Journal of Scientific Agriculture 2025, 9: 177-188
doi: 10.25081/jsa.2025.v9.9662
https://updatepublishing.com/journal/index.php/jsa

Review Article

ISSN: 2184-0261

Current trends and future directions of hydroponics in urban agriculture: A competent technology for food production and wastewater management

Shardesh Kumar Chaurasia[1]*, Navdeep Sharma[2]

[1]Eastern Youth Empirical Society, Gorakhpur-273001, Uttar Pradesh, India, Present address: Patanjali Research Foundation, Haridwar-249405, Uttarakhand, India, [2]Central University of Punjab, VPO-Ghudda, Bathinda-151401, Punjab, India

Received: July 24, 2025
Revised: August 27, 2025
Accepted: August 29, 2025
Published: September 12, 2025

***Corresponding Author:**
Shardesh Kumar Chaurasia
E-mail: shaardesh@hotmail.com

ABSTRACT

The surge in the global population foresees a significant increase in the demand for food. Due to the scarcity of arable land and water resources crucial for agriculture, there is a shortfall in food production, posing a daunting challenge, nonetheless. Specific technological advancements in agriculture must be integrated to mitigate this pressing issue. These technologies aim to conserve or recycle water, positively influencing food production and accessibility. One such technology is hydroponics, which operates without soil and minimizes water consumption. It efficiently uses horizontal and vertical space, demonstrating the potential to generate higher yields than traditional farming methods. Its global traction stems from its ability to optimize resource management, facilitate year-round crop cultivation, and reduce susceptibility to pest infestations. In addition, hydroponics gains a notable edge over conventional farming techniques by offering the capability for real-time monitoring of environmental variables. Alleviating the strain on agricultural resources and bolstering food security on a global scale is a promise that the adoption of hydroponics holds, as a result.

KEYWORDS: Hydroponics, Horizontal and Vertical farming, Wastewater, Real-time monitoring

INTRODUCTION

In the coming years, there is the potential for a pivotal juncture in human history to be marked. To meet the escalating demand for food, a nearly 70% increase in global output from 2007 levels is required, as the United Nations' Food and Agriculture Organization (FAO) projected, with the global population reaching 9 billion. As urbanization accelerates, an estimated three-quarters of the global population is expected to inhabit urban areas by 2050. Despite urban areas encompassing just 3% of the Earth's landmass, they are home to 56% of the population and account for 60%-80% of high energy consumption and 75% of carbon emissions (FAO, 2018; United Nations, 2018; World Bank Group, 2018).

According to a report by the United Nations (United Nations, 2018), the global urban population is expected to increase by 2.5 billion people by 2050. This surge in urbanization is mainly due to natural population growth, rural-to-urban migration, and reclassification dynamics. However, this trend poses significant challenges for the agricultural sector, as it increases competition for essential resources like soil, water, and labor (United Nations, 2019).

Now that agriculture is entrusted with the critical responsibility of preserving habitats, protecting endangered species, and maintaining biodiversity, it puts considerable pressure on the industry as the backbone of the food supply chain. Despite the extensive utilization of open-field agriculture globally, numerous acres have become unsuitable for farming due to climate change, water scarcity, and soil degradation caused by chemical pesticides and fertilizers, as stated by Aquino (2014). As a result of rising food demand in tandem with population increase, agriculture must make significant and drastic shifts toward efficiency and sustainability, employing technology not only for the sake of innovation but to better satisfy consumers' actual requirements. In fertile places where agricultural land and sources of water are limited, technology like hydroponics is being employed to meet the demand for affordable, nutritious, and sustainable food. According to the estimate, the Europe and Asia-Pacific regions will use hydroponic techniques to produce a high yield of tomatoes by 2030 (Grand View Research, 2024). Hydroponics is more productive than traditional farming because it uses both horizontal and vertical space. This increases the number of plants per unit area, making it a popular choice for vertical farming. This approach addresses the need for fresh and nutritious produce in densely populated areas. Moreover, hydroponics facilitates year-round cultivation of multiple crops with minimal reliance on pesticides and fertilizers, as well as reduced land and water usage compared to conventional open-field agriculture. It accomplishes this by utilizing smart greenhouses equipped with various technologies that regulate essential factors for optimal plant growth and development (Van Delden *et al.*, 2021).

Hydroponics emerges as a promising solution to address these challenges, particularly in regions with limited arable land and water resources. By employing hydroponic techniques, which optimize space and resource utilization, agriculture can boost yields while minimizing environmental impact. Moreover, hydroponics offers the potential to mitigate wastewater pollution by efficiently treating domestic and industrial effluents, thereby conserving freshwater resources and enhancing agricultural sustainability (Cifuentes-Torres *et al.*, 2021).

This review comprehensively explores the principles, methodologies, and applications of hydroponics, delving into its historical evolution, operational techniques, and environmental benefits. It analyzes the advantages and limitations of hydroponic systems, discusses various substrate options, and offers insights into optimal crop selection, environmental monitoring, and wastewater treatment strategies. By synthesizing essential knowledge and insights, this review aims to provide a foundational resource for establishing and optimizing robust hydroponic systems poised to meet the challenges of modern agriculture.

HISTORY OF HYDROPONICS

Hydroponics traces its origins back to ancient Egypt and was practiced by civilizations such as the Babylonians and the Mexican Aztecs. The Xochimilco region in Mexico City stands as a testament to the potential of urban agriculture and has gained recognition as a UNESCO World Heritage Site.

In 1600, Jean Baptiste Van Helmont conducted experimental research demonstrating that plants can absorb nutrients from water. Nearly a century later, British Scientist John Woodward furthered this understanding by cultivating plants in aqueous mediums and confirming the importance of fertilizers for optimal growth. Additionally, in 1800, French scientists De Saussure and Boussingault validated the necessity of carbon, hydrogen, oxygen, and nitrogen for plant growth. Building upon this knowledge, Sachs and Knop of Germany in 1860 expanded the French scientists' work by introducing salts of phosphorus, calcium, and magnesium to the nutrient mix, furthering plant cultivation in aqueous solutions (Velazquez-Gonzalez *et al.*, 2022).

The term "*hydroponics*," derived from the Greek words "*hydro*" (water) and "*ponos*" (labor), was first coined by Californian Professor Dr. Gericke in 1929. Dr. Gericke transformed laboratory experimentation into a commercial enterprise for plant cultivation. During World War II, the United States Army used aquaponics to grow produce for troops stationed on remote Pacific islands. By the 1950s, hydroponic agriculture had become viable on commercial scales across Africa, America, Asia, and Europe. Its popularity soared in 1990 with its utilization in space programs, plant growth in extreme environments, vertical farming, and large-scale manufacturing (Khan *et al.*, 2021).

In 1946, a British scientist established a hydroponics laboratory in the Kalimpong region of West Bengal, India, introducing the technique to the country. He wrote a book titled 'Hydroponics - The Bengal System'. Hydroponics is also known as '*aquaculture*', '*hydroculture*', '*nutriculture*', '*soilless culture*', '*soilless agriculture*', '*tank farming*', or '*chemical culture*' (Pant *et al.*, 2018).

Hydroponics gained further traction in India with the initiation of the "*Pet Bharo Project*" in October 2008 by Lieutenant Commander CV Prakash. Executed by the Institute of Simplified Hydroponics in Australia, the project aimed to provide cost-effective and easily learnable hydroponic production methods to both urban and rural vegetable, fruit, and herb growers in India. Presently, "CV HYDRO," a company, offers materials, consulting services, and training for establishing hydroponic setups.

HYDROPONICS CULTIVATION TECHNIQUES

Hydroponics is a highly efficient farming technique that eliminates the need for soil. Instead, the plants anchored on natural or man-made substrates with roots dipped in specialized nutrient solutions allow them to absorb nutrients. The process of growing food using hydroponics tailors to specific plants, local climate, and budgetary constraints. Hydroponic systems typically feature a nutrient solution storage tank and an aerator (Figure 1). The different types of systems are discussed below.

Nutrient Film Technique (NFT)

In NFT systems, farmers cultivate vegetation within channels known as gullies. A continuous flow of nutrient solutions circulates through these channels, creating a thin film that consistently moistens the plant roots. Direct contact with the nutrient solution enables efficient absorption of nutrients without the need for a timer, as the system regularly replenishes the solution. Dr. Allan Cooper pioneered the Nutrient Film Technique (NFT) at the Glasshouse Crops Research Institute in Little Hampton, England, during the late 1960s, with subsequent refinements made by the same organization (Graves, 1983).

NFT is a particularly suitable method for plants with extensive root systems, with channels typically providing a flow rate of approximately 1 liter per minute (Turner, 2008). The nutrient solution is prepared in a reservoir and circulated through the channels before returning to the reservoir. This method is well-

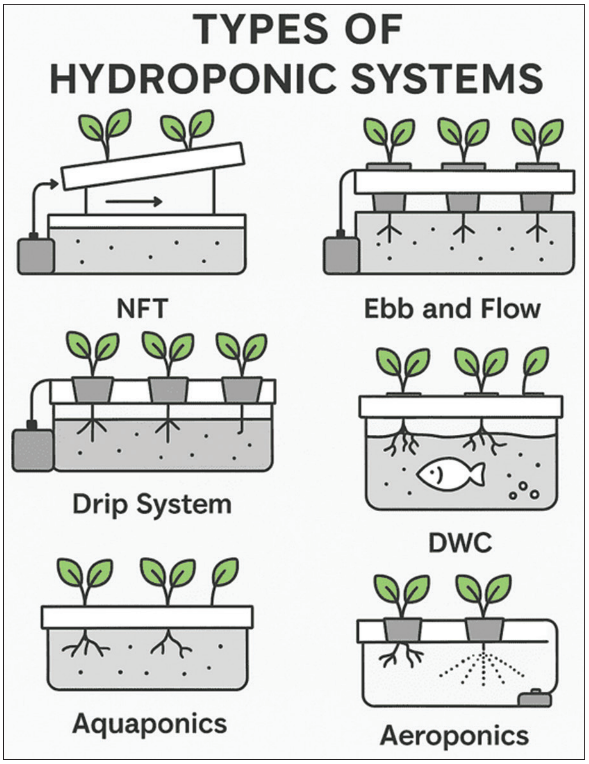

Figure 1: Hydroponics systems

suited for the cultivation of short-cycle crops such as herbs, leafy greens, lettuce, onions, and tomatoes. However, for long-cycle crops like tomatoes and cucumbers, larger channels with increased nutrient flow are necessary. This technique offers farmers the advantage of soil-less cultivation, resulting in cleaner produce that requires no post-harvest washing (Nederhoff & Stanghellini, 2010; Saaid *et al.*, 2013).

Ebb and Flow

This hydroponic system employs a flood and drain method, wherein plants are placed in a tray and periodically supplied with nutrient-rich water from a reservoir positioned underneath, at intervals of 5-10 minutes. Subsequently, gravity drains the water back into the reservoir, allowing for its repeated use through recycling (Dubey & Nain, 2020). Primarily designed for small-scale crop cultivation, this system uses substrates such as perlite, rock wool, or expanded clay pebbles.

Drip Irrigation System

Farmers often use a drip irrigation system for long-term cultivation when growing crops like cucumbers, tomatoes, peppers, and onions in hydroponic facilities. This system uses drip emitters to provide nutrient solutions to the plants, which are timed to operate for around 10 minutes every hour based on the plant's growth stage and the amount of available light. The drip cycle aids in purging the growing medium while delivering a fresh supply of water, nutrients, and oxygen to the plants.

Plants in a drip irrigation system don't need soil, as they obtain all the necessary nutrients from the system. Using a timer, the system distributes a nutrient solution to the base of each plant through drippers in a hydroponic drip irrigation system. There are two types of hydroponic systems: recovery and non-recovery. Recovery systems circulate the nutrient solution back to the reservoir for reuse, whereas non-recovery systems discard it. While recovery systems are more cost-effective because of their efficient use of the nutrient solution, non-recovery systems demand less maintenance since they consistently maintain pH balance and nutrient strength with fresh solution (Chauhan & Sharma, 2017).

The Floating Raft Systems/Deep Water Culture (DWC)

Jensen developed a floating raft technique in 1976 in Arizona involving the use of expanded plastic to cultivate leafy vegetables like lettuce (Jensen & Collins, 1985). This approach has gained popularity in Japan for its effectiveness in large-scale vegetable production. In the Caribbean, farmers have accomplished lettuce cultivation by reducing the temperature of the nutrient solution to impede further lettuce maturation. In this method, the floating raft or mat system, comprised of Styrofoam rafts with perforations floated on nutrient-rich water is used (Sweat *et al.*, 2003).

The dynamic root floating technique (DRFT) works well for shallow-rooted short-season crops like lettuce, basil, and watercress that require high moisture conditions for root growth. The DRFT's primary benefit is its ability to maintain a consistent temperature for nutrient solutions, making it ideal for hydroponic farming in warm regions where oxygen is less soluble (Kao, 1991).

Aquaponics Systems

A highly efficient system can be created by utilizing the interaction between plants and animals. The waste produced by fish provides the necessary nutrients for the plants to grow. A healthy bacterial population is essential for aquaponics. Microbes speed up the nitrification and denitrification processes, enabling plants to absorb nutrients and reuse fish tank water. Consequently, a balanced micro-ecosystem is created (Ezzahoui *et al.*, 2021).

Aeroponics systems

Aeroponics represents a significant advancement in hydroponics, wherein plant roots are suspended in the air and nourished through periodic misting with water and nutrients. A pump, regulated by a timer, intermittently sprays the nutrient solution, ensuring consistent moisture for optimal root growth. Continuous operation of the pump is essential to provide the necessary moisture to the roots without interruption. This cultivation method is particularly well-suited for leafy vegetables such as lettuce and spinach. Two prominent techniques employed are the Root Mist Technique (RMT) and the Fog Feed Technique (FFT) (Alimuddin *et al.*, 2018).

NASA has paid particular attention to aeroponics methods because, in a zero-gravity situation, a mist is simpler to control than a liquid (Cooper, 1976). In 1983, GTI produced and sold the first commercially viable aeroponics device named "Genesis Machine" and the "Genesis rooting system" label was used to promote it. Even though it is an uncommon method of production, it is a unique way to grow (Chen *et al.*, 2015).

OPPORTUNITIES AND CHALLENGES USING A HYDROPONIC SYSTEM

Hydroponics is a promising way to grow food, but it is not a complete solution. However, the technique is independent of area and location and provides higher yields with high-quality produce. The system and the environmental conditions can be automatically controlled using sensors for better monitoring and execution. Though the technique is quite simple as compared to traditional farming still has some flaws like high cost, requiring extensive expertise, and proper disposal of a nutrient solution that can be responsible for excessive growth of algae and microorganisms. It's important to review both the opportunities and challenges of hydroponics to find ways to improve it with technology (Velazquez-Gonzalez *et al.*, 2022).

Substrates for Hydroponics

A substrate serves as a support for plants and provides a sterile environment with a good oxygen supply and nutrient flow to promote healthy growth. The growing mediums that are commonly used in hydroponics are

Coconut coir (coconut fiber)

Coconut coir is an exceptional organic medium that possesses a remarkable oxygen and water-holding capacity. It has a low density of 60 kg/m^3 and a pH range of 5-8, making it a top-grade medium that has been categorized based on its salt concentration. Before using coir, it is imperative to leach out its salt concentration. Besides, coir is an inert substance that has zero influence on the composition of the nutrient solution (Savvas & Gruda, 2018).

Sphagnum peat moss

Sphagnum moss is a natural material that is commonly used as a substrate in hydroponics. It features long strands of sponge-like material that have excellent properties for holding water and promoting aeration. Furthermore, it helps to prevent the leaching of nutrients from the solution. However, one major drawback of using moss is that it can be somewhat costly and has a tendency to decompose over time, which may lead to blockages in the system (Othman *et al.*, 2019).

Perlite

Perlite can be used multiple times and can be reused in the system as an insulator. It is extremely porous, allowing the roots to receive the necessary aeration. Moreover, perlite is biologically inert, has a low density of 90 kg/m^3, and has a neutral pH value. However, the only drawbacks of perlite are its high cost and low water-holding capacity, which is crucial for hydroponics (Vinci & Rapa, 2019).

Pumice

Pumice is a low-density, chemically inert substance that is cost-effective and readily available. Its water retention and aeration properties make it an ideal substrate for summer gardening, as it does not absorb heat (Gizas & Savvas, 2007).

Rockwool

Rockwool cubes are the first choice for commercial hydroponic gardeners. It is easy to use and is of low density (80 kg/m^3). Rockwool is inert and sterile from pathogens. It does not impart any changes while in contact with the nutrient solution. When reused, it only negatively affects human health (Gruda, 2019; Othman *et al.*, 2019).

Sand

Sand is incredibly affordable and easily accessible, making it one of the earliest hydroponic substrates ever discovered. However, because of its insufficient ability to hold water and high density (1500 kg/m^3), it is no longer commonly used. Coarser-grade sand is preferred for hydroponic use since finer-grade sand tends to compress, reducing the amount of air available to the roots. To increase the water-holding capacity and lighten the material, coarser-grade sand can also be combined with other materials (Olle *et al.*, 2012).

Vermiculite

Vermiculite is a highly efficient material that can be used similarly to perlite. It boasts a greater water retention capability than perlite and can extract water and nutrients. It can be combined with other materials to create specialized media for specific hydroponic requirements. Because of their low density (80 kg/m^3), perlite and vermiculite are highly recommended for seedlings and cuttings in their initial stages (Malik *et al.*, 2014).

Adequate considerations should be made before selecting a substrate, including porosity, providing anchorage and aeration to roots, being non-reactive with nutrient solution, and being biologically inert to avoid the spread of diseases through roots.

Some researchers prioritize the economic, social, and environmental sustainability of substrates as much as their chemical, biological, or physiological properties. Using environmentally friendly materials like organic waste and renewable resources should take precedence over traditional options such as peat and rock wool (Gruda, 2019). Along these lines, Rogers (2017) identified compost as a viable alternative substrate, while Vinci and Rapa (2019) conducted a life cycle impact assessment (LCIA) and life cycle cost (LCC) analysis of various substrates, including bark, coconut fiber, peat, perlite, rock wool, sand, and vermiculite. They aimed to assess the social and economic implications of production, alongside analyzing the carbon footprint to gauge environmental impact (Rogers, 2017; Vinci & Rapa, 2019).

COMPONENTS FOR ESTABLISHING A HYDROPONIC SYSTEM

As mentioned above, there are different types of hydroponic systems available according to setup, location, and depending on the characteristics and nature of the crop. But every system has some basic requirements, such as shallow plastic, fiberglass, or any other natural inert material of suitable size and depth for growing plants, a solution storage tank of required capacity (industrial scale, small scale, or experimental purposes, etc.) and a water pump for the nutrient solution circulation throughout the system with a timer and an aerator to maintain the oxygen level in the solution. It is quite necessary to align the trays to maintain a smooth flow of nutrient solution to avoid oxygen deficiency, a major cause of root damage. The growing trays must be covered with a certain material that provides proper humidity to young plants and allows their roots and nutrient solution to be in the dark. This also prevents algae growth and nutrient uptake in the absence of sunlight. All vents and channels are covered properly to prevent dirt and contamination of the nutrient solution (Pant *et al.*, 2018).

Nutrient Solution

Apart from iron, which is administered in chelated form to enhance its uptake, the nutritional solution is comprised solely of readily soluble inorganic salts. Additionally, specific inorganic acids are incorporated as required for crop cultivation. Among the water-soluble nutrients employed in hydroponics are ammonium nitrate (NH_4NO_3), calcium nitrate ($5[Ca(NO_3)_2{\cdot}2H_2O]\ NH_4NO_3$), phosphoric acid ($H_3PO_4$), nitric acid ($HNO_3$), and others. In-depth research on plant nutrition in hydroponics shows the nutrients involved have been divided into macro, trace, or micronutrients, and a common list of the provider fertilizers is shown in Table 1.

pH and Electrical Conductivity of Hydroponic Nutrient Solutions

Monitoring and adjusting the EC and pH levels of the nutrient solution is essential for achieving optimal plant growth, particularly in soilless agriculture, where maintaining a pH range of 5.5 to 6.5 is ideal. Accurate readings from EC and pH sensors are indispensable for ensuring plant health and productivity (Pant *et al.*, 2018). When the pH deviates towards the basic side, the solubility of Fe and H_2PO_4 decreases, resulting in the formation of Ca and Mg precipitates, hindering the absorption of iron, boron, copper, zinc, or manganese. Conversely, when pH drops below 5, it prevents adsorption of nitrogen, phosphorus, potassium, calcium, magnesium, and molybdenum (Figure 2). Table 2 illustrates the optimal pH ranges for various popular vegetables. Occasionally, hazardous contamination may arise from the supply of certain micronutrients such as manganese (Bosques, 2010).

The EC (dS m^{-1}) value, determined by total ion concentration, is crucial, with accuracy influenced by temperature, measured using EC meters. For high-quality crops, the EC range should ideally be between 1.8-2.4 dS m^{-1}. Low EC values signify nutrient deficiency, while high values may induce salt stress in plants (Kozai, 2018). Organic substrates exhibit higher EC values than inorganic ones, with peat displaying significantly higher EC (1.06 dS m^{-1}) compared to peat moss (1.065 dS m^{-1}) (Abad *et al.*, 2002).

Table 1: List of major and micronutrients required in nutrient solution along with the common fertilizers used

Elements	Ionic form	Role in Plant	Range of concentration (ppm or mgL^{-1})	Common fertilizers
Macronutrients				
Nitrogen (N)	NO_3^- , NH_4^+	Chlorophyll, amino acid, and protein synthesis	100-200	Calcium nitrate - $Ca(NO_3)_2$ Potassium nitrate - KNO_3
Phosphorus (P)	$H_2PO_4^-$	Photosynthesis and growth	30-15	Monopotassium Phosphate - KH_2PO_4
Potassium (K)	K^+	Enzyme activity	100-200	Monopotassium Phosphate - KH_2PO_4 Potassium nitrate - KNO_3 Potassium sulphate - K_2SO_4 Potassium chloride - KCl
Calcium (Ca)	Ca_2^+	Cell growth	200-300	Calcium nitrate -$Ca(NO_3)_2$
Magnesium (Mg)	Mg_2^+	Enzyme activation	30-80	Magnesium sulfate - $MgSO_4.xH_20$
Sulfur (S)	SO_4	Formation of amino acids and proteins	70-150	Potassium sulfate - K_2SO_4 Magnesium sulfate - $MgSO_4.xH_20$
Micronutrients				
Boron (B)	BO_3^-	Vital for reproduction	0.03	Boric acid - H_3BO_3
Chlorine	Cl^-	Important for growth and metabolism	-	Not added through fertilizers Potassium chloride - KCl
Copper (Cu)	Cu^{2+}	Enzyme activation	0.01-0.10	Copper sulfate, Cupric nitrate $CuSO_4$, $Cu(NO_3)_2$
Iron (Fe)	Fe^{2+}, Fe^{3+}	Used in photosynthesis	2-12	Chelated Iron (Fe EDTA)
Manganese (Mn)	Mn^{2+}	Components of chlorophyll	0.5-2.0	Manganese Sulphate - $MnSO_4.4\ H_20$
Molybdenum (Mo)	MO^{2-}	Nitrogen fixation	0.5	Sodiun molybdate - Na_2MoO_4
Zinc (Zn)	Zn^{2+}	Components of Enzymes	0.5-0.50	Not often added through fertilizers

Table 2: Electric conductivity and pH for some popular crops

Crops	pH	EC (mS/cm)
Cucumber	5.0-5.5	1.7-2.0
Basil	5.5-6.0	1.0-1.6
Ficus		1.6-2.4
Peppers		0.8-1.8
Rhubarb		1.6-2.0
Rose		1.5-2.5
Banana	5.5-6.5	1.8-2.2
Sage		1.0-1.6
Bean	6.0	2.0-4.0
Carnation		2.0-3.5
Courgettes		1.8-2.4
Eggplant		2.5-3.5
Marrow		1.8-2.4
Strawberry		1.8-2.2
Parsley	6.0-6.5	1.8-2.2
Tomato		2.0-4.0
Asparagus	6.0-6.8	1.4-1.8
Broccoli		2.8-3.5
African violet	6.0-7.0	1.2-1.5
Lettuce		1.2-1.8
Spinach		1.8-2.3
Cabbage	6.5-7.0	2.5-3.0
Leek		1.4-1.8
Celery	6.5	1.8-2.4
Okra		2.0-2.4
Pak Choi	7.0	1.5-2.0

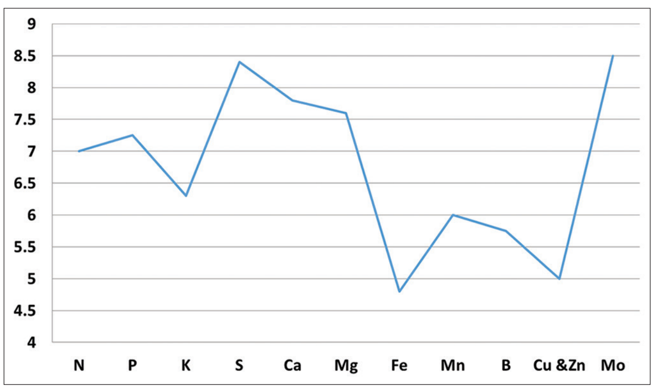

Figure 2: Effect of pH on the availability of nutrients

Tomato plants face severe water uptake constraints at EC levels exceeding 4-6 dS m^{-1} (Cuartero & Fernandez-Munoz, 1998). Rockwool-grown tomatoes exhibit notable effects on root growth and yield at an EC of around 3.5 dS m^{-1}. Refer to Table 2 for the specific EC and pH ranges recommended for various popular crops (Singh & Dunn, 2016).

Sterilization of Nutrient Solutions

Recirculating the nutrient solution enhances sustainability by reducing water consumption and minimizing waste generation. However, implementing systems that effectively manage natural resources, energy, and financial costs isn't always practical. Considering both advantages and limitations, incorporating a blend of methods outlined in Table 3 to prevent infections in hydroponic solutions could offer a more comprehensive solution to fertilizer solution sepsis (Velazquez-Gonzalez *et al.*, 2022).

Control of Contaminants

Hydroponic systems require an aseptic environment to grow effectively and generate. Additionally, various parasitic species, such as *Pythium* and *Phytophthora*, pose threats to the plant's roots. Manifestations of plant damage typically include leaf withering induced by *Fusarium* and *Verticillium* fungi. *Cladosporium* leaf mold, leaf miners, nematodes, pinworms, viruses, and whiteflies have all been reported in hydroponic setups. Unfortunately, the use of fungicides in hydroponics without compromising consumer health remains unfeasible (Savvas & Passam, 2002). Methylation, although effective against *Pythium*, lacks approval for usage. Implementing heat at 20-22 °C to the nutrient solutions effectively prevents pathogenic infections in the root zone (Raviv *et al.*, 1998). In a study by Sardare and Admane (2013), ginger plants cultivated in an aeroponic system with heated nutrient solutions exhibited accelerated maturation and slightly higher yields of fresh rhizomes compared to those grown under similar conditions without bottom heat.

Ideal Crops for Hydroponics

Many fruits and vegetables can be grown hydroponically, but they must adhere to certain requirements, such as root size, fruit size, and harvesting cycle. Table 4 shows the crops suitable for hydroponics (Aquino, 2014).

Real-time Monitoring and Control of Environmental Factors

The plants are very much dependent on temperature, humidity, moisture, and light for their growth, quality, and productivity. Temperature controls and affects developmental processes, such as respiration, flowering, and transpiration. The reduction in transpiration rate correlates directly with the humidity concentration in the surrounding environment, indicating that humidity plays a significant role in regulating moisture loss (Siddaq *et al.*, 2019). Moisture is one of the crucial factors by which plants get nutrients through roots and lose water through transpiration processes. Moreover, plants produce glucose by photosynthesis, and the energy required for the process is directly absorbed by the sun (Filipović, 2020). The selective utilization of the nutrients because of plant growth and the evapotranspiration process leads to the alteration in the nutrient concentration and accumulation of unwanted counter ions (i.e., Na^+, Cl^-). This change may alter the EC, qualitative, and quantitative composition of the solution, drastically affecting the crop yield and quality. It is crucial to tune the nutrient solutions promptly to ensure satisfactory production. One potential method for monitoring hydroponic solutions online is by utilizing ion-selective electrodes (ISEs) (Sambo *et al.*, 2019). Continuous exposure to nutrient solutions without proper calibration procedures can lead to potential problems with signal drift and reduced sensitivity over time when using ISEs as online monitoring systems (Kim *et al.*, 2013). Automated tunnel hydroponics, an automated system, was introduced to overcome the problems that occur with manual control. To create a controlled environment for

Table 3: Nutrient solution sterilization techniques with pros and cons

Technique/Type	Pros	Cons
Filtration		
Sand	Economical and flexible	High space requirements, Pathogen-dependent effectiveness
Membrane	Highly efficient	Choking and leakage, High cost and maintenance.
Heat treatment		
Pasteurization	Extremely effective, No coagulation.	High capital and maintenance costs.
Radiation		
Ultraviolet Rays	Highly potent (without turbidity), Less space needed	Very little impact in turbid solution.
Chemical treatment		
O_3 (Ozone)	Effective	Highly expansive, not completely inert
H_2O_2 (Hydrogen peroxide)	Efficient in cleaning water systems	Affects the roots severely when the dose is>0.05%, Temperature and pH-dependent, Formation of harmful residues on interaction with the nutrient solution

Table 4: List of ideal crops for hydroponics

Type	Scientific & Common Name	Cultivation Techniques		
		Drip irrigation	NFT	DWC
Bulb vegetables	*Allium cepa* (Onion)	✓	✓	×
	Allium porrum (Pore)	✓	✓	×
	Allium sativum (Garlic)	✓	×	×
Fruit crops	*Capsicum annuum* (Chile)	✓	×	×
	Citrullus vulgaris (Watermelon)	✓	×	×
	Cucumis melo (Cantaloupe)	✓	✓	×
	Cucumis sativus (Cucumber)	✓	✓	×
	Cucurbita pepo (Zucchini)	✓	✓	×
	Phaseolus vulgaris (Green bean)	✓	×	×
	Physalis ixocarpa (Tomatillo)	✓	✓	×
	Sechium edule (Squash)	✓	×	×
	Solanum licopersicum (Tomato)	✓	✓	×
	Solanum melongena (Eggplant)	✓	×	×
Inflorescent vegetables	*Brassica oleracea* var. Botrytis (Cauliflower)	✓	✓	×
	Brassica oleracea var. Italica (Broccoli)	✓	✓	×
	Chenopodium sp. (Huauzontle)	×	✓	✓
	Cynara scolymus (Artichoke)	✓	×	×
Leafy greens	*Apium graveolens* (Celery)	×	✓	✓
	Beta vulgaris var. cicla (Chard)	×	✓	✓
	Brassica nigra (Mustard)	×	✓	✓
	Brassica oleracea var. *capitata* (Cabbage)	×	✓	✓
	Brassica oleracea var. *gemmifera* (Brussels sprouts)	×	✓	✓
	Coriandrum sativum (Coriander)	✓	✓	✓
	Lactuca sativa (Lettuce)	×	✓	✓
	Nasturtium officinale (Watercress)	×	✓	✓
	Petroselinum crispum (Parsley)	×	✓	✓
	Portulaca oleracea (Purslane)	×	✓	✓
	Spinacea oleracea (Spinach)	×	✓	✓
Leguminous vegetables	*Pisum sativum* (Pea)	✓	×	×
	Vicia faba (Bean)	✓	×	×
	Zea mays (Sweet Corn)	✓	×	×
Root crops	*Beta vulgaris* (Beetroot)	✓/Aeroponics	×	×
	Brassica rapa (Turnip)	×	✓	×
	Daucus carota (Carrot)	✓/Aeroponics	×	×
	Manihot esculenta (Yucca)	✓	✓	×
	Pachyrrhizus erosus (Jicama)	✓	×	×
	Raphanus sativus (Radish)	✓/Aeroponics	×	×
Stem vegetables	*Asparagus officinalis* (Asparagus)	×	✓	✓
	Brassica oleracea var. gongyloides (Swede)	✓	×	×
Tuber crops	*Ipomoea batatas* (Sweet potato)	✓	×	×
	Solanum tuberosum (Potato)	✓	×	×

the growth of crops, Automatically Controlled Hydroponic Agriculture (ACPHA) regulates environmental parameters such as temperature, humidity, and moisture using sensors located at practical distances and a centralized controller (Siddaq *et al.*, 2019). A block diagram is given below to understand the technique (Figure 3).

A cost-effective, smart IoT-controlled monitoring system has been created for hydroponics, incorporating three distinct types of sensor nodes (Figure 4). The primary node oversees pump control and water quality monitoring, while environment sensing nodes observe the surrounding conditions. Additionally, security nodes track activity within the area. This system vigilantly monitors water quality, greenhouse temperature, and humidity to facilitate crop growth in line with hydroponic standards (Tatas *et al.*, 2022). A digital twin framework is also developed for real-time monitoring of pH, EC, temperature of water and air, light intensity, and humidity, and supports the use of artificial intelligence techniques to determine the growth rate and weight of growing crops. This system is also based on IoT technology. It consists of a centralized control system and a virtual interface that provides feedback control of the system to the users in real-time (Yanes *et al.*, 2022).

Environmental Benefits of Hydroponics

Using recycled wastewater is a critical strategy in mitigating the water shortage prevalent in various regions globally. Employing treated wastewater for agricultural irrigation yields significant benefits for both the economy and the environment. Alternative options for providing essential nutrients to support the cultivation of crops in soil-based or hydroponic setups encompass domestic and industrial wastewater. Reusing wastewater for irrigation in hydroponic systems prevents soil salinization, groundwater pollution, and surface water contamination. This choice also permits the growth of plants that produce vegetables and fruits and the use of inexpensive water sources while reducing the application of commercial fertilizer.

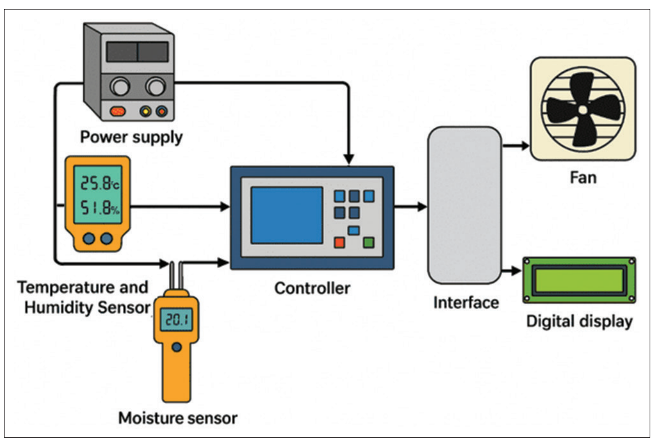

Figure 3: Block diagram

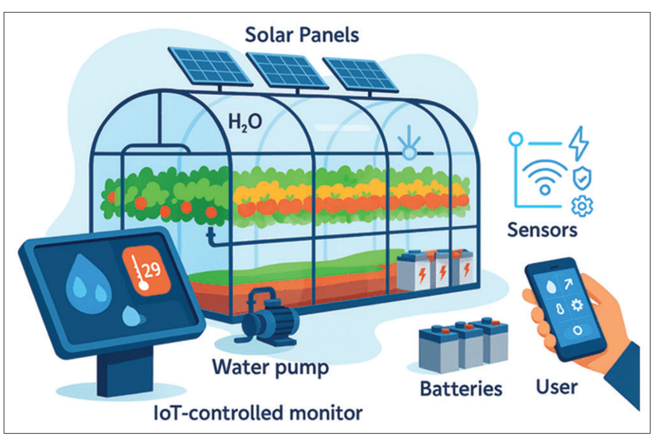

Figure 4: Iponics system concept

Conservation of Water for Irrigation

Hydroponics should be adopted instantly as it saves up to 70 to 90% more water than required and keeps the roots submerged and moist all the time compared to conventional farming. The root avails an unstoppable nutrient supply. The waste nutrient solution can effectively be used to cultivate crops under the system or can be used as a source of nutrients in traditional farming. Salinity, dissolved solids, and pathogens are all frequently occurring elements in groundwater and dam/river water that can impair plant condition and production; however, hydroponics completely avoids this sort of issue. The use of sprinklers, sprayers, and drip irrigation systems also reduces the water requirement. Reusing wastewater can have positive effects on the environment and the economy if the study, planning, and implementation are done sustainably.

Utilization of Septic Wastewater in Hydroponics

Treated wastewater is a boon in agriculture for not only serving as a source of extra water but also providing free nutrients to the crops. Plants play a tremendous role in extracting macro and micronutrients for their growth, evading the accumulation, and the resulting salinization of the soil and toxification of surface and groundwater (Reetika *et al.*, 2024). Two primary applications of wastewater in hydroponics involve the cultivation and maturation of commercially valuable fruit-bearing plants and vegetables, alongside the regulation and biological neutralization of organic materials and nutrients (Rana *et al.*, 2011). In a study conducted by Cui *et al.* (2003), septic tank water was purified through an artificial soil filtration system for the hydroponic cultivation of romaine lettuce and water spinach. The efficiency of both plants varied concerning their capacity to treat wastewater. Romaine lettuce exhibited greater efficacy in reducing biological oxygen demand (BOD) to 82% and total suspended solids (TSS) to 89%, compared to water spinach, which achieved a 43% BOD elimination and 69% TSS reduction. Additionally, romaine lettuce demonstrated significant effectiveness in decreasing chemical oxygen demand (COD) by 37%, total phosphorus (TP) by 48%, and total nitrogen (TN) by 67%. Moreover, using septic wastewater also increases vegetable production with 119.42 g/stem when compared to treated effluent (88.59g/stem) and soil cultivation (81.57 g/stem) (Cui *et al.*, 2003). Moreover, vetiver grass showed its efficiency in the treatment of grey and black water. Research in China proves the removal of soluble nitrogen and phosphorus from wastewater. The total concentration of nitrogen and phosphorus found initially was 100 mg/L and 10 mg/L, respectively, and the treatment with vetiver grass reduced this concentration by 96% and 90%. The coliform bacteria count decreased from ≥1600 organisms/100 mL to 900 organisms/100 mL, marking a reduction of 40%. Similarly, the treatment resulted in a decrease in *E. coli* count from ≥1600 org/100 mL to 140 org/100 mL, reflecting a percentage change of 91% (Truong & Hart, 2001).

Brewery Industry Wastewater in Hydroponics

Typha latifolia was cultivated hydroponically using wastewater from the brewery industry. The plant thrived in this system, exhibiting significant potential for phytoremediation by efficiently removing nutrients. The efficacy of nutrient removal ($p<0.05$) varied, with Total Kjeldahl Nitrogen (TKN) removal ranging between 54-80%, NH_4^+ -N between 42-65%, NO_3^- -N between 47-58%, and PO_4^{3-}-P between 51-70%. The system demonstrated a clearance rate of up to 29% compared to the control, yielding a biomass of 0.61-0.86 kg dry weight (DW) m^{-2}. Nutrient reserves were observed to be as high as 21.17 g N kg^{-1} DW and 2.87 g P kg^{-1} DW (Gebeyehu *et al.*, 2018).

Similarly, in Ethiopia, vetiver grass was grown hydroponically using brewery wastewater, exhibiting significant phytoremediation potential in root systems for contaminant removal. The removal potential for BOD_5 was notable ($p<0.05$), reaching up to 73% (743-1642 mg L^{-1} inlet), and for COD, up to 58% (835-2602 mg L^{-1} inlet). Root systems efficiently removed pollutants in the range of 26-46% for TKN (14-21 mg L^{-1} inlet), 28-46% for NH_4^+-N (13-19 mg L^{-1} inlet), 35-58% for NO_3^- -N (4-11 mg L^{-1} inlet), and 42-63% for PO-34-P (4-8 mg L^{-1} inlet). Nutrient accumulation varied between 7.4 and 8.3 g N kg^{-1} dry weight and 6.4-7.5 g P kg^{-1} dry weight for samples collected from the hydroponics unit (Worku *et al.*, 2018).

Plants employ a range of techniques to acquire essential nutrients, such as phytoextraction, phytotransformation, phytofiltration, and phytodegradation. These methods entail the discharge of exudates from the roots, which can effectively stabilize, immobilize, and bind organic pollutants. As a result, this may decrease biodiversity and promote better water treatment by potentially lowering nutrient discharges through plant uptake (Magwaza *et al.*, 2020).

Achieving complete nutrient and raw matter removal through hydroponics is not feasible, as residual recalcitrant contamination persists in the final effluent of this biological treatment process (Rana *et al.*, 2011). Saxena and Bassi (2013) noted that hydroponic emissions typically contain high levels of nitrates and phosphorus, a finding corroborated by Park *et al.* (2008) regarding nitrate concentrations. So, before application, hydroponic effluents require post-treatment to reduce contaminant levels to meet regulatory standards. Effluent treatment in hydroponics has been explored using denitrification filters with an organic carbon source, constructed wetlands, alkali precipitation, and cultivation systems employing marine algae such as *Dunaliella salina* (UTEX 1644) (Prazeres *et al.*, 2017).

Table 5: List of startups and their specializations

Name	Location	Founding year	Specialty
Brio Hydroponics	Ahmedabad (Gujarat)	2014	NFT, installation, Dutch Bucket Supply, Vertigrow Tower Setup, Indoor Models, Automation, Autodosar, AMC, Polyhouse
Future Farms	Chennai (Tamil Nadu)	2014	Pest-free food, hi-tech nursery
Bit-Mantis innovations	Bengaluru (Karnataka)	2015	IoT and data analytics
Letcetra agritech (indoor farm)	Dongurli (Goa)	2016	AI-powered monitoring and automation, Consultation
Junga Freshgreen	Shimla (Himachal Pradesh)	2017	Automated Hydroponics, Pest-free, Sustainable
Kamala Farms	Bangalore (Karnataka)	2017	Urban Farming, Buyback, Training
Akasrshak Hydroponics	Noida, (Uttar Pradesh)	2017	Indoor Saffron, Microgreens cultivation, Polyhouse Engineering
Urban Kisaan	Hyderabad (Telangana)	2017	Future farming, Advanced Automation, Sustainable, Minimal Carbon Footprint
Evergreen Farms	Bangalore (Karnataka)	2019	Urban Farming, IoT, Aeroponics, Robotics
Nurtifresh (the largest farm in India)	Pune (Maharashtra)	2019	AI precision, hygienic, sustainable, and pest-free
Groflo Hydroponics	Mumbai, (Maharashtra)	2020	Low-cost hydroponic equipment
Rise Hydroponics	Ahmedabad (Gujarat)	2020	Indoor and Outdoor Setup, Polyhouse Structure Development, Live Training Workshops, Project Development
Balcony Crops	Chennai (Tamil Nadu)	2021	Balcony Farming and Kit

Hydroponics and global scenario

The locations where access to soil is restricted or limited, hydroponics is frequently used and becomes relevant globally. The developed countries promoted and adopted the technique well and became the biggest producers worldwide. At present, European nations like France, the Netherlands, and Spain own the greatest market share in the global hydroponics market and are expected to keep leading during the projection period. An important factor driving the growth of the European hydroponics market is the increased use of cutting-edge hydroponics techniques to improve crop yields in terms of both quality and quantity. Because of the rising use of hydroponics in nations like Australia, China, India, and Japan, the hydroponics market in the Asia Pacific is predicted to expand at the quickest rate over the upcoming years (Fortune Business Insights, 2023).

The hydroponics market in the Middle East and Africa is anticipated to rise considerably because of countries like Israel, where considerable strides have been putting soilless farming into practice. They are attempting to cultivate citrus fruits, berries, and other commercial fruits that cannot be grown in dry regions. The system is fully automated and runs by robots like an assembly line in industries (Karne *et al.*, 2023). Australia is a giant in hydroponics lettuce production around the globe and holds first place above the United States in the cultivation of strawberries (Hydroponics Market Size, Industry Share, & Forecast, 2030, 2023). The growing population and to save valuable land forced Japan to adopt hydroponic rice farming to feed its people. North America has significant development potential because of the large number of businesses and the rising usage of alternative farming techniques in urban areas. The hydroponics market in North America is expected to increase at a compound yearly growth rate of 17.3% from its projected value of USD 70.92 million in 2021 to USD 128.63 million in 2027. Pennsylvania, New York, and Michigan are the states with the highest turnover in crop farming. Growth in developing nations from the Middle East, Africa, and South America is hampered by a lack of government incentives and a lack of necessary equipment to build up huge hydroponic farms (Grand View Research, 2021).

Hydroponics, being new in India, is facing some implementation challenges like a lack of awareness and education about these agricultural advancements. High cost is another issue, making it unsuitable for the farmers. However, the government provides subsidies for large-scale projects related to hydroponics (Karne *et al.*, 2023). The technique is growing slowly in India, and people have started investing on a larger scale. Many startups have been using technology to grow fruits and vegetables and deliver them to customers as per their needs. The few startups and their specialties are discussed in Table 5 (Mandal, 2023).

FUTURE SCENARIOS, RECOMMENDATIONS, AND CONCLUSION

Conventional farming cannot fulfill the future demands of food due to the rise in the global population. Urbanization reduces the fertile land for conventional farming, and excessive use of chemicals (Fertilizers and pesticides, etc.) turns the land into barren. The rivers are the primary sources of water for irrigation in developing countries, but unfortunately, the dumping of toxic industrial waste into the rivers and anthropogenic factors make the water polluted with toxins and heavy metals. These circumstances are havoc on traditional farming and irrigation. Therefore, we need to acquire certain techniques that can stimulate plant growth faster and require less amount of water. Thus, hydroponics will be the new generation technique that needs to be adopted, where 80-90% less water is required with year-round cultivation possibilities. To fully harness the potential of hydroponics in the coming years, several key recommendations emerge. Sustainable practices, such as efficient water management and climate-resilient infrastructure, should be at the forefront. Additionally, advancements in genetic engineering to create crops optimized for hydroponic growth, coupled with the integration of cutting-edge technologies like automation and data analytics, will be pivotal. Education and training programs must be established to equip individuals with the necessary skills, while policymakers should consider incentives and quality standards to foster hydroponic adoption. Collaborative research, community engagement, and economic viability initiatives round out the holistic approach needed to shape the promising future of hydroponics.

For the first hardening of plants cultivated using plant tissue culture, hydroponics can be an excellent choice. Plants grown in a laboratory setting must adapt to the natural environment so they can flourish outside. Before the second hardening phase, we can treat those plants to hydroponics in the polyhouse and offer a nurturing environment for growth and adaptation. It would also provide the strengthening of roots and exposure to the environment. It deeply acclimates the plants, and we get a lot more seedlings to multiply, compared to the other ways.

In conclusion, the future of hydroponics holds great promise for sustainable agriculture, efficient resource utilization, and food security. To realize this potential, stakeholders should focus on innovation, education, policy support, and collaboration to promote the widespread adoption of hydroponic farming methods.

ACKNOWLEDGMENT

The authors are humbly grateful to their parents and teachers for their extreme support, guidance, and blessings.

AUTHORS' CONTRIBUTION

N.S. and S.K.C. contributed to the planning and drafting of the work, with S.K.C. also preparing the tables and designing the figures.

REFERENCES

Abad, M., Noguera, P., Puchades, R., Maquieira, A., & Noguera, V. (2002). Physico-chemical and chemical properties of some coconut coir dusts for use as a peat substitute for containerised ornamental plants.

Bioresource Technology, 82(3), 241-245. https://doi.org/10.1016/S0960-8524(01)00189-4

Alimuddin, Subrata, D. M., Nurmayulis, Khastini, R. O., & Arafiyah, R. (2018). Analysis of chilli plant physiology conventional system, greenhouse hydroponic utilization system using fuzzy logic. *IOP Conference Series: Materials Science and Engineering, 434*(1), 012219. https://doi.org/10.1088/1757-899X/434/1/012219

Aquino, M. A. Z. (2014). *Manual de hidroponia* (1st ed.). Universidad Nacional Autónoma de México. Retrieved from https://www.gob.mx/cms/uploads/attachment/file/232367/Manual_de_hidroponia.pdf

Bosques, J. H. (2010). *Curso Basico de Hidroponia*. CA, USA: Lulu.

Chauhan, S., & Sharma, S. (2017). Hydroponic irrigation system- Feasible, suitable and sustainable method. *International Journal of Innovations in Management, Engineering and Science, 5*(3), 20-26.

Chen, R., Liu, H., Song, S., Sun, G., & Chen, R. (2015). Effects of light quality on growth and quality of lettuces in hydroponic. 2015 12th China International Forum on Solid State Lighting (SSLCHINA) (pp. 154-156). IEEE. https://doi.org/10.1109/SSLCHINA.2015.7360712

Cifuentes-Torres, L., Mendoza-Espinosa, L. G., Correa-Reyes, G., & Daesslé, L. W. (2021). Hydroponics with wastewater: A review of trends and opportunities. *Water and Environment Journal, 35*(1), 166-180. https://doi.org/10.1111/wej.12617

Cooper, A. (1976). *Nutrient film technique of growing crops*. London, UK: Grower Books.

Cuartero, J., & Fernández-Muñoz, R. (1998). Tomato and salinity. *Scientia Horticulturae, 78*(1-4), 83-125. https://doi.org/10.1016/S0304-4238(98)00191-5

Cui, L.-H., Luo, S.-M., Zhu, X.-Z., & Liu, Y.-H. (2003). Treatment and utilization of septic tank effluent using vertical-flow constructed wetlands and vegetable hydroponics. *Journal of Environmental Sciences, 15*(1), 75-82.

De Clercq, M., Vats, A., & Biel, A. (2018). *Agriculture 4.0: The future of farming technology*. World Government Summit. Retrieved from https://www.oliverwyman.com/content/dam/oliverwyman/v2/publications/2021/apr/agriculture-4-0-the-future-of-farming-technology.pdf

Dubey, N., & Nain, V. (2020). Hydroponic-The future of farming. *International Journal of Environment, Agriculture and Biotechnology, 5*(4), 857-864. https://doi.org/10.22161/ijeab.54.2

Ezzahoui, I., Abdelouahid, R. A., Taji, K., & Marzak, A. (2021). Hydroponic and aquaponic farming: Comparative study based on Internet of Things (IoT) technologies. *Procedia Computer Science, 191*, 499-504. https://doi.org/10.1016/j.procs.2021.07.064

FAO. (2009). *How to feed the world in 2050*. Paper presented at the High-Level Expert Forum, Rome, Italy. Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

Filipović, A. (2020). Water, plant, and soil relation under stress situations. In R. S. Meena & R. Datta (Eds.), *Soil Moisture Importance* London, UK: IntechOpen Limited. https://doi.org/10.5772/intechopen.93528

Fortune Business Insights. (2023). *Hydroponics Market Size, Industry Share, & Forecast 2030*. Retrieved from https://www.fortunebusinessinsights.com/hydroponics-market-102275

Gebeyehu, A., Shebeshe, N., Kloos, H., & Belay, S. (2018). Suitability of nutrients removal from brewery wastewater using a hydroponic technology with *Typha latifolia*. *BMC Biotechnology, 18*(74), 1-13. https://doi.org/10.1186/s12896-018-0484-4

Gizas, G., & Savvas, D. (2007). Particle size and hydraulic properties of pumice affect growth and yield of greenhouse crops in soilless culture. *HortScience, 42*(5), 1274-1280. https://doi.org/10.21273/HORTSCI.42.5.1274

Grand View Research. (2021). *Hydroponics Market Size & Share Report, 2021-2028*. Retrieved from https://www.grandviewresearch.com/industry-analysis/hydroponicsmarke

Grand View Research. (2024). *Hydroponics Market Size, Share and Growth Report, 2030*. Retrieved from https://www.grandviewresearch.com/industry-analysis/hydroponics-market/request/rs1

Graves, C. J., & Hurd, R. G. (1983). Intermittent solution circulation in the nutrient film technique. *Acta Horticulturae, 133*, 47-52. https://doi.org/10.17660/ActaHortic.1983.133.5

Gruda, N. S. (2019). Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy, 9*(6), 298. https://doi.org/10.3390/agronomy9060298

Jensen, M. H., & Collins, W. L. (1985). Hydroponic vegetable production. In J. Janick (Ed.), *Horticultural Reviews* (Vol. 7, pp. 483-558). Hoboken, New Jersey: Wiley. https://doi.org/10.1002/9781118060735.ch10

Kao, T. C. (1991). *The Dynamic Root Floating Hydroponic Technique: Year-round Production of Vegetables in ROC on Taiwan*. Taipei, Taiwan: Food and Fertilizer Technology Center.

Karne, H., Iyer, V., Joshi, S., Diwan, S., Gole, M., Sunthankar, S., & Phansalkar, S. (2023). Hydroponics: A review of modern growing techniques. *European Chemical Bulletin, 12*(4), 11231-11256. https://doi.org/10.48047/ecb/2023.12.si4.1016

Khan, S., Purohit, A., & Vadsaria, N. (2021) Hydroponics: current and future state of the art in farming. *Journal of Plant Nutrition, 44*(10), 1515-1538. https://doi.org/10.1080/01904167.2020.1860217

Kim, H. J., Kim, W. K., Roh, M. Y., Kang, C. I., Park, J. M., & Sudduth, K. A. (2013). Automated sensing of hydroponic macronutrients using a computer-controlled system with an array of ion-selective electrodes. *Computers and Electronics in Agriculture, 93*, 46-54. https://doi.org/10.1016/j.compag.2013.01.011

Kozai, T. (2018). *Smart plant factory*: *The Next Generation Indoor Vertical Farms.* Singapore: Springer. https://doi.org/10.1007/978-981-13-1065-2

Magwaza, S. T., Magwaza, L. S., Odindo, A. O., & Mditshwa, A. (2020). Hydroponic technology as decentralised system for domestic wastewater treatment and vegetable production in urban agriculture: A review. *Science of the Total Environment, 698*, 134154. https://doi.org/10.1016/j.scitotenv.2019.134154

Malik, A., Iqbal, K., Aziem, S., Mahato, P., & Negi, A. K. (2014). A review on the science of growing crops without soil (soilless culture)- A novel alternative for growing crops. *International Journal of Agriculture and Crop Sciences, 7*(11), 833-842.

Mandal, R. (2023). *Top 10 hydroponics companies in India*. *Times of Agriculture: E-Magazine*. Retrieved from https://timesofagriculture.in/top-hydroponics-companies-in-india

Nederhoff, E. M., & Stanghellini, C. (2010). Water use efficiency of tomatoes-in greenhouses and hydroponics. *Practical Hydroponics & Greenhouses, 115*, 52-59.

Olle, M., Ngouajio, M., & Siomos, A. (2012). Vegetable quality and productivity as influenced by growing medium: A review. *Agriculture, 99*(4), 399-408.

Othman, Y., Bataineh, K., Al-Ajlouni, M., Alsmairat, N., Ayad, J., Shiyab, S., Qarallah, B., & St. Hilaire, R. (2019). Soilless culture: Management of growing substrate, water, nutrient, salinity, microorganism and product quality. *Fresenius Environmental Bulletin, 28*(4), 3249-3260.

Pant, T., Agarwal, A., Bhoj, A., Prakash, O., & Dwivedi, S. K. (2018). Vegetable cultivation under hydroponics in Himalayas: Challenges and opportunities. *Defence Life Science Journal, 3*(2), 111-119. https://doi.org/10.14429/dlsj.3.12575

Park, J. B., Craggs, R. J., & Sukias, J. P. (2008). Treatment of hydroponic wastewater by denitrification filters using plant prunings as the organic carbon source. *Bioresource Technology, 99*(8), 2711-2716. https://doi.org/10.1016/j.biortech.2007.07.009

Prazeres, A. R., Albuquerque, A., Luz, S., Jerónimo, E., & Carvalho, F. (2017). Hydroponic system: A promising biotechnology for food production and wastewater treatment. In A. M. Grumezescu (Ed.), *Food biosynthesis* (pp. 317-350) Cambridge, US: Academic Press. https://doi.org/10.1016/B978-0-12-811372-1.00011-7

Rana, S., Bag, S. K., Golder, D., Roy, S. M., Pradhan, C., & Jana, B. B. (2011). Reclamation of municipal domestic wastewater by aquaponics of tomato plants. *Ecological Engineering, 37*(6), 981-988. https://doi.org/10.1016/j.ecoleng.2011.01.009

Raviv, M., Krasnovsky, A., Medina, S., & Reuveni, R. (1998). Assessment of various control strategies for recirculation of greenhouse effluents under semi-arid conditions. *The Journal of Horticultural Science and Biotechnology, 73*(4), 485-491. https://doi.org/10.1080/14620316.1998.11511003

Reetika, Chauhan, C., Singh, G., Shubham, & Kaushal, S. (2024). Wastewater hydroponics: Foundations, advancements and prospects for pollutant elimination and food production. *International Journal of Research in Agronomy, 7*(S4), 201-204. https://doi.org/10.33545/2618060X.2024.v7.i4Sc.587

Rogers, M. A. (2017). Organic vegetable crop production in controlled environments using soilless media. *HortTechnology, 27*(2), 166-170. https://doi.org/10.21273/HORTTECH03352-16

Saaid, M. F., Yahya, N. A. M., Noor, M. Z. H., & Ali, M. S. A. M. (2013).

A development of an automatic microcontroller system for deep water culture (DWC). 2013 IEEE 9th International Colloquium on Signal Processing and its Applications (pp. 328-332). IEEE. https://doi.org/10.1109/CSPA.2013.6530066

Sambo, P., Nicoletto, C., Giro, A., Pii, Y., Valentinuzzi, F., Mimmo, T., Lugli, P., Orzes, G., Mazzetto, F., Astolfi, S., Terzano, R., & Cesco, S. (2019). Hydroponic solutions for soilless production systems: Issues and opportunities in a smart agriculture perspective. *Frontiers in Plant Science, 10*, 923. https://doi.org/10.3389/fpls.2019.00923

Sardare, M. D., & Admane, S. V. (2013). A review on plant without soil-hydroponics. *International Journal of Research in Engineering and Technology, 2*(3), 299-304.

Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry-A review. *European Journal of Horticultural Science, 83*(5), 280-293. https://doi.org/10.17660/eJHS.2018/83.5.2

Savvas, D., & Passam, H. (2002). *Hydroponic production of vegetables and ornamentals*. Athens, Greece: Embryo Publications.

Saxena, P., & Bassi, A. (2013). Removal of nutrients from hydroponic greenhouse effluent by alkali precipitation and algae cultivation method. *Journal of Chemical Technology & Biotechnology, 88*(5), 858-863. https://doi.org/10.1002/jctb.3912

Siddaq, A., Tariq, M. O., Zehra, A., & Malik, S. (2019). ACHPA: A sensor-based system for automatic environmental control in hydroponics. *Food Science and Technology, 40*(3), 671-680. https://doi.org/10.1590/fst.13319

Singh, H., & Dunn, B. (2016). *Electrical conductivity and pH guide for hydroponics*. Oklahoma Cooperative Extension Service. Retrieved from https://shareok.org/bitstream/handle/11244/331022/oksa_HLA-6722_2016-10.pdf?sequence=1

Sweat, M., Tyson, R., & Hochmuth, R. (2004). Building a floating hydroponic garden: HS943/HS184, Rev. 9/2003. *EDIS, 2004*(1). https://doi.org/10.32473/edis-hs184-2003

Tatas, K., Al-Zoubi, A., Christofides, N., Zannettis, C., Chrysostomou, M., Panteli, S., & Antoniou, A. (2022). Reliable IoT-based monitoring and control of hydroponic systems. *Technologies, 10*(1), 26. https://doi.org/10.3390/technologies10010026

Truong, P. N., & Hart, B. (2001). *Vetiver system for wastewater treatment*. Technical Bulletin No. 2001/21, Pacific Rim Vetiver Network, Office of the Royal Development Projects Board, Bangkok (Thailand).

Turner, B. (2008). *How hydroponics works*. HowStuffWorks. Retrieved from https://home.howstuffworks.com/lawn-garden/professional-landscaping/hydroponics.htm

United Nations. (2018). *Goal 11: Make cities inclusive, safe, resilient, and sustainable*. Retrieved from https://www.un.org/sustainabledevelopment/cities

United Nations. (2019). (2019). *World urbanization prospects: The 2018 revision*. United Nations, Department of Economic and Social Affairs, Population Division. Retrieved from https://population.un.org/wup/assets/WUP2018-Report.pdf

van Delden, S. H., SharathKumar, M., Butturini, M., Graamans, L. J. A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R. S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R. E., Stanghellini, C., van Ieperen, W., Verdonk, J. C., Vialet-Chabrand, S., Woltering, E. J., van de Zedde, R., Zhang, Y.,… Marcelis, L. F. M. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. *Nature Food, 2*(12), 944-956. https://doi.org/10.1038/s43016-021-00402-w

Velazquez-Gonzalez, R. S., Garcia-Garcia, A. L., Ventura-Zapata, E., Barceinas-Sanchez, J. D. O., & Sosa-Savedra, J. C. (2022). A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations. *Agriculture,* 12(5), 646. https://doi.org/10.3390/agriculture12050646

Vinci, G., & Rapa, M. (2019). Hydroponic cultivation: Life cycle assessment of substrate choice. *British Food Journal, 121*(8), 1801-1812. https://doi.org/10.1108/BFJ-02-2019-0112

Worku, A., Tefera, N., Kloos, H., & Benor, S. (2018). Bioremediation of brewery wastewater using hydroponics planted with vetiver grass in Addis Ababa, Ethiopia. *Bioresources and Bioprocessing, 5*(39), 1-12. https://doi.org/10.1186/s40643-018-0225-5

World Bank Group. (2018). *Urban population (% of total population)*. Retrieved from https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS

Yanes, A., Abbasi, R., Martinez, P., & Ahmad, R. (2022). Digital twinning of hydroponic grow beds in intelligent aquaponic systems. *Sensors, 22*(19), 7393. https://doi.org/10.3390/s22197393