heating and cooling loads, the energy consumption in hydroponic methods is nearly 100 to 110 times more than the conventional methods [7].

In the case of nutrient composition, the yield obtained by conventional methods was richer too. Using methods including FRAP (Fluorescence recovery after photobleaching) analysis, ABTS analysis, total phenols and anthocyanin analysis, the antioxidant activity in the leaves of both green and red lettuce was higher using conventional soil-based agriculture [34].

By maximising the use of growing space, vertical column-based VFS offered a competitive alternative to traditional horizontal growth systems by increasing crop production per unit area. By reducing the observed PPFD (Photosynthetic Photon Flux Density) gradient using artificial lighting inside the VFS, additional yield gains could be made [80]. The use of microbubbles also promotes better overall growth in lettuce production. Microbubbles are very small gas bubbles, with mean of diameter of 50 mm or less in water. Microbubbles act as carriers of nutrients and provide an effective transport method of nutrients to the roots.

In conclusion, Lettuce achieved better growth and productivity at all levels when grown hydroponically. The percentage of water saved reached about 79% in each hydroponic system, relative to conventional agriculture [2].

Cucumbers/ Armenian Cucumbers

Cucumbers are a widely cultivated vegetable crop that is renowned for its refreshing taste, high water content, and nutritional value. A recent study published in the International Journal of Food Sciences and Nutrition has revealed that cucumbers are a rich source of vitamins A, C, and K, as well as minerals such as potassium, magnesium, and manganese.

Additionally, cucumbers contain beneficial phytochemicals, including flavonoids, lignans, and triterpenes, which possess potent antioxidant and anti-inflammatory properties. The consumption of cucumbers has been associated with several health benefits, including improved digestion, hydration, and skin health. Although cucumbers are commonly consumed raw in salads, they are also used in pickling and cooking [53], [67].

Gashgari *et al.,* 2018 studied hydroponic system and traditional system for growth of different plants. Traditional methods had a yield of around 94mm while hydroponics yield had a length of 190mm for cucumber. They also reported a similar trend in the case of Armenian Cucumbers. However, the rate of growth of the growing plant and the difference in the length of the leaves remain comparable in both methods [24].

Potatoes

Potatoes are widely grown and consumed vegetables, high in carbohydrates, fibre, and essential vitamins such as vitamin C and potassium. Potatoes are recognized as the fourth most important crop globally, having a critical part in food security [83]. Potatoes have high fibre content helping to maintain gastrointestinal health and reducing the chance of certain diseases such as colon cancer. Furthermore, potatoes contain several beneficial compounds, such as carotenoids and phenolic acids, which have antioxidant qualities and may have health benefits [66]. Potatoes are versatile and nutritious vegetables versatile in their usage and offer numerous health benefits.

The crops grown hydroponically had significantly longer life span than those with traditional methods and avoided several soils induced infections and pathogens. Using repetitive harvesting methods, we can achieve a yield of 3500 tubers from density of just 800 plants/m^2. Larger minitowers are needed under traditional conditions in order to plant them in the dense soil of the nearby fields and get a yield that is satisfactory. When it's dry outside and there's no irrigation, this is very crucial.

The downside is that, the tuberization of potatoes was seen very late due to unlimited availability of Nitrogen and a lack of firm soil to hold roots in place. Also lack of chemical and water buffering capacities, which must be made up for by security measures (alarms, pumps), expensive infrastructure, advanced technology, and a specialised organisation of growers are needed for the better use of the technology [65].

Green Fodder

Green Fodder as a part of the cattle diet is very important as it provides the cattle with all the essential components needed for healthy growth and a fruitful product (milk) [27]. There was a difference in the overall health of animals. The conception rate also increased significantly. With the use of hydroponically grown Green Fodder, an increase in the overall quality of milk was seen, with an increase in the fat content and solid non-fat. There was also an increase in the taste (sweetness) and freshness of the milk [44].

The sustainability problem for the same is the high amount of water needed for its cultivation. In terms of water usage research, the hydroponic system's output of scarcely green fodder had a much better water use efficiency than an open field. Additionally, hydroponically, the WUE dropped with moving up the harvest date based on the new fodder and dry matter weights. The hydroponic system produced the greatest WUE, 411.1 kg m^3, based on fresh feed weight, and the lowest, 4.5 kg m^3, based on dry matter weight.

Fresh green fodder output from the hydroponic method was 2.83 times greater per square metre than that from an open
field, and the dry matter yield was 2.3 times greater. As a result, hydroponically growing one tone of scarcely green fodder needed 2.83 m^3, as opposed to the open field's 117 m^3 [22].

Tomatoes

The Solanum lycopersicum, commonly known as Tomato, is a highly cultivated vegetable crop holding significant economic and nutritional value. Various studies have revealed that tomatoes are a rich source of essential vitamins, minerals, and antioxidants, including lycopene, a carotenoid pigment that has potential health benefits, such as reducing the risk of cancer, cardiovascular diseases, and inflammation [26], [63]. Tomatoes also help reduce the effects of Dorsal Erythema because of some pigments and the presence of lycopene [77]. Overall, we can say that tomatoes are a great source of essential minerals and dietary fibres with fewer to no side effects.

It can be said that the nutrient solution, growth stimulants, and growth substrate are the primary factors influencing tomato output using hydroponics. Compared to in-soil cultivation, tomato plants in the soilless method grew more quickly and produced a higher overall output. In comparison to in-soil cultivation, soilless agriculture produced an average marketable output of 92.1% as opposed to 77.0% [48].

The planting density and plant development rate both affect food output. In comparison to traditional agriculture, hydroponic tomato farming has a planting density (plants/m^2) that is four times higher and a development rate that is 30–40% higher. When compared to traditional cultivation, the output of tomatoes grown hydroponically is typically seven times greater per hectare. Hydroponic tomato production used 22 L/kg of water per kilogramme, which is three times less than traditional farming [62]. Table I shows the allowable nutrients requirement for vegetables. Khan *et al.*, 2020, reported comparison of hydroponic yield and open agriculture yield of different cereals and vegetables as shown in
Table 1 It is observed that hydroponic yield of cereals and vegetables are higher than open agricultural yield.

Table I Yield comparison; hydroponic vs conventional agriculture [38]

Type of Crops	Name of Crops	Hydroponic Yield [kg/ha]	Open Agriculture Yield [kg/ha]
Cereals	Rice	13,456.56	841.03-1,009.25
	Maize	8,971.0	1,682.07
	Wheat	5,606.9	672.83
	Oat	3,364.14	953.18
	Soybean	1,682.07	672.83
	Peas	15,699.32	2,242.76
Vegetables	Tomato	4,03,335.81	11,203.75-22,407.47
	French bean	47,097.96	-
	Beet	22,427.6	10,092.42
	Potato	1,56,852.29	17,925.98
	Cabbage	20,184.84	14,577.94
	Cauliflower	33,641.4	11,213.8-16,820.7
	Cucumber	31,398.64	7,849.66
	Lady's finger	21,306.22	5,606.9-8,971.04
	Lettuce	23,548.98	10,092.42

Table I Allowable Nutrient range [39]

Elements	Ionic form	Concentration range [mg/l or ppm]
Nitrogen (N)	NO3- , NH4 +	100-200
Phosphorus (P)	H2PO4	30-15
Potassium (K)	K+	100-200
Calcium (Ca)	Ca2+	200-300
Magnesium (Mg)	Mg2+	30-80
Sulfur (S)	SO4	70-150
Micronutrients		
Boron (B)	BO3-	0.03
Copper (Cu)	Cu2+	0.01-0.10
Iron (Fe)	Fe2+, Fe3+	2-12
Manganese (Mn)	Mn2+	05-20
Molybdenum (Mo)	MO2-	0s
Zinc (Zn)	Zn2+	05-050

8. Current Scenario of Hydroponics Worldwide

Hydroponics, being a new technology, faces some challenges during implementation in India. The key issue is the lack of education and knowledge among farmers about all of these hightech advancements. Technological understanding is essential, to the point of micromanaging temperature and humidity. A single blip in ambient temperature could cause considerable crop losses. Many farmers are unfamiliar with hydroponics and how to use it. Hydroponics requires a huge initial investment, making it impractical for the average Indian farmer to bear all the costs. In India, the central and state governments have subsidized capital expenditures for farmers wishing to invest in hydroponics. Furthermore, the specific subsidy appropriate for each state varies. Putting up a hydroponic farm is substantially more expensive than traditional farming, particularly in developing nations such as India [82].

The lack of government incentives and the unavailability of essential equipment to set up large hydroponic farms hinder growth in developing countries from the Middle East, Africa, and South America [31].

The situation of hydroponic farming is a lot different when it comes to developed nations. Israel has shown significant developments in implementing soilless agriculture techniques. They are trying to grow fruits like berries, citrus fruits, and bananas, which are impossible to grow in arid regions. The procedure is automated, with robots controlling it on an assembly line-style system similar to those used in manufacturing factories. The cargo containers are then moved throughout the country [73]. Because of the city's growing population, land in Tokyo is exceedingly valuable. Japan has turned to hydroponic rice farming to feed its inhabitants while protecting valuable land mass. The rice is harvested without the use of soil in underground vaults. Because the atmosphere is thoroughly regulated, four harvest cycles can be completed annually rather than the typical single harvest [5]. With the help of a controlled environment, rice can be harvested over the entire year. Land, water, and energy needs of hydroponic lettuce production in Yuma, Arizona, USA, were compared to conventional agriculture. The study found that hydroponics provided 11 times better yields but consumed 82 ± 11 times more energy. To the best of the authors' knowledge, this is the first quantitative comparison of traditional versus hydroponic food production using lettuce produced in the southwestern United States [7]. North America has a strong growth potential due to the region's numerous companies and the increased use of alternative farming practices in urban areas [31].

9. Automation in Hydroponics

With the rise in Industry 4.0 and advancing technology, automating hydroponics provides an approach to increase production while maintaining quality. Domingues *et al.* reported the creation of an automated system that can manage pH and conductivity online using the software. A webcam was used to monitor and report the data to the software for interpretation. The plants were being monitored regardless of the temperature in the greenhouse.

A fully automated hydroponic system with low operating costs and a manageable learning curve was the goal of Palande *et al.* Smartponics technology. The automated hydroponic system integrated an IoT network for remote monitoring and control and kept the conditions necessary for the test plant to thrive. The Titan Smartponics system has several benefits, including total control over the factors that enable a plant to survive, tailored to meet the needs of different plants, and it is not dependent on an external environment or atmosphere to function.

Based on the internet of things technology, Zhang *et al.* created a distributed environmental monitoring system combining hydroponics and aquaculture that primarily consists of the information perception layer, the information transmission layer, and the system architecture. The system uses several sensor terminals for real-time acquisition, such as those that measure dissolved oxygen, air and water temperatures, and more. Fish and vegetables need an appropriate environment to grow making it crucial to monitor the aquaponics environment in real-time. An environment monitoring system was designed and implemented using wireless sensor networking and distributed sensor monitoring. This was used to monitor the water and greenhouse environments along with the outdoor environment for breeding purposes. The system continuously gathered data from the hydroponic, outdoor, and water quality environments. A historical database was composed to aid in scientific management. The findings demonstrated that the suggested monitoring system could support and manage hydroponic and aquaculture production through overall operation stability and accurate data transfer.

10. Challenges

Hydroponics is a method of growing plants in a soilless medium that delivers all the nutrients and water they need as a nutrient solution straight to their roots. Hydroponic cultivation has many advantages, such as faster growth and higher yields, but there are also some challenges that growers can face. Here are some examples:

- Maintaining correct pH balance: a specific pH range is required by plants to effectively absorb nutrients. In hydroponics, the pH of the nutrient solution is tracked and adjusted regularly to keep it in the optimum range for growing plants [71].
- Ensure adequate oxygen supply: Roots need oxygen to thrive, and oxygenation can be challenging in hydroponic systems. Failure to properly aerate the nutrient solution can lead to root rot and other problems [71].
- Disease and pest control: Without soil as a natural buffer, hydroponic plants are susceptible to disease and pests. Growers should maintain a clean and sterile environment to avoid problems [71].
- Nutritional balance: While hydroponics allows growers to control the nutrient levels of their plants, it can be tough to maintain the proper balance of nutrients.
- High initial cost: Hydroponics systems can be expensive to set up and maintain, especially if you want to incorporate advanced features such as automation and monitoring [3].

Overall, hydroponics is a very effective way to grow plants requiring great attention to detail and a willingness to invest time and resources to create the ideal growing environment.

11. Advantages

There are plenty of benefits to hydroponic farming. It allows for year-round crop production without being hindered by seasonal restrictions or climate factors that could adversely affect traditional cropping methods. The use of water as a growing medium eliminates soil-borne pests and diseases, reducing the need for pesticides and herbicides generally used in outdoor agriculture. Minimizing, environmental harm caused by agrochemicals.

- Enables plants to thrive under ideal conditions, leading to rapid development and large outputs in contrast to conventional techniques.
- Possible to optimize nutrients, lighting conditions, and temperature regulation stimulating faster plant growth than what is possible in traditional methods [19].
- Results in superior crop yields due to its ability for precise control over the growing environment [71].
- Controlling factors such as pH levels or nutrient intake can accelerate root system expansion leading to healthier and more fruitful plants.
- Implementing hydroponic farming entails a significant decline in water usage by up to 90% compared to conventional farming methods. This feature makes this method an ecologically responsible solution, especially in regions with limited access to or inadequate supply of clean water [71].

Hydroponic farming decreases the necessity for pesticides and herbicides, resulting in a cleaner, safer, and healthier product [3]. Through minimal use of these chemicals on their crops, hydroponic farmers avoid harmful effects on both, the consumers' health and the environment. A significant reduction in toxic residue levels renders essential benefits to plants by sustaining a profitable growth process ensuring desirable qualities with abundant nutrients helping to maintain healthy bodily functions when consumed. The practice's numerous advantages have put it at the forefront amongst others seeking eco-friendly methods yet producing a high yield. The cultivation of crops with hydroponic farming carried out indoors presents an opportunity for continuous growth and harvests regardless of outdoor climates enabling year-round production without relying on seasonal conditions beyond human control [3].

12. Disadvantages

Hydroponic farming has several downsides.

- Requires substantial financial investment upfront to set up the system correctly [19].
- Maintaining a hydroponic farm is labour-intensive and costly considering energy consumption for all the necessary artificial lighting and climate control measures that need constant attention [19].
- Pests still pose a significant threat to this type of agriculture without chemical intervention or physical barriers like netting over crops which may not always be effective enough against Establishment expenses [19].
- Substantial upfront costs in terms of machinery, infrastructure, and technology.
- It heavily relies on advanced infrastructure and modern tools, thus making the process susceptible to technical problems like equipment malfunctions, and outages of electricity supply, among others [19].

The assortment of crops that can be grown through hydroponic farming is restricted. This method works optimally for specific types of plants, including herbs, leafy greens, and tomatoes; however, it may not be ideal when attempting to cultivate other varieties.

13. Future Prospect

Hydroponics has the potential to revolutionize the way we grow crops in the future, with many researchers exploring new possibilities and innovations in the field. One area of focus is on implementing hydroponic systems for urban agriculture, where space is limited, and traditional farming is not feasible. Apart from the problem of increasing population and availability of arable land for open agriculture, climate change, and infertile land is forcing people to use newer technologies such as hydroponics and aeroponics.

Hydroponics will also be vital for the space program's future. NASA has major hydroponics research programs to aid present space exploration and eventual, long-term Mars or Moon colonization. Because we have yet to discover soil capable of supporting life in space, and the practicalities of transferring soil via space shuttles appear unrealistic, hydroponics may hold the key to the future of space exploration [36]. Sanyé-Mengual, 2015 stated that hydroponic systems could be set up in urban areas, such as rooftops and vertical gardens, allowing for fresh, locally grown produce yearlong.

Soon, people will become more aware of the negative health impacts of pesticides, increasing the demand for hydroponics as this approach eliminates the usage of such harmful chemicals. Climate control, nutrient film techniques, and sensor technologies, among other things, are expected to accelerate market growth shortly [9]. The advanced use of IoT enables autonomous and remote data collecting and monitoring. Because of such technological breakthroughs in hydroponics solutions, the market is predicted to grow at a rapid pace between 2021 and 2028 [81].

14. Conclusion

Hydroponics has emerged as a promising agricultural technique with the potential to change crop cultivation. As the world population grows and worries about food security and environmental sustainability grow, hydroponics provides a solution that may produce high-quality crops while using minimal resources. One of the primary benefits of hydroponics is its capacity to produce crops all year long, independent of weather or geographic location. It is a good technique for areas with little arable land, harsh weather, or water shortage. Additionally, hydroponics provides greater control over growing parameters like temperature, humidity, light, and nutrient levels, resulting in faster development, bigger yields, and higher nutritional quality.

This review paper has highlighted the various aspects of hydroponics, including the growth mediums available, factors affecting plant growth, and different techniques for growing plants using hydroponics. Out of the papers reviewed, aeroponics was a widely used technique for growing plants. It had the best produce, while techniques like NFT and DFT were the popular choices in terms of cost. Furthermore, the review studied the crop production of a few varieties of plants. From the literature surveyed, it was observed that crop yield using hydroponics was 10 times more than conventional methods with 80% water salvage. The only downside was the consumption of energy which was 100 times more than conventional farming. Hydroponics has evolved as an environmentally friendly form of plant culture that can provide year-round crop production, minimize water consumption, and boost agricultural yields. This strategy has been used successfully to cultivate several crops. To name a few, lettuce, cucumber, tomato, and potato, among others. Furthermore, hydroponic automation can improve crop management and maximize productivity. Despite its various advantages, hydroponics faces many challenges, including expensive setup and maintenance costs, specialized knowledge and skills, and reliance on technology.

There is a lot of opportunity to improve the agricultural sector using hydroponics. Future developments can focus on making food production using hydroponics popular with the correct infrastructure, training, and support. There is a need for better integration of technology with this system to increase control of parameters, with a hands-on extension to exotic varieties of plants. There is a need for cost-effective and efficient energy usage given hydroponics relies on artificial lighting heavily.

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