Review Article

Exploring the Potential of Soil-less Farming through Hydroponics: A Review

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ABSTRACT

Hydroponics is one of the modern and most demanded agricultural production technologies that ought to provide sustainability in agricultural production. It is identified as one of the most effective methods to combat the existing challenges like climate change, depletion in land and fresh water resources, and the unavailability of fresh and safe food. In this system, plants necessitate only water that is abundant in all essential macro and micronutrients for their development, and the role of soil is nil. On direct supply of the nutrients to roots, plants could save much of their energy, which would have been lost in search of those crucial inputs. This method is highly effective in eliminating many of the limitations associated with traditional soil farming. Therefore, it could serve as a turning point in feeding the global population.

Keywords: Hydroponics; soilless farming; nutrient solution; growing media; hydroponic systems

1. INTRODUCTION

In the contemporary era, rapid urbanization, industrialization, and population growth have resulted in reduction of cultivable land, depletion of water resources, and the unavailability of fresh and high-quality food. Under these perks, the major goal of the human race itself is to escalate the food production to sustain the continuously expanding population with the limited resources that are available around the world. The general base for crop growth is soil that delivers nutrients, air, and water for optimal development (Ellis *et al*., 1974). However, the soil based conventional farming itself has various restrictions including the diseases caused by microbes and nematodes, inadequate soil response, poor drainage, soil compaction, soil degradation, *etc*. (Beibel, 1960).

Under this situation, growing sufficient food in a sustainable and environment friendly way with limited resources becomes achievable by adopting soil-less techniques. The soil-less cultivation is regarded as an alternate method for growing healthy crops (Butler and Oebker, 2006). Based on availability of space and other inputs, expected productivity and quality, soilless culture is broadly classified into three, *i.e*., hydro agriculture (Hydroponics), aqua agriculture (Aquaponics) and aerobic agriculture (Aeroponics). Among these, Hydroponics is increasingly favoured due to its effective resource utilization and crop cultivation capabilities. A diverse array of commercial and speciality crops can be cultivated with hydroponics, including leafy greens, tomatoes, cucumbers, peppers, strawberries, and others.

Hydroponics has been proven to be a practical way of growing crops in an intensive manner, occupying the least amount of land while maximizing the use of water and mineral nutrients by delivering them directly to the plant roots all day long. It is considered as a revolutionary method of farming due to its ability to precisely control growth conditions, weed problems, and pest factors, as well as the adaptability of a wide variety of crops that can flourish in various environments, including urban areas, arid and barren land, and contaminated land.

Hydroponic plants are known for their continuously outstanding quality, excellent yield, nutritional value, and fast harvest (Hussain *et al*., 2014). Better crop yields are achieved through the unique ability of this technique to accelerate root system growth and effectively absorb vital nutrients from the culture solution. Besides these, hydroponics consumes 60 per cent less fertilizer and saves 70–90 per cent more water, as water is re-circulated and reused (Prakash *et al.,* 2020). Additionally, hydroponics is a healthier and safer alternative with year-round production of good quality food, without chaotic discharges of polluting chemical into the environment as compared to traditional open-field agriculture, and it has a stronger control and reliability in the productive process (Logendra *et al.,* 2001).

Since hydroponic systems are primarily housed indoors, such as in greenhouses, they might be less dependent on outside factors and have a smaller ecological impact than soil cultivation (Sundin *et al*., 1995). This system can be implemented not just in urban areas, but also in non-arable lands like deserts or polar regions. It is also utilized to provide food for astronauts in space and to support impoverished or rural communities. Even though hydroponic cultivation is still in its infancy in India, the progressive farmers are embracing this creative and novel farming method with hope to sustain in this era. This article enlightens the different technical aspects of hydroponics, their benefits and market potential as a whole.

2. WHAT IS HYDROPONICS

Hydroponics was derived from two Greek words: 'hydro' meaning water and 'ponos' meaning work (Beibel, 1960). Shortly, the ‘working water’ rich in dissolved nutrients, is delivered directly to the plant root zone while allowing plants to thrive in a controlled, soil-free environment (Hochmuth and Hochmuth, 2001). Plants can be established under the hydroponic system with or without the support of an artificial media such as perlite, rock wool, sand, gravel, coir, sawdust, *etc*. (Lee and Lee, 2015; Sharma *et al*., 2018; Walters *et al*., 2020; Niu and Masabni, 2022). This description implies that it includes both soilless culture, in which plant roots are physically stabilized in containers using soilless growing media that permits the absorption of nutrients and water, and solution culture, in which plant roots reside suspended directly into a nutrient solution (Walters *et al*., 2020; Niu and Masabni, 2022).

3. HISTORY OF HYDROPONIC CULTIVATION

Even though hydroponics is thought of as a contemporary technique, growing plants in pots above the earth has been attempted throughout history. The earliest known account of plants growing in containers was an old mural discovered in the Deir el Bahari temple (Naville, 1913). Soilless cultivation has been employed by numerous ancient civilizations to produce crops. The most obvious representation of hydroponics' initial phases is the hanging garden that was built in Babylon around 600 BC. Francis Bacon's book "Sylva Sylvarum," which was published in 1627, was the first published work on soilless culture. Water culture then gained popularity as a research method. The preliminary cultivation experiments on plants with roots immersed in water were documented in 1666 by the Irish scientist Robert Boyle.

Julius von Sachs and Wilhelm Knop undertook studies in 1842 and 1895, respectively, to develop optimal mineral fertilizer solutions for soilless crop production. The name "hydroponics" was first coined by Dr. William F. Gericke in 1937, who began commercial production utilizing soilless cultivation techniques in 1929. The formula for Dennis R. Hoagland's well-known Hoagland's solution, which is still the preferred solution for standard tests in many plant research labs, was released in 1933.

In 1970, the "Nutrient Film Technique" (NFT) was invented by Dr. Allen Cooper. He published the ‘ABC of NFT’, a small book that remains widely read, in 1979. NFT was quickly embraced globally for the commercial production of short-cycle crops like salad greens. In 1946, an English scientist named W. J. Shalto Duglas brought hydroponics to India and he wrote a book titled *Hydroponics: The Bengal System.*

Commercial hydroponic farms were established in numerous areas throughout the world between 1960 and 1970. Subsequently, in the 1980s, a large number of high-tech, automated hydroponic farms were created all over the world (Hussain et al., 2014). As materials and equipment (such as medium, tubes, connectors, valves, pots, water reservoirs or tanks, air or water pumps, and electronic timers) have advanced, a variety of hydroponic systems are now accessible. According to the needs of various plants, most hydroponic systems function automatically to control the quantity of water, nutrients, and light (Hochmuth and Hochmuth, 2011; Resh, 2013). NASA has conducted a great deal of hydroponic studies for its Controlled Ecological Life Support System, or CELSS, in the last few years. LED lighting allows hydroponics, which is slated to be used on Mars, to grow in different colour spectrum while using significantly less heat.

4. MAJOR COMPONENTS OF HYDROPONICS

The crop, growing media and nutrient solution are considered as the principal components of a hydroponic system (Fig. 1). Proper combination and management of the major components always lead the system to success. Selection of each component is again based on the type of hydroponic system that is being used. Apart from three major components, successful implementation of a hydroponic system is also dependent on reservoir, pump, nutrient delivery system, timer, aerator/ventilation, artificial grow lights, temperature controller and most importantly the structural frame which supports the entire system.

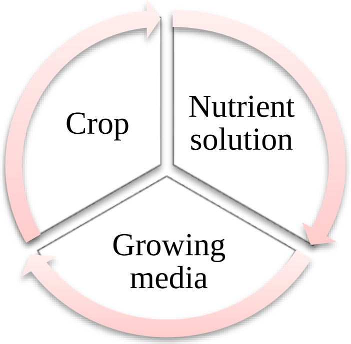


Fig. 1. Major components of a hydroponic system

4.1. Crops suitable for hydroponics

Theoretically, any plant can be cultivated without soil. Till date, this method has primarily been applied to the production of various vegetables and garden plants (Table 1).

Table 1. Crops suitable for hydroponics

Type of crop	**Name of crop**	**References**
Cereals	Rice (*Oryza sativa*), Maize (*Zea mays*)	Maharana and Koul (2011)
Vegetables	Lettuce (*Lactuca sativa* L.), Potato (*Solanum tuberosum* L.), Spinach (*Spinacia oleracea* L.), Pepper (*Capsicum annuum* L.), Kale (*Brassica alboglabra* L.), Tomato (*Solanum lycopersicum* L.), Cucumber (*Cucumis sativus* L.)	Sharma *et al*. (2018) Resh (2013) Chang *et al.* (2012) Janeczko and Timmons (2019) Singh *et al.* (2019) Yanti *et al.* (2020) Verdoliva *et al.* (2021) Zhang *et al.* (2023)
Fruit crops	Strawberry (*Fragaria ananassa* L.)	Talukder *et al.* (2019)
Forage crops	Barley (*Hordeum vulgare*), Alfalfa (*Medicago sativa*), Cowpea (*Vigna ungiculata*), Sorghum (*Sorghum bicolor*), Wheat (*Triticum aestivum*)	Al-Karaki and Al-Hashimi (2012)
Flower crops	Gerbera (*Gerbera jamesonii*), Carnation (*Dianthus caryophyllus*), Rose (*Rosa rubiginosa*), Aster (*Aster amellus*), Bouvardia (*Bouvardia longiflora*), Lily (*Lilium longiflorum*),Geranium (*Pelargonium graveolens* L. Hervitt.), Chrysanthemum (*Dendranthema grandiflora*)	Pisanu *et al.* (1994) Maloupa *et al.* (1993) Mattas *et al.* (2000) Sonneveld *et al.* (1999)

		Gent and McAvoy (2011)
Medicinal plants	Burdock root (*Arctium lappa*), Stinging nettles (*Urtica dioica*), Yerba mansa (*Anemopsis californica*), Ginger (*Zingiber officinale*), Skullcap herb (*Scutellaria lateriflora*), Chinese licorice (*Glycyrrhiza uralensis* Fisch.), Chinese cucumber (*Trichosanthes kirilowii* Maxim.), Pot marigold (*Calendula officinalis*), St. John's wort (*Hypericum perforatum*), Indian pennywort (*Centella asiatica*), Feverfew (*Tanacetum parthenium*), Yarrow (*Achillea millefolium*), Common dandelion (*Taraxacum officinale*), Common mugwort (*Artemisia vulgaris*), Valerian (*Valeriana officinalis*), Cannabis (*Cannabis sativa* L.)	Hayden (2006) Yoshimatsu (2012) Duan *et al.* (2020) Stewart and Lovett-Doust (2003) Brechner *et al.* (2007) Prasad *et al.* (2012) Leonhart *et al.* (2002) Dorais *et al.* (2001) Potter (2014)
Condiments	Mint (*Mentha spicata* L.), Parsley (*Petroselinum crispum*), Sweet basil (*Ocimum basilicum*), Oregano (*Oreganum vulgare*)	Surendran *et al.* (2017) Maharana and Koul (2011)

4.2. Growing Media

A crucial component of soilless cultivation is the selection of growing media, with a good amount of air and water holding capacity, flexibility, friability, drainability and is unencumbered harmful compounds, pests, infectious microorganisms, nematodes, *etc.* which are preferably employed after proper sterilization. Argo and Fischer (2002) suggested that a primary substrate component, which contributes more than 40 per cent of the substrate volume, includes organic materials such as peat moss and coconut coir fibre. Such materials are known for characteristics of low bulk density and high water-holding capacity. On the other hand, materials which improve aeration and nutrient retention by increasing drainage and cation exchange capacity are frequently found in secondary components, which contribute less than 40 per cent of the substrate volume. This category includes substrates like expanded minerals (e.g., perlite and vermiculite), clays, sand, gravel and composts. The organic and inorganic substrates may be either applied alone or in combination with two or more (Berndsen and Gardener, 2014). The results of some of the growing media tried under different studies for growing different crops are detailed below (Table 2).

Table 2. List of best growing media identified and crops grown under hydroponics

Best media found	**Crops grown**	**References**
Coir pith/ coir/ coconut fibre/ coco peat	Tomato Cucumber Pumpkin Lettuce	Abak and Celikel (1994) Cardarelli *et al.* (2012) Hansen *et al.* (2010) Martin *et al.* (2012) Islam *et al.* (2002) Reshma and Joseph (2016)
Rock wool	Tomato	Abak and Celikel (1994)

peat moss-vermiculite (1:1) and peat-sand (1:1)	Cucumber	Abou-Hadid *et al.* (1995)
Coconut fibre and perlite	Watermelon	Gi *et al.* (1999)
Rice husk and coir dust	Lettuce	Dayananda and Ahundeniya (2014)
coconut coir and carbonated rice husks	Tomato, Potted crops	Islam *et al.* (2002)
Perlite	Cucumber, Tomato	Hochmuth *et al.* (2003) Abbas (2009)
Date palm peat and coir peat	Tomato	Borji *et al.* (2010)
perlite and peat mixture + perlite	Lettuce	Abd-Elmoniem *et al.* (2006)
Expanded Clay Pellet	Tomato	Shahinrokhsar (2008)
gravel	Tomato	Neocleous and Polycarpou (2010)
compost mixed with sawdust	Tomato	Ortega-Martinez *et al.* (2010)
compost	Cherry tomato	Mazuela *et al.* (2012)
Mix of cocopeat+gravel+silex	Tomato	Joseph and Muthuchamy (2014)
Sawdust	Tomato	Maboko and Du-Plooy (2014)
Lignite and rockwool	Tomato	Dysko *et al.* (2015)
Red volcanic rock	Tomato	Ortega-Martinez *et al.* (2016)
Coir pith, perlite, and vermiculite (3:1:1)	Salad cucumber	Aparna *et al.* (2019)
coco peat + sawdust (1:1) and coco peat + vermiculite + sawdust (1:1:2)	Tomato	Subramani *et al.* (2020)
peanut shells + vermiculite or peanut shells + coconut coir	Cherry tomato	Mohamed and Hussien (2021)

4.3. Nutrient solution

The effectiveness of a hydroponic system largely depends on the nutrient solution supplied and how well it is managed. According to Argo and Fisher (2002), Bunt (1998) and Raviv *et al.* (2019), the primary sources of nutrients in hydroponic systems involve the water for irrigation, fertilizers or chemicals either mixed in the irrigation water or infused into a substrate, substrate components, and amendments used to alter the pH of the growing medium. Nutrient solution is the lifeblood of a hydroponic system, supplying all the vital nutrients required for plant to thrive. Maintaining a proper ion ratio should be prioritized for better establishment and yield of the crops. Usually, most of the nutrient solutions used in hydroponic crop production were made from inorganic materials and administered using various chemical mixes (Williams and Nelson, 2014). Any one of the mineral deficiencies from the nutrient solution may adversely affect the plant growth.

The majority of fertilizers or chemicals employed in hydroponics for nutrient solution preparation are highly soluble inorganic salts; yet, certain inorganic acids are also utilized (Ramazzotti *et al.*, 2013). The nourishment of plants in hydroponics has been thoroughly examined, categorizing the nutrients into three types: primary, secondary, and trace or micro-nutrients, as outlined below (Table 3). A multitude of formulations for hydroponic solutions exists, each involving various blends of chemicals to achieve comparable end compositions.

Table 3. Normal concentration range of major and micro nutrients found in most of the nutrient solutions (Singh and Rajan, 2022)

Element	**Ionic form**	**Concentration limit (ppm)**	**Average concentration (ppm)**
Major nutrients			
i. Primary nutrients			
Nitrogen (N)	NO_3^-, NH_4^+	150-1000	300
Phosphorus (P)	HPO_4^{2-}, H_2PO^{4-}	50-100	80
Potassium (K)	K^+	100-400	250
ii. Secondary nutrients			
Calcium (Ca)	Ca^{2+}	300-500	400
Magnesium (Mg)	Mg^{2+}	50-100	75
Sulphur (S)	SO_4^{2-}	200-1000	400
Micro nutrients			
Boron (B)	BO_3^{3-}	0.5-5.0	1.0
Copper (Cu)	Cu^{2+}	0.1-0.5	0.5
Iron (Fe)	$Fe^{2+,}$ Fe^{3+}	2-10	5.0
Manganese (Mn)	Mn^{2+}	0.5-5	2.0
Molybdenum (Mo)	MoO_4^-	0.001-0.002	0.001
Zinc (Zn)	Zn^{2+}	0.5-1.0	0.5

Almost all the hydroponic formulations are prepared with one or more of the soluble fertilizer or chemical reagents such as calcium nitrate [$Ca(NO_3)_2 \cdot 4H_2O$)], ammonium nitrate (NH_4NO_3), potassium nitrate (KNO_3), potassium dihydrogen phosphate (KH_2PO_4), magnesium sulfate ($MgSO_4 \cdot 7H_2O$), phosphoric acid (H_3PO_4), nitric acid (HNO_3), *etc*. (Ramazzotti *et al*., 2013). Regarding to the other important elements, particularly the micronutrients, B is supplied as either boric acid ($H_3BO_3 \cdot 5H_2O$) or borax ($Na_2B_4O_{24} \cdot 10H_2O$), Mo as ammonium molybdate [$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$] and Cu, Fe, Mn, and Zn are in their sulphate forms ((copper sulfate ($CuSO_4 \cdot 5H_2O$), ferrous sulfate ($FeSO_4$) or ferric ammonium sulfate [$FeSO_4(NH_4)_2SO_4 \cdot 6H_2O$], manganese sulfate ($MnSO_4 \cdot 4H_2O$), zinc sulfate ($ZnSO_4 \cdot 7H_2O$)], respectively)). Fe can be added into the solution as chelate forms like Fe-EDTA or Fe-DTPA, *etc*. While these formulations can be purchased commercially in liquid or solid forms, it is also feasible to make the mixture of salts, minerals, and fertilizer from scratch.

4.3.1 pH and EC regulation

Electrical conductivity (EC) and pH are the two key factors that affect the provision of nutrient solution to hydroponic crops. The ideal pH range for a nutrient solution used in hydroponics is 5.8 to 6.5, and a desirable EC range is 1.5 to 2.5

dS m^{-1} (Khan *et al*., 2018). The pH, electrical conductivity, and water level must all be adjusted promptly to ensure the solution lasts as long as possible. In order to prevent fluctuations in the nutrient solution, the volume level in the storage tank must be constant, resupplying the water that the plants absorb and that is lost through evapotranspiration. If this isn't done, the salt concentration will fluctuate, which will hinder the growth and health of plant. The pH of solution can be lowered with the use of sulphuric acid, nitric acid, phosphoric acid, citric acid, and acetic acid, while the pH can be raised with the use of potassium hydroxide, sodium hydroxide, and bicarbonate of soda.

Electrical conductivity is the expression of overall ion concentration in a solution. Since EC has a significant influence on crop growth and quality (Sonneveld and Voogt, 2009), it needs to be maintained within a specified range. While too-high EC values might put the plant under salt stress, lower values imply a shortage of nutrients in the form of ions (Savvas and Gruda, 2018).

4.3.2 Sterilization of nutrient solution

The potential for water-borne diseases to spread quickly because of the recirculating nutrient solution is one of the drawbacks of closed hydroponic systems. Ozone treatment, UV disinfection, heat treatment, slow sand filtering, electrolyzed water, hydrogen peroxide, membrane filtration, and chlorination are some of the disinfection techniques that can be employed to get rid of these microorganisms.

5. HYDROPONIC TECHNIQUES

The two main techniques involved in hydroponics are solution culture and medium culture and they are classified based on the type of substrate and container, nutrient delivery system to the plant and drainage. A comparison between solution culture and medium culture is tabulated below (Table 4).

Table 4. Media culture vs. solution culture (AlShrouf, 2017)

Parameters	**Hydroponic systems**			
	Media culture		**Solution culture**	
	Open	**Closed**	**Open**	**Closed**
% Irrigation water saving	80	85	85	90
% Fertilizer saving	55	80	68	85
% Productivity increase	100	150	200	250
% Water productivity	1000	1600	2000	3500

5.1. Solution culture

It is often referred to as the 'Liquid Hydroponics' approach. Roots of plants cultivated in solution culture are suspended directly in a nutritional solution (Maharana and Koul, 2011). It can further be classified into circulating method (closed system/continuous flow solution culture), and non-circulating method (open systems/ static solution culture). In circulating methods, flowing solution systems can offer roots a steady nutritional environment. Although they are exceptionally capable of automatic control (Jenner and Starkey, 1980), if the flow of solution is interrupted for any reason, the plants will quickly desiccate. As a result, regular attention is needed. This includes the Deep Flow Technique (DFT) and the Nutrient Film Technique (NFT). The nutrient solution is administered just once in the non-circulating approach rather than being circulated. It is replaced when the pH, EC, or nutrient concentration drops. Open system includes root dipping technique, floating technique and capillary action technique.

5.2. Medium Culture or Aggregate system

Cultivating crops in bags filled with materials (rockwool or slabs of coconut coir) or containers with drip emitters mounted to apply the nutrient solution is known as aggregate culture. It includes hanging bag technique, grow bag technique, trench or trough technique and pot technique. Long-term fruit crops like tomatoes, cucumbers, sweet peppers, and strawberries are generally cultivated in aggregate culture, while short-term, non-fruiting crops like leafy greens and herbs are typically grown in solution culture, including NFT and DWC systems.

6. TYPES OF HYDROPONIC SYSTEMS

Depending on methods of applying the nutrient solution, hydroponic systems are of six types, *viz*., nutrient film technique (NFT), deep flow technique (DFT), ebb and flow, deep water culture (DWC), wick system and drip systems (Fig. 2).

6.1. Nutrient Film Technique (NFT)

NFT is a true hydroponics system where the plants are grown in net pots fixed on a slanting tray or pipe, and the roots are directly placed in nutrient solution. Pumped into the growth tray, the nutrient solution continuously runs over the plant roots before returning to the reservoir (Domingues *et al.*, 2012). Within the pipe or gully, the running solution level is kept between 0 and 1 cm (Cooper, 1975; Pardossi *et al*., 2002). By regulating flow and water depth, NFT systems can continuously supply water and nutrients and create environments that are rich in oxygen (Jones, 1997). The solution is collected and reused, and the inclination of the tray and the strength of the water pump regulate the volume of water used.

6.2. Deep flow technique (DFT)

DFT system setup is almost similar to that of NFT without any slope for the tray or pipe. Using this method, a nutrient solution that is 3-4 cm deep continuously flows via pipes that are connected to plastic net pots that contain plants.

6.3. Wick system

It is the simplest of all types of hydroponic systems. Plants placed in the containers are connected to the nutrient reservoir via a piece of absorbent material that uses capillary action to draw the nutrient solution up into the growing media. A water pump is not necessary because it is a self-feeding model (Shrestha and Dunn, 2013). Although the wick system has been utilized in small-scale gardens, it seldom finds use in commercial settings.

6.4. Deep water culture (DWC)

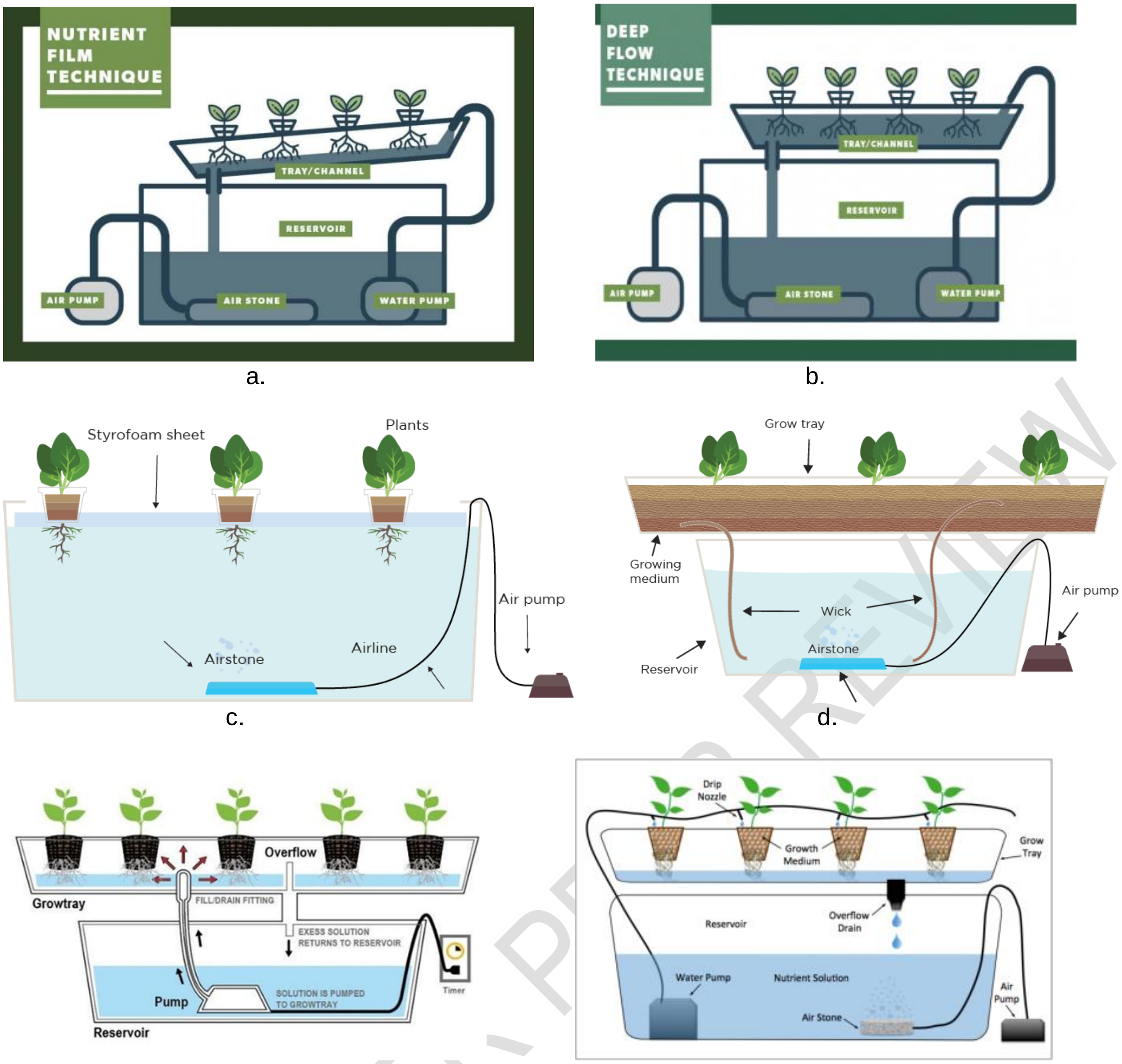
DWC is the most common and easiest model, composed of a reservoir, an air stone, a tubing system, an air pump, and a floating platform (Hoagland and Arnon, 1950). In this system, plant pots with holes in the bottom are placed on a floating structure, and an air pump and air stone provide oxygen while the root sections are continuously submerged in water or nutrient solution (Saaid *et al.*, 2013). The deep water culture system served as the base model for the majority of modified hydroponic systems (Harris, 1988). Herbs, lettuce, and strawberries are the most practical plants in this setup.

6.5. Drip system

The nutrient solution stored in the reservoir is delivered to each plant roots in the right proportions using a pump (Rouphael and Colla, 2005). Drip systems deliver nutrients at a slow pace through nozzles, and any excess solutions can be recovered and returned, or let to drain. This method is best suited for plants like tomato and pepper.

6.6. Ebb and flow system or flood and drain system

Ebb and flow was one of the earliest marketed hydroponic systems, consisting of two containers, one on top carrying the plants in pots with substrate and the other on the bottom carrying the nutritional solution. It employs an automatic flood and drain irrigation approach in which plants are drenched both temporarily and frequently (Buwalda *et al.*, 1994). The mechanism recycles the water by returning it to the reservoir by gravity.



a.

b.

c.

d.

e.

f.

Fig. 2. Different types of hydroponic systems; a-nutrient film technique, b-deep flow technique, c-deep water culture, d-wick system, e-ebb and flow system, f-drip system

7. COMPARISON OF HYDROPONIC SYSTEMS ON GROWTH AND YIELD OF DIFFERENT CROPS

Although the nutrient film technique (NFT) and the deep flow technique (DFT) are widely used for hydroponic tomato production in commercial and amateur systems, DFT is less popular than NFT and uses a comparable system of channels that are filled with a deep flow of nutrient solution instead of a thin film (Morgan, 2003). Tomato plants cultivated in NFT with regular nutrient solution renewal showed higher yields, fresh weights, and dry weights than plants with extended recycling of nutrient solutions (Zekki *et al.*, 1996).

Of the two hydroponic techniques, the Deep Flow Technique demonstrated higher output of tomato per unit area, higher planting density, and more effective use of vertical space than the Ebb and Flow Technique (Reshma, 2016). According to Rodriguez-Ortega *et al.* (2019), in a comparison of three hydroponic cultivation systems, the maximum tomato yield was obtained from DFT (5 kg plant^{-1}), followed by perlite substrate system (4.5 kg plant^{-1}), and the NFT (3.8 kg plant^{-1}). In contrast, the water productivity was higher for tomato plants that are grown using the NFT system.

The drip system outperformed the NFT and raft culture systems with regard to tomato production. However, the plant mineral status showed relatively slight impacts, suggesting that all three systems can be used effectively (Schmautz *et al.*, 2016). Even though the tomato yield was comparable from both the drip system and deep-water culture (DWC), DWC was found to be more efficient with respect to WUE (Verdoliva *et al.*, 2021).

The NFT method was found to be more effective in leafy vegetables like lettuce. NFT produced much more leaf area and leaf output on both the fresh weight and dry weight basis of lettuce compared to the deep flow technique (DFT) and aeroponics system (Kim *et al.*, 1995). According to Lennard and Leonard (2006), gravel bed (5.05 kg m^{-2}) system was more efficient in terms of lettuce yield, followed by floating rafts (4.47 kg m^{-2}) and NFT (4.13 kg m^{-2}) systems.

Hydroponic systems shown superiority over conventional growth methods in every regard; nonetheless, each system possesses distinct benefits as well as drawbacks (Table 5).

Table 5. Advantages and disadvantages of different hydroponic systems

Hydroponic system	**Advantages**	**Disadvantages**	**References**
NFT	Space efficient, plentiful oxygen supply to the roots	Susceptible to power outages and pump failure, chance of clogging of the tube with plant roots, higher upfront costs, more technical skills required	Thinggaard and Middelboe (1989)
DFT	Plant roots are always submerged in the solution	Limited oxygen supply to roots, prone to algal growth and clogging with roots, not suitable for large plants	Kumar *et al.* (2023)
Wick system	Requires less maintenance, affordable, does not require electricity, pump and aerator, inhibits the diseases common to overwatering	Not suitable for long term plants, Prone to algal growth, limited oxygen access to roots, no nutrient recirculation	Harris (1988) Shrestha and Dunn (2013)
Deep Water Culture (DWC)	Cheapest of the active system, reliable, simple setup, no nutrient pump is required	Rapid growth of algae and molds, risk of root rot, require frequent refill of solution, continuous monitoring of pH and aeration	Lee and Lee (2015) Domingues *et al.* (2012)
Drip system	Precise control, appropriate for large-scale manufacturing, lower maintenance, and resource conservation	Costly and time-consuming set up, more expensive over time, requires technical expertise, prone to clogs if filters are not utilised, and is susceptible to power outages.	Lee and Lee (2015)
Ebb and flow	Affordable, low maintenance, recirculation of excess nutrient solution, variety of media can be used around root area	Requires lots of growing media, susceptible to pump failure and power outages, Prone to algal growth	Nielsen *et al.* (2006)

8. MARKET POTENTIAL OF HYDROPONIC FARMING IN INDIA

Globally, there has been a dramatic surge in hydroponic crop production in recent years. Europe is regarded as the biggest market for hydroponics, with France, The Netherlands, and Spain being the three top producers, followed by the United States of America and the Asia-Pacific region. In India, the hydroponic industry is expected to expand at a compound annual growth rate of 13.53 per cent between 2020 and 2027 whereas, on a global level the growth is estimated at just 6.8 per cent (Verma, 2023). Since the consumers are more concerned about the quality of the food they intake, are ready to pay a premium price for organically grown produce that is fresh, safe, and healthy. With continuous improvements in evolving technologies and a rise in food inflation, the price differentials between hydroponic technology and state and central government's incentives to set up hydroponic farms on their fields are also adding to their popularity. With the current growth rate, the cost of setting up such farms has gone down and will reduce further over a period of time. This will further increase the adoption of the technique, and with the market ready having a demand for such products, this can be a new and upcoming form of business in the near future. Still, given the inherent limitations of what can be grown with hydroponics, farmers and other project proponents may require financial and technological support from entities like banks, KVKs, agronomists *etc*., initially.

Factors like ever growing urbanization, land constraints, market demand for safe food, diversified and sustainable production, advancement in technology, *etc*. contribute to the growth and potential of the hydroponics industry. Recognizing the potential of hydroponic farming to boost agricultural productivity and income, the Indian government is introducing policies, subsidies, and incentives to encourage investment in the sector. Schemes promoting entrepreneurship, skill development, and technology adoption are creating a conducive environment for aspiring hydroponic farmers to enter the market and thrive.

9. BENEFITS OF HYDROPONIC SYSTEM

- **Efficient Resource Utilization**

Hydroponic systems use water, nutrient and land, more efficiently than traditional farming methods (Baddadi *et al*., 2019; Rufí-Salís *et al.*, 2020). Romeo *et al.* (2018) stated that hydroponics requires four times less water than open-field and seven times less than traditional greenhouse cultivation. Compared to soil farming, hydroponics uses 25 per cent less land, enables vertical crop growing, and addresses world poverty (Bradley and Marulanda, 2001).

- **Higher Yields**

By providing plants with precisely controlled nutrient solutions and optimal growing conditions, hydroponic systems can significantly increase crop yields. Studies have shown that hydroponically grown crops yield more produce in less time than soil-grown counterparts. Lettuce had 11 times more yield (Barbosa *et al.*, 2015), 30–50 per cent faster growth rate than soil cultivation (Joshi and Joshi, 2018).

- **Ubiquity and Space Optimization**

Hydroponic systems are highly versatile and can be adapted to various indoor and outdoor settings, making them ideal for urban agriculture and small-scale farming. Vertical farming techniques further maximize space utilization, allowing for high-density cultivation in limited areas (Rufí-Salís *et al.*, 2020). Anywhere a controlled environment can be established, food can be grown. In fact, hydroponics is the primary supply of nourishment for spaceship crews, even in distant space travel.

- **Sustainability and Environment Friendliness**

Hydroponic farming minimizes the need for chemical pesticides and fertilizers, reducing environmental pollution (Russo and Mugnozza, 2005). Additionally, the closed-loop water recirculation systems used in hydroponics help conserve water and prevent nutrient runoff, mitigating the negative impact on surrounding ecosystems, including effective sewage disposal (Grewal *et al.*, 2011). Hydroponics is a self-sustainable and environmentally friendly system (Alshrouf, 2017).

- **Year-Round Cultivation**

Unlike traditional farming, which is often seasonal and weather-dependent, hydroponic farming enables year-round cultivation, regardless of climatic conditions. This ensures a steady and reliable supply of fresh produce throughout the year, contributing to food security and stability.

- **Nutrient Density and Quality**

Hydroponically grown crops are known to have higher nutrient densities and superior taste compared to conventionally grown produce. By optimizing nutrient delivery and environmental conditions, hydroponic systems produce healthier and more flavorful fruits, vegetables, and herbs.

- **Scalability and Automation**

Hydroponic systems can be scaled up or down to meet specific production requirements, making them suitable for both small-scale hobbyists and large commercial operations. Furthermore, advancements in automation technology enable efficient management and monitoring of hydroponic farms, reducing labor costs and increasing productivity. Hydroponics reduces expenses for soil preparation, pesticides, fungicides, and losses from drought and ground floods by cultivating crops in a sterile environment under optimal circumstances.

- **Prevention of pests, diseases and weeds**

Compared to soil-based crop production, hydroponic crop production offers an environment devoid of soil-borne diseases and pests (Barbosa *et al.*, 2015) and weed problems. So the plants grown hydroponically are healthier than their soil grown counterparts.

10. LIMITATIONS OF HYDROPONIC SYSTEM

- **High initial cost**:- A hydroponic system requires a comparatively large initial investment because of the high cost of the necessary equipment and raw materials (Souza *et al.*, 2019)
- **High energy consumption**:- The annual energy consumption makes up 95.3 per cent of the total energy, while electricity needs account for 4.7 per cent (Vourdoubas, 2015).
- **Highly skilled labor**:- Large-scale hydroponic operations employ staff with extensive backgrounds in chemistry, plant physiology, agriculture, and advanced control and information systems.
- **Risk of water-borne diseases**:- waterborne diseases can contaminate and spread through the water tubing systems. Species of *Colletotrichum, Fusarium, Phytophthora, Pythium*, and *Rhizoctonia* are the common plant pathogens detected in hydroponic systems (Nahalkova *et al.*, 2008; Win *et al.*, 2009; Constantino *et al.*, 2013; Li *et al.*, 2014).
- Continuous assistance and monitoring are required to properly run the system.
- System failure threats
- Water and electricity risks
- Only chemical or mineral based nutrients can be used

11. SUCCESSFUL HYDROPONIC STARTUPS OF INDIA

India has been witnessing the rise of new startups focused on hydroponics in both major cities and rural areas. These ventures not only aim to produce high-quality crops but also seek to share knowledge and insight into the principles of hydroponics. They provide public support by setting up hydroponic systems and offering proper guidance and necessary raw materials. Some of the prominent and successful hydroponic initiatives and their activities are detailed in Table 6.

Table 6. Major hydroponic startups of India

Sl.No.	**Hydroponic venture**	**Founder and year of establishment**	**Major activities**
1	Acqua Farms, Chennai	Rahul Dhoka 2019	Hydroponic consultancy. Uses a PVC pipe planter to raise lettuce, spinach, mint, and Italian basil.
2	L*etc*etra Agritech, Goa	Ajay Naik and Harish Usgaonker 2016	Produces bell peppers, lettuce, salad greens, cherry tomatoes, and other veggies without the use of chemicals.
3	Urban Kissan, Hyderabad	Vihari Kanukollu, Sairam Reddy, Sampath Vinay, and Srinivas Chaganti 2017	Grow greens, lettuce, herbs, and exotic foods all year round. Delivers hydroponic kits and farm-fresh produce. Reduce carbon footprint significantly while producing 30 times more with up to 95 per cent less water.
4	Future Farms, Chennai	Sriram Gopal	Spreads over 10 states growing leafy vegetables. Top supplier of precision agricultural automation and hydroponic

		2014	systems in India. Offers hydroponic solutions, effective installation, reduced commissioning procedures.
5	Rise Hydroponics, Ahmedabad	Tusshar Aggarwal 2020	Offers support for the building of hydroponic farms and polyhouses both indoors and outdoors. Provides hydroponic farming classes, live training, and project development ideas.
6	GroFlo Hydroponics, Mumbai	Alok Doshi 2020	Support urban farmers. Makes farming more accessible to the general public
7	Brio Hydroponics, Ahmedabad	Bhavik Patel, Jayantkumar Chathurbh, Pathak Mihir, Pravinkumar Patel 2014	Provide cost-effective and environmentally sustainable farming practices. Offers tools and policies to farmers.
8	Kamala Farms, Hyderabad	Meghana Rao and Sandeep Reddy 2017	Produces fresh, nutritious, pesticide-free food. Assists in hydroponic farm setups.
9	Evergreen Farms, Bangalore	Prasanth Ramachandran 2019	Supplies fresh, clean, nutritious greens at affordable prices. Experimenting, growing new varieties of crops.
10	Balcony Crops, Chennai	Adarsh Sridharan 2020	Production methods use 90 per cent less water and produce more revenue. Sustainable farming methods that can be applied to both home gardening and commercial operations.
11	Akarshak Hydroponics, Noida	Ramesh Gera 2017	High quality Saffron production. Conducts the best training program in the world, "Indoor Saffron Hydroponics Farming in India".
12	NutriFresh, Pune	Sanket Mehta and Ganesh Nikam 2019	Supply clean, premium-quality, non-GMO, residue- and pesticide-free fruits, vegetables, and herbs. To guarantee sustainable agriculture, new technologies are being developed and modifications are being made.

4. CONCLUSION

Hydroponics, being one of the most promising yet a bit underrated technologies, balances the hurdle between earning maximum profit without compromising environmental safety. Hydroponics can be highly helpful in places with limited soil and water resources, as well as for the impoverished and landless, because it allows crops like vegetables to be grown year-round in relatively small spaces with little work. Along with high-space research, hydroponics holds enormous promise in many nations to address the shortage of arable land in areas where suitable cultivable land is not readily available. The hydroponics sector in India is predicted to expand rapidly in the near future. In order to provide farmers the opportunity to experiment, it is time to encourage them to implement hydroponic systems across the nation. India can make the most of hydroponic farming for sustainable agriculture by clearing up the main obstacles and misunderstandings, such as the initial risks and financial outlay.

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