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Review Article

Hydroponics as an advanced vegetable production technique: an overview

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ABSTRACT

In the recent past, population explosion across the globe has presented many challenges that include the availability of arable land diminishing per capita for traditional soil-based farming. Therefore, the development of advanced agricultural technologies and methods has become important in response to these persistent situations. Amongst these innovations, soilless crop cultivation has emerged as one of the promising solutions, leading from the forefront. This current review offers a comprehensive investigation of hydroponics as an advanced technology for vegetable production. It explains many aspects related to hydroponic systems, viz., methods used in hydroponics, its advantages, challenges as well as application in vegetable production. This paper also explores the hydroponics evolution historically, various hydroponic systems, their essential components, and nutrient solution role in plant growth facilitation. Furthermore, it highlights various advantages of farming under hydroponic culture, viz., increase in yields, efficient usage of water, optimum space utilization, and less environmental impact. Additionally, this review also sheds light on challenges related to hydroponics, like initial setup cost, technical complexity, and management of diseases. Moreover, it also enlightens about vegetables that are suitable to cultivate under hydroponic culture and provides insight into continuing research, and forthcoming projections in the area of vegetable production under hydroponic cultivation.

Keywords: Soilless cultivation, nutrient solution, hydroponic culture, vegetable production.

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INTRODUCTION

1.5 billion hectares of land are needed to produce food and support for the 7.8 billion people that live on the planet today. With 10.9 billion people expected on the planet by 2050, every person will need at least 1,600 calories each day. Continuing current cultivation practices could necessitate an additional 2.1 billion acres of land, a prospect that is simply unsustainable given the finite availability of arable earth. Moreover, agriculture currently consumes the world's 70% water for irrigation, rendering much of it unsuitable for drinking owing to contamination from various fertilizers, herbicides, and pesticides. This trend poses a grave threat to the availability of drinking water for future generations. Anthropogenic activities also contribute to the emission of greenhouse gases, leading to rising temperatures and diminishing groundwater levels, further exacerbating the challenges of feeding an extra 3 billion individuals by 2050. Considering these urgent problems such as scarce water supplies and space alternative farming techniques are essential. The drawbacks of horizontal farming can be addressed by vertical agriculture (Butler & Oebker, 1962).

Hydroponics, sometimes known as soilless farming, is one such alternate technique through which plants can be grown in a solution of nutrients with- or without the physical support of inert material, viz., cocopeat, coconut coir, sand, and rock wool. The term hydroponic was coined by William Gericke in the early 1930s. Hydro is a Greek word meaning water and ponos means work. Various crops, flowers, and vegetables have been grown successfully (Asao, 2012). It has various benefits over conventional growing methods that include quick growth, higher yield and easy to handle (Barbosa et al., 2015), and lower fertilizer required (Cuba et al., 2015). Under hydroponic culture concentration of nutrients in aqueous solutions is being monitored and controlled to detect and accordingly address if there is nutrient toxicity or deficiency in plants (Adrover et al., 2013; Cuba et al., 2015).

Furthermore, it has been confirmed that research related to toxicology and experimental studies in which researchers are looking for toxins accumulation in plants using various crops for medicinal and commercial reasons like ornamental plants, and conventional foods. Although soil plays a significant role in conventional agricultural methods, soil-based agriculture is not without its challenges. Arable land continues to be encroached upon by industrialization and urbanization, and biotic and abiotic stresses in the soil can harm agricultural and horticulture production. To address these challenges, soilless cultivation methods such as hydroponics, aeroponics, and aquaponics offer promising alternatives. This document aims to underscore the soilless culture's importance in the efficient cultivation technique for vegetable production, applications, principles, advantages, and challenges.

Historical Evolution of Hydroponics

Hydroponics, a method dating back thousands of years, has been utilized by numerous civilizations throughout history. One of the earliest records of hydroponics dates back to around 600 BC in Babylon, where the renowned hanging gardens featured plants irrigated from the Euphrates River on terraces. Similarly, around 40 AD, the Aztecs created an island city in Tenochtitlan, where plants floated over water with direct contact with roots, a precursor to modern hydroponic techniques (González Carmona and Torres Valladares, 2014). Chinampas, a type of ancient Mesoamerican agriculture utilizing hydroponic principles, continues to thrive today, producing approximately 40,000 tons of vegetables and flowers annually (Arano, 2007). Recognized as an important agricultural heritage system, Chinampas highlight the enduring efficacy and sustainability of hydroponic practices (Aquastat, 1999). Even in the early modern era, hydroponics garnered attention. In 1627, Sir Francis Bacon, renowned as the father of the scientific method, published "Sylva Sylvarum," which included insights into growing terrestrial plants without soil. Bacon termed this method "Water Culture," laying the groundwork for modern hydroponic techniques.

In 1666, Robert Boyle conducted his experiment on plants having roots submerged in water. Similarly, John Woodward's work in 1699 on a soilless system in spearmint revealed that plants have performed better in distilled water than impure water. The foundation for inorganic nutrition for soilless culture in solutions was laid by German botanists Julius Von Sachs and Wilhelm Knop in 1842 and 1895. In the early 20th century, Professor William Frederick Gericke proposed a commercial water culture system, coining the term "hydroponics" in 1937. He further detailed hydroponic techniques in his 1940 book, "Complete Guide to Soilless Gardening." In 1938, plant nutritionists Dennis R. Hoagland and Daniel I. Arnon at the University of California developed the "Hoagland Solution," a nutrient solution still used commercially today. Hydroponics was introduced to India in 1946 by English scientist W.J. Shalto Duglas, who established a laboratory in Kalimpong, West Bengal, and authored the book "Hydroponics: The Bengal System." These milestones mark the evolution of hydroponics into the advanced agricultural technique it is today.

Selection, Suitability, and Applications of Hydroponics for Vegetable Production Across Different Sectors

The choice of crop species in hydroponic systems has a significant impact on nutrient uptake as well as the acceptance of the technology in urban settings. Vegetables suitable to grow on a commercial scale using soilless culture have been presented in Table 1. Because ornamentals like tomatoes, cucumbers, lettuce, and cut flowers have short growth cycles and allow for greater cultivation control, studies primarily focus on these types of crops or vegetables (Prazeres et al., 2016). Crop selection is also determined by market demand and consumer expectations, which place a premium on qualities like flavor, color, nutrition, firmness, shelf life, and pathogen resistance. Although the use of treated wastewater in hydroponic vegetable farming has been investigated, worries regarding decreased crop quality and shelf life endure. Because there is less interaction between irrigation water and edible plant portions, soilless farming dramatically lowers the danger of microbial contamination in fresh produce, according to commercial research. There are still issues, though, such as the high infection rates found in small-scale hydroponic systems that use treated gray water (Tangahu et al., 2011). Despite these difficulties, there are no clear guidelines for crop selection in the literature; instead, species or varieties with better growth performance are usually found through pilot research.

While permitting water and nutrients to flow freely, an inert medium such as pine needles, rock wool, farmyard manure, perlite, coco coir, or sugarcane bagasse serves as a physical support for plant roots (Alam et al., 2022). Vegetables can be grown successfully under a soilless culture farming system. The commonly cultivated vegetables under the hydroponic system include spinach, lettuce, and kale, which grow well in hydroponic culture owing to their shallow root systems and quick growth cycle (Jones, 2014). Moreover, tomatoes (Balashova et al., 2019), cucumbers, peppers, and strawberries also can be grown effectively in hydroponic culture (Jones, 2014). Vegetable production through a hydroponic system depends on delivering the essential nutrients to roots directly via nutrient solution. Commercially, hydroponic culture is employed by farmers to cultivate valuable vegetables on a large scale (Croft et al., 2017). Farms produce various types of vegetables around the year that ensure consistent and better quality to fulfill the demands of the growing population (Hochmuth & Cantliffe, 2021).

Due to limited land in urban areas, hydroponic cultivation is very well-suited. In compactly populated areas farmers can cultivate different vegetables through using rooftop and vertical hydroponic culture, which decreases food distance, increases food security, and supports food production locally (Payen et al., 2022). Under greenhouse conditions hydroponic system is used to expand agricultural production and environmental management. Through this system, better quality vegetables can be produced around the year because in this system vegetables are less prone to pests, and disease (Bisbis et al., 2018).

This system can be implemented in various fields of study like educational and research institutions to undertake studies on plant growth, nutrition, and sustainability of the environment (Sambo et al., 2019). In educational institutions, hydroponics can be used to teach the youth about the production of food, the biology of plants, and sustainable agricultural practices. Urban agriculture and community gardening are the key indicators of enhancing the number of projects related to hydroponics. According to Ben-Othmen et al. (2023), This system supports the self-sufficiency of food and ensures fresh, nutritious vegetable availability in ignored groups. Farmers can harvest various crops through hydroponic production which is difficult to manage in orthodox systems based on soil (Ampim et al., 2022). Using hydroponic culture growers can grow rare types of vegetables, flowers, microgreens, and herbs.

Small growers and home gardeners looking at easy and space-saving methods for vegetable production are increasingly attracted to hydroponic systems (Caputo et al., 2020). Installation of hydroponics in homes enables the public to enjoy fresh vegetables around the year irrespective of the exterior growth factors and this system ranges from modest systems to countertop gardens. Furthermore, these systems can be applied for environmental remediations, particularly in programs related to phytoremediation that removes contaminations from soils (Kumar et al., 2024). Yan et al. (2020) have shown that certain Plants cultivated in hydroponic systems can absorb and detoxify the contaminations, viz., heavy metals and organic chemicals. This method can thus reduce pollution and restore ecosystems.

Table 1. Vegetables suitable for growing on a commercial scale using soilless culture (Maharana and Koul, 2011).

Crop Type	Name of crops	Botanical name
	Beet Root	*Beta vulgaris*
	Green Bean	*Phaseolus vulgaris*
	Bell pepper	*Capsicum annum*
	Tomato	*Lycopersicon esculentum*
	Cabbage	*Brassica oleracea var. capitata*
	Melons	*Cucumis melo*
Vegetables	Celery	*Apium graveolens*
	Winged Bean	*Psophocarpus tetragonolobus*
	Lettuce	*Lactuca sativa*
	Cucumber	*Cucumis sativus*
	Chilli	*Capsicum frutescens*
	Cauliflower	*Brassica oleracea var. botrytis*
	Brinjal	*Solanum melongena*
	Radish	*Raphanus sativus*
	Kang Kong	*Ipomoea aquatica*
	Onion	*Allium cepa*

Conclusively, vegetable farming through hydroponic can address the issues of food security, help environmentally friendly practices, and fulfill the rising demand for fresh and locally grown vegetables. It has several applications in agricultural fields, education, research, community development, and sustainable environment are also provided by it.

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Types of Hydroponic Systems

Numerous soilless culture techniques have been used to produce vegetables. Commercial hydroponics started during the late 1960s and many countries like Abu Dhabi, Denmark, Arizona, Germany, Belgium, Iran, California, Italy, Holland, Japan, and Russia made significant contributions to the field (Sardare & Admane, 2013). The NFT was created by Englishman Allen Cooper in the 1960s, and it was quickly embraced. Hydroponic kits that were automated and computerized were first introduced in the 1980s and became more and more popular in the 1990s.

Hydroponics has been the subject of much research in recent years, especially for NASA's Controlled Ecological Life Support System, which aims to grow different plants in space for extended periods (Gruda 2009; Savvas & Passam, 2002). A hydroponically operated farm in Arizona produced 200 million pounds of tomatoes in 2007. (Arumugam et al., 2021). Furthermore, some private businesses have made major advancements in AI-supported software, allowing for remote management and monitoring of hydroponic systems via mobile devices via Bluetooth or the Internet (Lakshmanan et al., 2020). There are many different types of hydroponic systems available, each with special qualities and benefits of its own. Hydroponic systems come in various varieties, each with unique benefits and drawbacks.

Types of Circulating system in Hydroponics

There are two main categories into which hydroponic systems can be divided: 1. Open-system; 2. A closed framework. Both hydroponic systems open (right) and closed (left) have been presented in Figure 1.

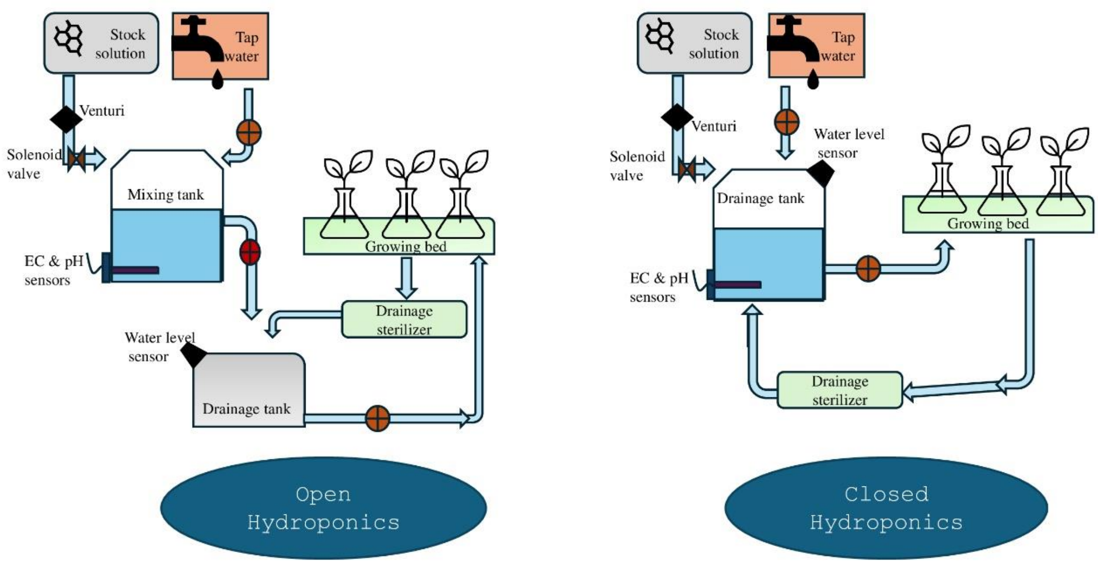

Figure 1. Diagrams of open system (right) and closed framework (left) hydroponic system.

Open system

The nutrient solution directly contacts with the root system in an open hydroponic system and cannot be recycled or recirculation is not used. This setup eliminates the risk of plant system infection since the nutrient solution is regularly refreshed (Jones, 2005).

Closed system

The whole nutrient solution that is supplied to the roots and used for plant growth in a closed hydroponic system is collected and refilled regularly. Plants are usually grown in a liquid medium or with solid substrates like sawdust, sugarcane bagasse, charcoal, pine needles, rice husk, sand, or gravel, and this system recycles the nutritional solution. When they are recycled, water and nutrients are closely observed. However, this system's dependency on power for functioning is a major limitation (Lee and Lee, 2015). The NFT, wick system, drip hydroponic system, ebb and flow system, and deep-water culture (DWC) are examples of closed hydroponic systems.

Hydroponics

Hydroponics is a simple technique for growing plants in aqueous solution without using soil. Its underlying theory is that plants can develop without soil as long as they have access to vital nutrients, light, water, carbon dioxide (CO_2), and oxygen (O_2) in their root zone. Thus, in hydroponic systems, plant roots are supported by inert growth media like pumice or perlite, and their growth is aided by nutrient-rich solutions that include vital macro- and micronutrients (El-Kazzaz & El-Kazzaz, 2017).

Types of hydroponics systems

Nutrient film technique

Through a network of polymerized vinyl chloride (PVC) pipes, the NFT simulates a closed system of hydroponic in which an aqueous solution of nutrients is continuously recycled and supplied to plant roots in a well-oxygenated combination (Figure 2). Allan Cooper developed this technique in the 1960s (Cooper, 1988). It allows plants to take up O_2 and essential nutrients employing a thin coating of nutritional solution that circulates through their roots (Morgan, 2009). Generally, a reservoir holds the nutrient solution, which is pushed to sloping pipes where plant roots are suspended. The leftover solution is continuously recycled to the reservoir (Waiba et al., 2020). This system was developed initially for growing plants with opaque containers having inert media, but recently it has used different growing arrangements with supporting materials.

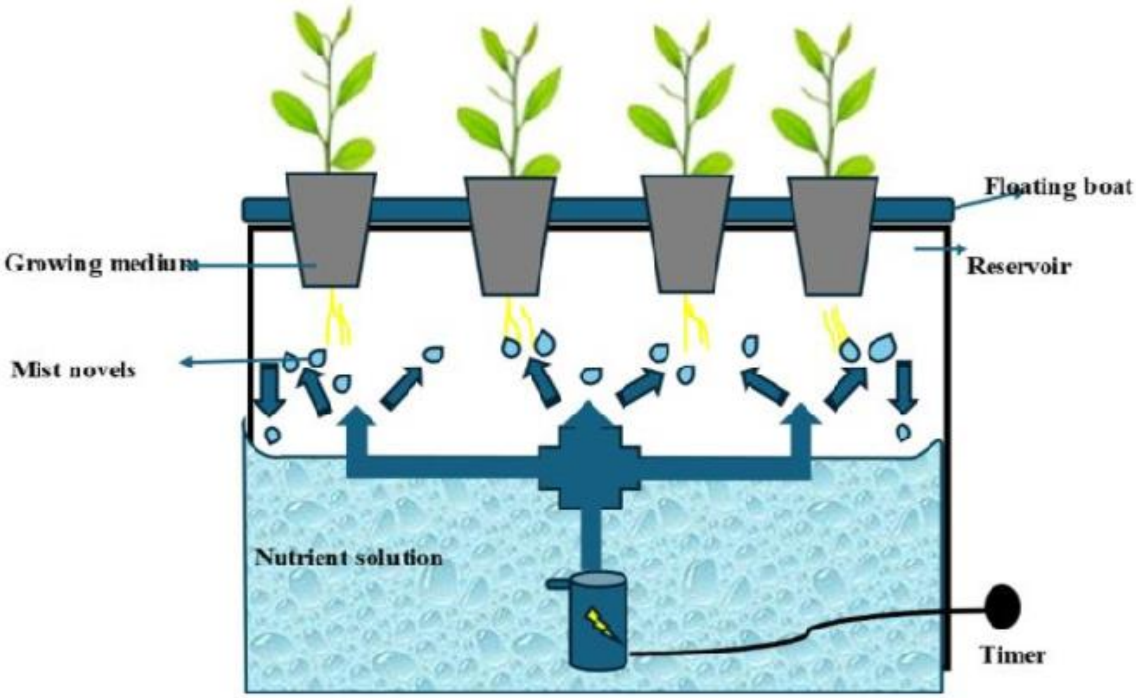

Figure 2. Aquaponic system based on nutrient film technique.

Wick or Passive System

Wick system is also known as a passive system, and it is a low-cost hydroponic system however it cannot recycle nutrient solution and has been shown in (Figure 3). In this system, plants absorb the nutrient from the solution via capillary action through roots and inert material which carries water (Ferrarezi & Testezlaf, 2016). This method is specifically useful in areas with limited power access because it does not involve energy to deliver the nutrients (Arumugam et al., 2021). Owing to its simplicity in use wick system is perfect in educational institutions which gives the instructors a simple and straightforward method to enlighten the students on the basics of hydroponics culture in a classroom (El-Kazzaz & El-Kazzaz, 2017). Small farmers can use this technique for crop production however it is not suitable for crop production in a sustainable manner.

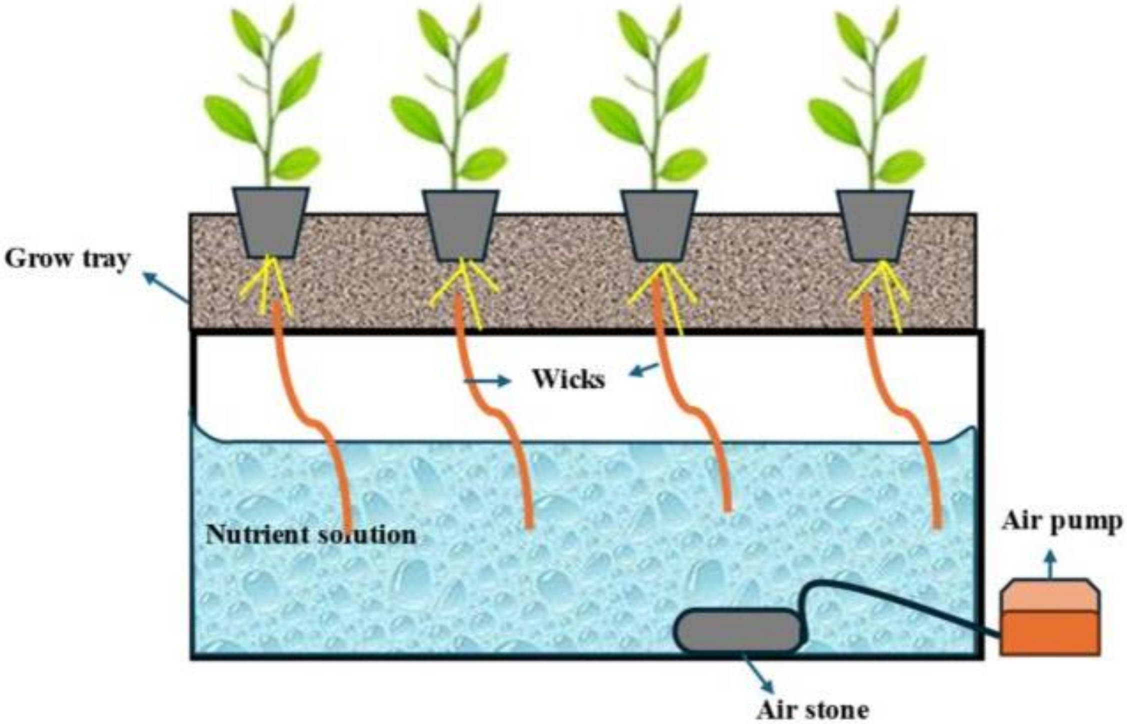

Figure 3. Aquaponic system based wick or passive system.

Ebb and flow system

It comprises two containers one is used overhead the plants, and the other is below the plants which carries fertilizer in solution form and this system is substantially comparable with the drip method (Benko et al., 2023). This technique downpours nutrients into the roots of plants directly which is different from the drip method because the drip method uses drippers to deliver the nutrients to plants (Figure 4). Nutritional solution quantity is regulated through an overflow pipe from the overhead container which directs any surplus solution to the container's bottom (Baras, 2018). This technique is very effective for plants having deep root balls, similar to drip hydroponic systems (Halveland, 2020).

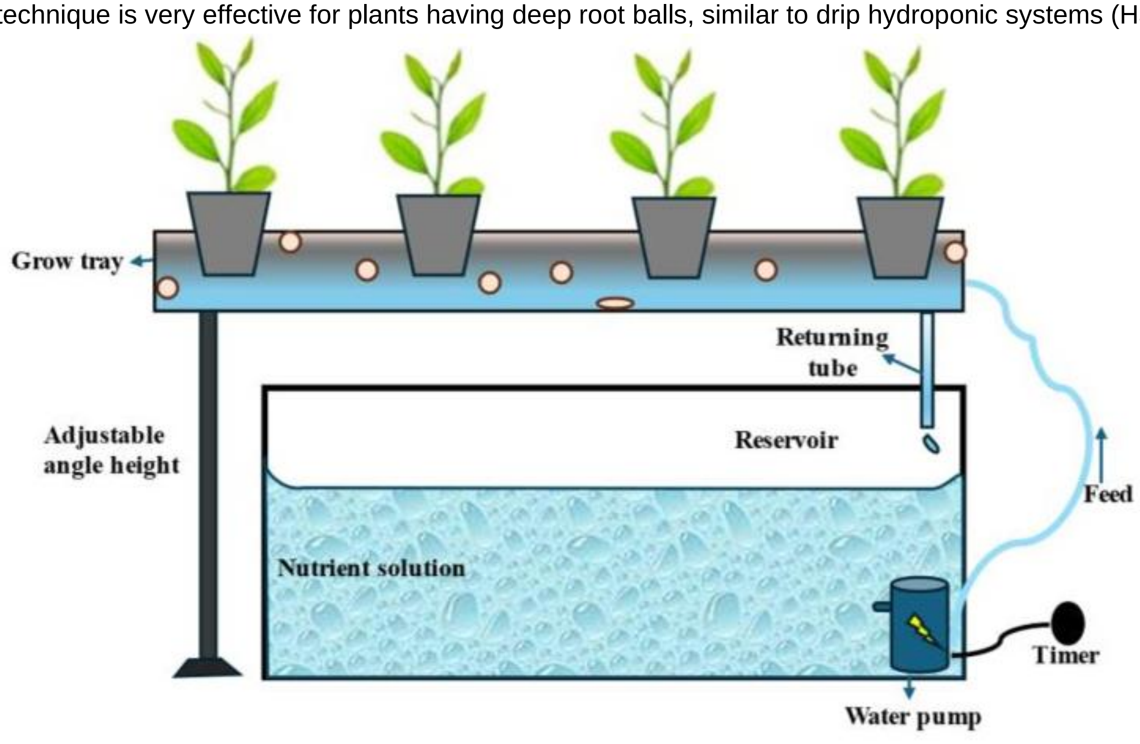

Figure 4. The aquaponic system based on ebb and flow .

Deep water culture

Van Os et al. (2002) reported that in deep water hydroponic culture, plants can be grown on floating conditions or through hanging supports like boards, rafts, or panels in the container which encompasses a solution of nutrients typically from 10-20 cm deep. Numerous recent developments in hydroponic techniques are based on this technology (Figure 5). It contains a pump and an aeration system to promote root growth (Hoagland and Arnon, 1950). Plant roots require precise control over the pH, conductivity, and O_2 content in order to enhance growth. This requires the roots to be continuously submerged in the nutritional solution with proper aeration (Jones, 2005).

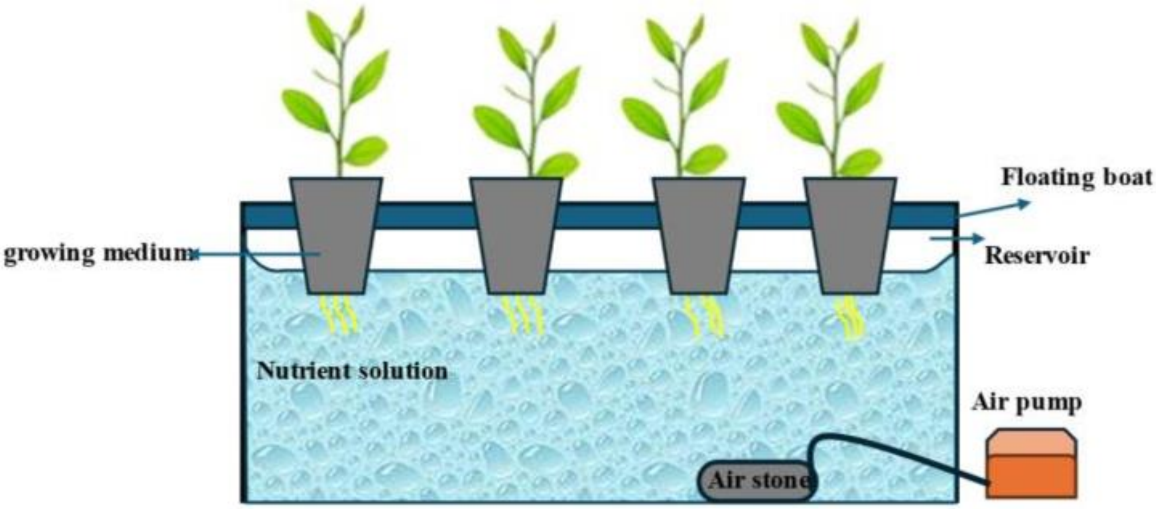

Figure 5. Aquaponic system based on deep-water culture.

Drip hydroponic System

Two containers make up the drip hydroponics system; one is stacked on top of the other (Waller et al., 2016). Plants are positioned in the upper container in this setup, while the lower container holds nutritional solutions (Figure 6). Through a pumping process, elevated nutrient solutions are sent toward drippers near the plant roots (Torabi, 2011). After filtering, the nutrient solution is fed back for cycling to the nutrient tank.

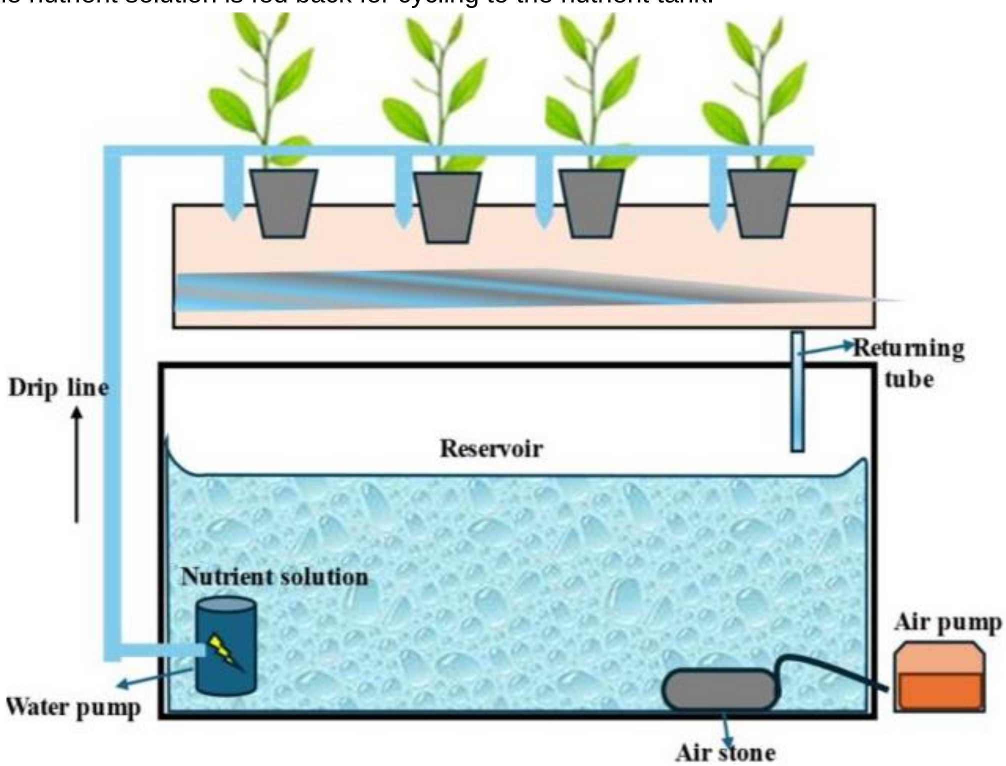

Figure 6. Aquaponic system based on the drip system.

Aeroponics system

An advanced kind of hydroponics known as aeroponics uses inert panels made of polystyrene or plastic to support plants above the growing container (Figure 7). This system is composed of three primary frameworks: ultrasonic foggers, low-pressure (soakaponics), and high-pressure (Maucieri et al., 2019). To avoid root zone dryness, nutrient solutions are sporadically sprayed directly onto the suspended roots using a variety of nozzle types. Liu et al. (2018) state that pressurized airless nozzles, high-pressure atomization nozzles, and ultrasonic atomization foggers enable this misting. A computerized system usually maintains and controls a static pressure of 60-90 Psi, and spray durations of 30-60 seconds are regulated according to crop type, growth stage, and culture period (Burrage, 1998; Domingues et al., 2012). Despite its potential for horticultural crops, aeroponics has seen limited adoption due to its high initial investment and operational costs (Rakocy, 2012).

Aquaponics combines hydroponics and aquaculture systems, enabling dual harvests of fish and vegetables in a symbiotic environment (Rakocy, 2007). In this system, an H2O pump transfers water from the fish tank to the growing container, passing via a biofilter where nitrifying bacteria break down toxic compounds. Recycled into the growing container, the nutrient-rich water containing fish excrement supplies vital nutrients for plant growth (Rakocy et al., 2012). In cities with limited space, degraded soil, and little freshwater, aquaponics provides an answer for food security (Bindraban et al., 2012; Klinger and Naylor, 2012). India, Israel, China, and Africa are the world leaders in aquaponics (Kalaivanan, 2022). Both air-breathing and water-breathing fish species, such as ornamental fish and Tilapia, Anabas, Pangasius, Rohu, Mrigal, and Gourami, can be raised with plants (Azad et al., 2016).

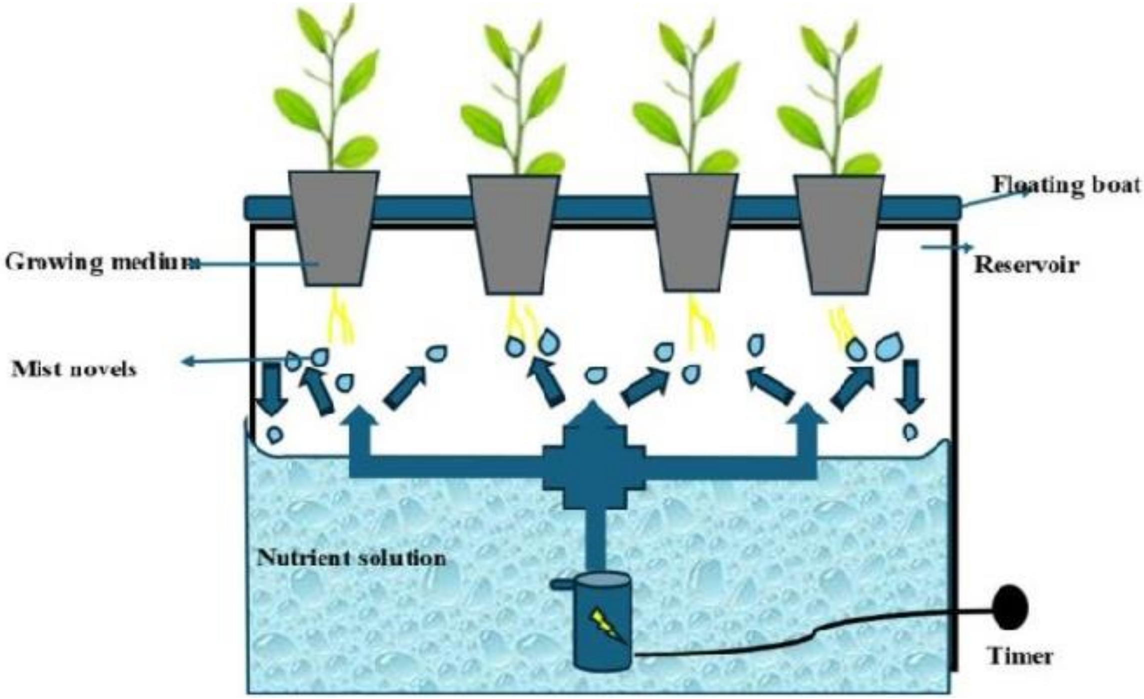

Figure 7. Aquaponic system based on aeroponics.

Nutrient Solutions and Management

The vital component of hydroponic systems is the nutrient solution, which needs to be carefully formulated and continuously monitored to fulfill the special requirements of farmed crops and to maintain ideal nutrient levels and pH balance (Domingues et al., 2012). With an emphasis on critical macronutrients like nitrogen (N), phosphorus (P), and potassium (K), as well as micronutrients like iron, calcium (Ca), and magnesium (Mg) required for robust plant growth and development, an understanding of the composition of nutrient solutions is essential to hydroponic vegetable production.

Together with O_2 and water, the aqueous solution contains critical nutrients that are necessary for the growth and development of plants. Presently, seventeen nutrient elements carbon (Ca), hydrogen, O_2, N, P, K, Ca, Mg, sulfur, Fe, copper, zinc, manganese, molybdenum, boron, chlorine, and nickel are acknowledged for their essential involvement in plant growth (Salisbury and Ross, 1992). Nutrients like Ca and O_2 are naturally sourced from the atmosphere (Trejo-Téllez and Gómez-Merino, 2012). Nutrient solutions are meticulously prepared by dissolving inorganic salts in water, with the resulting ions absorbed by the crop plant root system (Table 2). Monitoring nutrient levels is essential, ideally conducted around 6:00-8:00 am, as water and nutrient requirements fluctuate daily based on crop type and plant age. Application of the nutrient solution directly to the plant roots is recommended to avoid leaf scorching. Regular drainage and replacement of 20-50% of the nutrient solution in hydroponic culture mitigate the risk of toxic ion accumulation (Sardare & Admane, 2013).

Table 2. Commonly used acids and fertilizers in soilless culture (Trejo-Téllez and Gómez-Merino, 2012; Jain et al., 2019).

Fertilizers	Nutrient (%)	Solubility gL^{-1} (20 ºC)
Magnesium Sulphate ($MgSO_4.7H_2O$)	Mg:10; S:13	111
Monopotassium Phosphate (KH_2PO_4)	P:23; K:28	226
Ammonium Nitrate (NH_4NO_3)	N:35	1920
Monoammonium Phosphate ($NH_4H_2PO_4$)	N:12; P:60	226
Potassium Nitrate (KNO_3)	N: 3; K:38	316
Magnesium Nitrate ($Mg(NO_3)2.6H_2O$)	N:11; Mg:9	760
Ammonium Sulphate ($(NH_4)2SO_4$)	N:21; S:24	754
Potassium Chloride (KCl)	K:60; Cl:48	330
Potassium Sulphate (K_2SO_4)	K:45; S:18	365
Calcium Nitrate ($Ca(NO_3)_2.5H_2O$)	N:15.5; Ca:19	1290

Advantages of Hydroponics Vegetable Production

The advantages of hydroponic farming over traditional methods are extensive and varied, as illustrated in Table 3. Plants grow more quickly and develop smaller root systems when nutrients are delivered directly to the roots; this enables denser planting (Kumar et al., 2012). These systems provide good substitutes by providing better yield per acre, enhanced fertilizer control, better plant density, and improved quality of output (Sardare et al., 2013). It is more suitable, particularly in those areas where arable land is limited.

Hydroponic agriculture produces significantly higher crop growth and yield compared to soil-based farming as it controls nutrients precisely, water, and conditions of the surroundings (Kannan et al., 2022). It is particularly beneficial to increase crop production on a small piece of land. Hydroponic cultivation is the most suitable choice in arid areas as it could save around 90% water used compared to orthodox methods (Michelon et al., 2020). Water resources conservation importance is further emphasized by using recycled water in hydroponic culture, which decreases freshwater needs. Contrasting conventional farming, farms of hydroponic are not affected by the seasons and crops may be produced around the year under controlled conditions (Mitchell, 2022). Due to the shrinkage of fertile soil more sustainable ways to grow vegetables are being encouraged, which reduces the transmission of pests and disease incidence from soil and decreases pesticide use (National Research Council, 1996; Kumar & Akhtar, 2018). Additionally, vegetables grown hydroponically commonly have more shelf life and higher nutrient contents, which reduces wastage and rotting (Manzocco et al., 2011; Aires, 2018).

Table 3. Soilless culture advantages over conventional farming.

Soilless Agriculture	Conventional Agriculture
There are several places where crops can be grown, including contaminated or desolate ground.	Crops that are planted in barren or polluted lands are affected
Vegetable grown are resistant to the effects of salt.	Soil salinity adversely affects vegetable crops
Soilless farming enables the biofortification of crops with nutrients	Achieving this goal can be challenging but feasible through biotechnological approaches
Disease and pest incidence is reduced	Disease and pest incidence attacks are more
In soilless farming, labor-intensive tasks are minimized	It is labor-intensive
Automated monitoring through a computer system is feasible in soilless farming.	Not possible in conventional farming.
Soilless farming requires only 1/10th of the water needed in conventional farming	More water is required
The nutrient solution contains only 25% of the essential elements required	There is a higher wastage of fertilizer in soil-based farming
Required less space for cultivation	Required more space for cultivation
Plant growth is accelerated and results in larger plants	Plant growth is influenced by climatic factors
The yield per unit area is higher	Lower yield

Polycarpou et al. (2005) state that Hydroponic technology is more suitable for areas having harsh climatic conditions because it decreases the use of pesticides, eases constraints of the environment and rationalizes methods of production. Commercial hydroponic culture decreases the requirement for pesticides, simplifies maintenance, and boosts yield through the automation of agricultural processes by streamlining labor (Jovicich et al., 2004). Furthermore, compared to conventional farming, hydroponic farming generates more produce per unit area and requires less weed and pest management (Sharma et al., 2018). With less space, nutrient, and water requirements and regular nutrient and water availability for plant roots, hydroponic greenhouse systems present an effective way to cultivate high-nutrient crops (Jones, 2012; Muhd, 2023). In hydroponic greenhouse systems, plants endure less stress because they have easy access to nutrients and water, which further optimizes growth and productivity (Sorenson & Relf, 2009; Khan et al., 2018).

Disadvantages of Hydroponics

Hydroponic vegetable cultivation has many advantages, but it also has some drawbacks and difficulties. A hydroponic system may require more initial setup costs than traditional soil-based farming. Hydroponic systems also require frequent maintenance and a thorough understanding of plant nutrition in order to operate at their best. Electricity-dependent pumps and environmental control systems could be problematic, especially in places with unstable power sources. Since diseases like powdery mildew and root rot can affect hydroponic crops, it's imperative to employ efficient disease management techniques to keep the plants healthy and productive. Commercial hydroponic culture growth needs a higher initial investment along with technical knowledge. Since the shared solution of fertilizer in the hydroponics culture, infections caused by waterborne spread rapidly among the plants.

Lower O_2 levels and higher temperatures cause crop growth reduction and ultimately decrease yield. For ideal plant growth, various factors like the pH of a solution, its EC, and balanced nutrient contents must be maintained. Furthermore, to run the system more effectively, an adequate supply of energy and lighting is also required. Despite popular growth, hydroponics system has many disadvantages, viz., few crops can accumulate a higher quantity of nitrate-N (NO_3-N) from the system (Guo et al., 2019). The hydroponic system must support around 40 plants, such as tomatoes, and 72 small plants like strawberries and spinach, etc. (Tyson et al., 2004).

To maximize hydroponic production under greenhouse conditions various parameters, viz., temperature, intensity of light, humidity, and CO_2 concentration should be checked regularly. To check and control these parameters the most useful method is the use of systems like temperature control on Arduino based (Hochmuth & Hochmuth, 2021). During the installation of these systems, the factors that need to be considered are availability, transportation costs, effectiveness, and initial expenditure (Taig, 2012). For commercial hydroponic culture, an Arduino-based control system costs around US$500-US$2000 (Takakura and Hashimoto, 2014; Khan et al., 2018; Manju et al., 2020).

Future Trends and Innovations in Hydroponics

Urbanization and rapid population growth laid pressure on productive and arable lands which led to soilless farming quickly (Singh et al., 2017). The most suitable production methods that can be used to resolve this issue are hydroponics, aquaponics, and aeroponics. For example, by using hydroponics Israel has grown a range of crops effectively, necessitating very limited water (Sabir & Singh, 2013). Businesses like as Israel-based OrganiTech have shown impressive results in cultivating vegetables and other products like bananas, oranges, and berries into ordinary shipping containers that are 12.19 m (40 feet) in length. According to Jain et al. (2019), this novel approach produces 1000 times more produce than traditional techniques. Additionally, the containers' mobility allows for flexible deployment across the nation. Effective soilless farming holds promise for mitigating food scarcity in areas with limited land and water resources, mainly in Asia and Africa. For instance, Tokyo's expanding population has made hydroponic rice farming more common there (De Kreij et al., 2003). Since rice is grown in regulated underground structures, this technology, as opposed to traditional ones, enables for up to four harvest cycles annually (Van Os et al., 2002).

Hydroponic farming is expected to have increasingly more importance, especially in space initiatives. Organizations like NASA are conducting extensive studies on space exploration and longstanding colonization projects on the Moon (Van Os et al., 2002). As soil is not available in these worlds and cannot be transported by space shuttles, soilless farming techniques offer a viable alternative for growing plants, including fruits, vegetables, and herbs, in interplanetary dwellings. When given access to bio-regenerative support systems, plants can assist sustain life on space stations and other celestial bodies by collecting CO_2 and producing O_2 through photosynthesis (Barman et al., 2016).

Automation and sensor technologies are receiving more attention as a means of enhancing soilless farming through precise nutrient delivery, environmental control, and monitoring. Additionally, the incorporation of renewable energy sources into hydroponic systems enhances sustainability by reducing reliance on conventional power sources. In order to enhance the efficiency and scalability of soilless agriculture in urban areas with spatial constraints, research is also being conducted on stacked hydroponic systems.

CONCLUSION

It is estimated that the population will be around 9.5 billion on the earth in the next 40 years, meaning that food production will need to double. However, there will probably be less land available for agriculture. As a global answer to this issue, hydroponic farming using soilless cultivation is gaining popularity. One of the numerous advantages of this technology is its ability to yield a large quantity of high-quality vegetables in a small space with minimal labor. By promoting farming entrepreneurship, hydroponics has the potential to help destitute and landless communities while simultaneously promoting economic prosperity. The hydroponics sector is expected to grow significantly, but low-cost technologies and government support are required to sustain commercial hydroponic farms. Notwithstanding obstacles, recent developments have increased the economic viability and commercial applicability of hydroponic systems. The growing worldwide need for food can potentially be met by hydroponics, a sustainable and effective approach, with sustained technological innovation and study.

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