Journal of Experimental Agriculture International

Volume 46, Issue 12, Page 902-922, 2024; Article no.JEAI.129699
ISSN: 2457-0591
(Past name: American Journal of Experimental Agriculture, Past ISSN: 2231-0606)

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

Anusree. G [a++*], Sajitha Rani, T. [b#] and Shalini Pillai, P. [a#]

[a] Department of Agronomy, College of Agriculture, Vellayani, Thiruvananthapuram, Kerala, India.
[b] Department of Agronomy, College of Agriculture, Padannakkad, Kasaragod, Kerala, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jeai/2024/v46i123221

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/129699

Review Article

Received: 28/10/2024
Accepted: 30/12/2024
Published: 31/12/2024

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. Furthermore, traditional agriculture encounters significant hurdles from biotic and abiotic stresses that impede crop production, resulting in economic losses. Consequently, it became imperative to develop innovative technology alongside sophisticated production methods to address the current situation and ensure future stability. Hydroponics is highly effective in eliminating many of the limitations associated with traditional soil farming and offers significant advantages, including higher crop yields, efficient water

---

[++] Research Scholar;
[#] Professor and Head;
**Corresponding author: E-mail: anusreegirija@gmail.com;*

***Cite as:** G, Anusree., Sajitha Rani, T., and Shalini Pillai, P. 2024. "Exploring the Potential of Soil-Less Farming through Hydroponics in India: A Review". Journal of Experimental Agriculture International 46 (12):902-22. https://doi.org/10.9734/jeai/2024/v46i123221.*

and nutrient use, and reduced environmental footprint. 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. Plants can save enormous energy by providing nutrients directly to their roots, which would otherwise be squandered in the pursuit of these vital inputs. This review examines the potential of hydroponic technology and its contribution to boosting the productivity and quality of agricultural crops. Additionally, it covers various hydroponic systems used, their advantages and limitations, the role of different components, the market potential of hydroponics in India, and existing successful hydroponic firms. Relevant studies were analyzed to assess the performance of different hydroponic systems in growing different crops, in terms of crop growth, productivity, and resource efficiency. In conclusion, the hydroponics system can now serve as a potential method of sustainable agriculture, promising to cultivate resilience and ensure food availability for future generations amidst the challenges of land and water degradation and climate change.

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. Optimal plant growth and development necessitate soil that offers support, essential nutrients, aeration, and water, as well as the capacity to act as a buffer during abrupt fluctuations in soil pH (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).

In this context, cultivating adequate food sustainably and environmentally responsibly with constrained resources is feasible through the implementation of soil-less techniques, considered as an alternative approach for producing healthy crops (Butler and Oebker, 2006). As the world grapples with the pressing need for sustainable practices to ensure food security, these soil-less alternatives emerge as vital solutions that not only enhance agricultural efficiency but also contribute to a more resilient and eco-friendly food system. Embracing such advancements will be crucial in our collective journey towards a future where sustainable agriculture becomes the norm, ensuring that we can nourish both people and the planet.

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 (Rajendran et al*.,* 2024). A diverse array of commercial and speciality crops can be cultivated with hydroponics, including leafy greens, tomatoes, cucumbers, peppers, strawberries, and others (Sharma et al*.,* 2018).

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 (Hussain et al., 2014; Sharma et al*.,* 2018).

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 areas with limited access to advanced technology, particularly in rural communities (Jain et al., 2019; Dhananjani and Pakeerathan, 2022). 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.

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).

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).

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 of all the essential nutrient elements should be prioritized for better establishment and yield of the crops (Yang et al*.,* 2021). The nutrient supply in hydroponics can profoundly affect the nutrition, flavour, texture, colour, and other attributes of fruit and vegetable crops (Levine et al*.,* 2021).

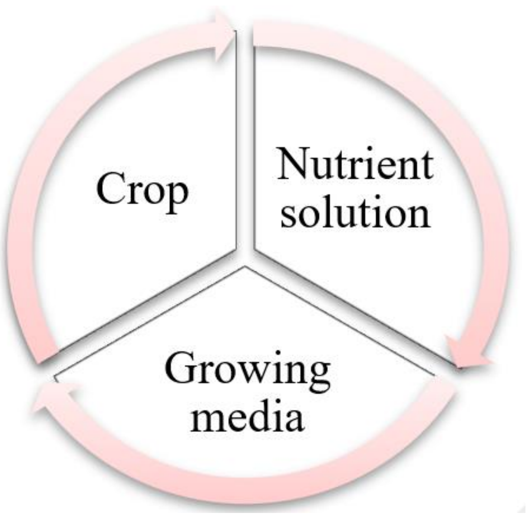

Fig. 1. Major components of a hydroponic system

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)

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	Abak and Celikel (1994)
	Cucumber	Cardarelli et al. (2012)
	Pumpkin	Hansen et al. (2010); Martin et al. (2012)
	Lettuce	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)

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

Element Major nutrients	Ionic form	Concentration limit (ppm)	Average concentration (ppm)
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
iii. 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

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). Inadequate or excessive concentrations of minerals or an imbalanced ion composition in the nutrient solution may inhibit plant growth development, resulting in toxicity or nutrient-induced deficiencies (Chrysargyris et al*.,* 2021).

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.

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 (Kulkarni et al., 2017). 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. Wang et al. (2017) found that a mixture of three (HNO_3, H_3PO_4, and H_2SO_4) acids was much more effective than only single acid for maintaining an optimal solution pH of 5.5–6.5.

In general, stabilizing the pH of a nutrient solution is necessary for optimum crop productivity in hydroponics (Frick and Mitchell, 1993), and maintaining an adequate nutrient solution and pH level are often cited as major obstacles to hydroponic production (Alexopoulos et al., 2021). Despite the fact that the optimal pH in the root zone of most crops grown hydroponically ranges from 5.5 to 6.5, although values as low as 4.0 have been proposed for preventing the incidence of infections from *Pythium* and *Phytophthora* spp. (Hoagland and Snyder, 1933; Gillespie et al., 2021).

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). Inadequate management of the nutrient solution, or an imbalanced ion composition could inhibit plant growth due to either toxicity or nutrient-induced deficiency (Grattan and Grieve, 1999). Delivering the optimal nutrient solution and electrical conductivity (EC) level for cultivating crops in hydroponic systems minimizes nutrient solution waste, hence saving production costs and lowering the impact on the environment (Al-Meselmani, 2022).

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).

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.

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

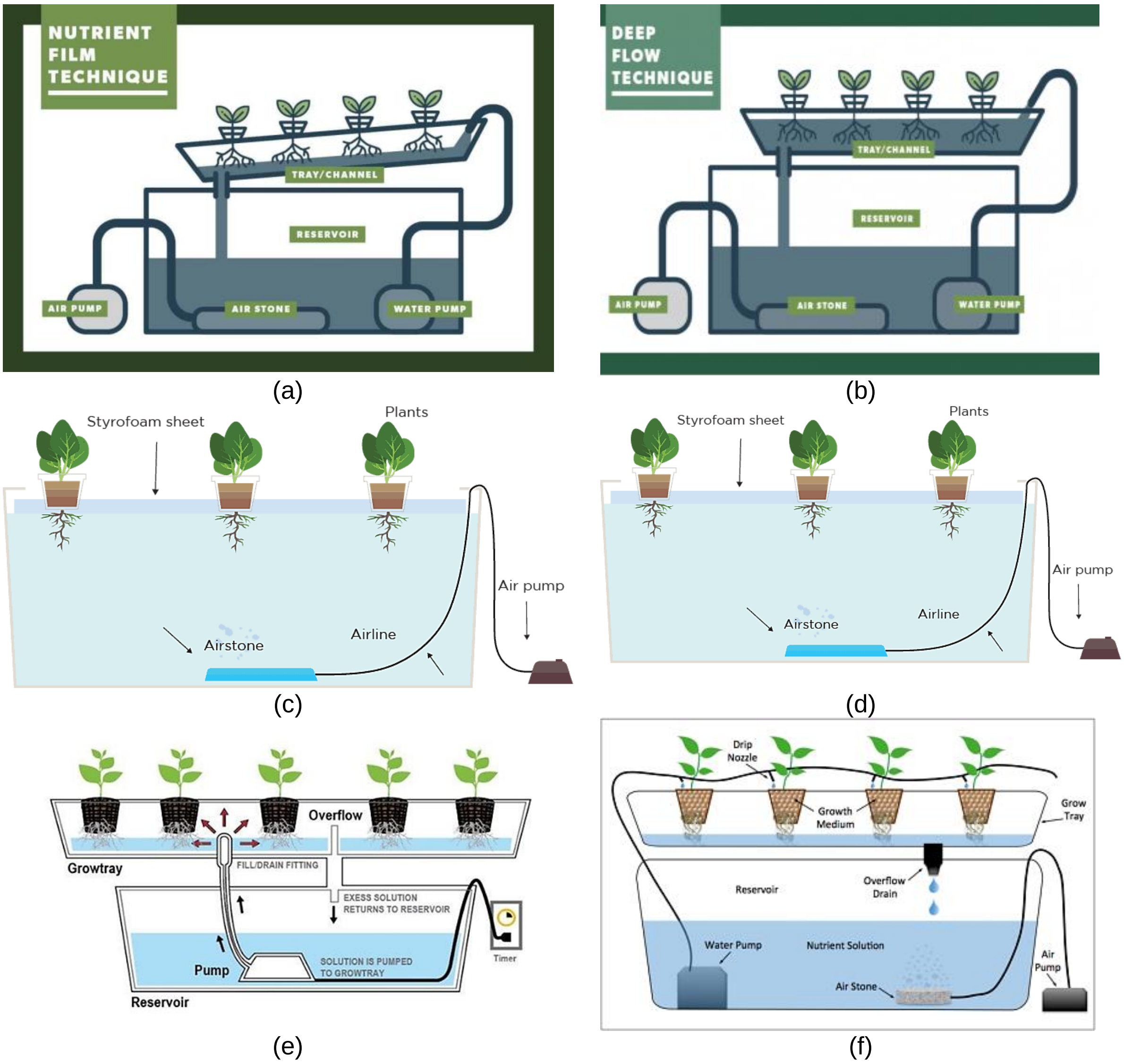

Fig. 2. Different types of hydroponic systems; (a)-nutrient film technique, (b)-deep flow technique, (c)-deep water culture, d-wick system, (e)-ebb and flow system, (f)-drip system

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). During flooding, the plants are supplied with nutrient rich water, and subsequent draining exposes the roots to oxygen, ensuring enough aeration for the plant roots (Bildirici, 2024). The mechanism recycles the water by returning it to the reservoir by gravity.

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.

Yang et al. (2023) compared NFT and deep water culture (DWC) systems in lettuce production and found that although a 30 per cent yield increase was observed with NFT, total chlorophyll and total carotenoid contents were greater in DWC. The assessment of five distinct hydroponic systems, namely NFT, deep film technique, ebb and flow, aeroponic system, and floating raft system, utilizing lettuce as a test crop, indicated that fresh and dry shoot and root weight, plant height, and the shoot-root ratio were significantly affected by the hydroponic systems, with the NFT system exhibiting a yield increase of 6-10 per cent relative to the other system (Frasetya et al., 2021).

Majid et al. (2021) evaluated the viability of hydroponic farming as a feasible alternative to soil-based agriculture. Despite plants cultivated in deep water system exhibited accelerated maturation, increased yield, superior quality, and the best photosynthetic rate, the NFT was identified as the most water-efficient system, reducing consumption by around 64 per cent. A comparative analysis of the growth rates of leafy green spinach species in two distinct hydroponic systems, namely Nutrient Film Technique (NFT) and Deep Water Culture (DWC), was conducted in a controlled environment, revealing superior plant development in terms of height and leaf count in the NFT system (Srivani et al., 2022).

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); Bildirici (2024)
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, considering the expanding demand for organic products and the rising curiosity among farmers and researchers regarding its viability as a sustainable farming method (Kumar and Verma, 2024), and with the market already 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 (Swain et al., 2021), 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,	Vihari Kanukollu, Sairam Reddy,	Grow greens, lettuce, herbs, and exotic foods all year round. Delivers hydroponic kits and farm-fresh produce.

	Hyderabad	Sampath Vinay, and Srinivas Chaganti 2017	Reduce carbon footprint significantly while producing 30 times more with up to 95 per cent less water.
4	Future Farms, Chennai	Sriram Gopal 2014	Spreads over 10 states growing leafy vegetables. Top supplier of precision agricultural automation and hydroponic 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.

12. 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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Abak, K., & Celikel, G. (1994). Comparison of some Turkish ongmated organic and inorganic substrates for tomato soilless culture. *Acta Horticulturae*, 366, 423-428.

Abbas, S. (2009). Effect of particle size distribution of perlite and organic media on cucumber in hydroponics. Indian Journal of Horticultural Science, 66, 326-332.

Abd-Elmoniem, E. M., Abdrabbo, M. A., Farag, A. A., & Medany, M. A. (2006). Hydroponics for food production: comparison of open and closed systems on yield and consumption of water and nutrient. In 2nd International Conference on Water Resources and Arid Environments. *Riyadh, Saudi Arabia: King Saudi Universit*y, pp. 1-8.

Abou-Hadid, A. F., El-Beltagy, A. S., Medany, M. A., & Hafez, M. M. (1995). Performance of Soilless Media on Greenhouse Production of Cucumber, *Cucumis sativus*, in Egypt. *Journal of Vegetable Crop Production*, 1(1), 93-98.

Alexopoulos, A. A., Marando, E., Assimakopoulou, A., Vidalis, N., Petropoulos, S. A., & Karapanos, I. C. (2021). Effect of Nutrient Solution pH on the Growth, Yield and Quality of *Taraxacum officinale* and *Reichardia picroides* in a Floating Hydroponic System. Agronomy, 11(6), 1118. https://doi.org/10.3390/agronomy11061118

Al-Karaki, G. N., & Al-Hashimi, M. (2012). Green fodder production and water use efficiency of some forage crops under hydroponic conditions. *International Scholarly Research Notices*, (1), 924672.

Al-Meselmani, M. A. (2022). Nutrient solution for hydroponics. In *Recent Research and Advances in Soilless Culture*. IntechOpen. https://doi.org/10.5772/intechopen.101604

AlShrouf, A. (2017). Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. *American Academic Scientific Research Journal for Engineering, Technology and Sciences*, 27(1), 247-255.

Aparna, P. V., Silpa, S. J., & Rema, K. P. (2019). Irrigation scheduling studies on soilless culture media for Polyhouse cultivation of vegetable crops. Project Report. Department Of Irrigation and Drainage Engineering, Kelappaji College Of Agricultural Engineering and Technology, Tavanur, Kerala Agricultural University.79p.

Argo, W. R., & Fisher, P. R. (2002). Understanding pH management for container-grown crops. Meister Publishing, Willoughby, OH.

Baddadi, S., Bouadila, S., Ghorbel, W., & Guizani, A. (2019). Autonomous Greenhouse Microclimate through Hydroponic Design and Refurbished Thermal Energy by Phase Change Material. *Journal of Cleaner Productio*n, 211, 360–379.

Barbosa, G. L., Daiane, F., Gadelha, A., & Kublik, N. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health*, 12(6), 6879–6891.

Beibel, J. P. (1960). Hydroponics-The Science of Growing Crops Without Soil‖. *Florida Department of Agric. Bull.* 180p.

Berndsen, C., & Gardener, M. (2014). Backyard Hydroponics. University of California Cooperative Extension, San Diego County, 9p.

Bildirici, N. (2024). The Design of an Innovative Aquaponic System for the Climate Conditions of Van City. Bildirici, N. & Espinal, C. A. (Ed.). The Design of an Innovative Aquaponic System for the Climate Conditions of Van City. UBAK Publishing House, Ankara, Turkey, pp. 1-83. https://doi.org/10.5281/zenodo.13950354

Borji, H., Ghahsareh, A. M., & Jafarpour, M. (2010). Effects of the substrate on tomato in soilless culture. *Research Journal of Agriculture and Biological Sciences*, 6(6), 923-927.

Bradley, P., & Marulanda, C. (2001). Simplified hydroponics to reduce global hunger. *Acta Horticulturae*, 554, 289-296.

Brechner, M. L., Albright, L. D., & Weston, L. A. (2007). Impact of a variable light intenity at a constant light integral: effects on biomass and production of secondary metabolites by Hypericum perforaturm. *Acta Horticulturae*, 756, 221-228.

Bunt, A. C. (1988). Media and mixes for container-grown plants. Unwin Hyman Ltd., London, UK

Butler, J. D., & Oebker, N. F. (2006). Hydroponics as a Hobby Growing Plants Without Soil. Circular 844. Information

Office, College of Agriculture, University of Illinois, Urbana, *IL* 6180p.

Buwalda, F., Baas, R., Van-Weel, P. A., (1994). A soilless ebb-and-flow system for all-year-round chrysanthemums. *Acta Horticulturae*, 361, 123–132.

Cardarelli, M., Rouphael, Y., Darwich, S., Rea, E., Fiorillo, A., & Colla, G. (2012). Substrate type affects growth, yield and mineral composition of cucumber and zucchini squash. *Journal of Life Sciences*, 6(7), 766.

Chang, D. C., Park, C. S., Kim, S. Y. & Lee, Y. B. (2012). Growth and tuberization of hydroponically grown potatoes. Potato research, 55, 69-81.

Chrysargyris, A., Petropoulos, S. A., Prvulovic, D., & Tzortzakis, N. (2021). Performance of hydroponically cultivated geranium and common verbena under salinity and high electrical conductivity levels. *Agronomy*. 11(6), 1237. https://doi.org/10.3390/agronomy11061237

Constantino, N. N., Mastouri, F., Damarwinasis, R., Borrego, E. J., Moran-Diez, M. E., Kenerley, C. M., Gao, X., & Kolomiets, M. V. (2013). Root-expressed maize lipoxygenase 3 negatively regulates induced systemic resistance to *Colletotrichum graminicola* in shoots. Frontiers in Plant Science, 4, 510.

Cooper, A. J. (1975). Crop production in recirculating nutrient solution. Scientia Horticulturae, 3, 251–258.

Dayananda, M. A. I., & Ahundeniya, W. M. K. B. (2014). Effect of different hydroponic systems and media on growth of lettuce (*Lactuca sativa*) under protected culture, 3, 456-459.

Dhananjani, B. A., & Pakeerathan, K. (2023). Organic nutrient solutions for Hydrophonic spinach (Basella alba) production in urban agriculture. Journal of Agricultural Sciences - Sri Lanka 8(1): 1-13. http://doi.org/10.4038/jas.v18i1.10095.

Domingues, D. S., Takahashi, H. W., Camara, C. A. P., & Nixdorf, S. L. (2012). Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production. Computers and Electronics in Agriculture, 84, 53–61.

Dorais, M., Papadopoulos, A. P., Luo, X., Léonhart, S., Gosselin, A., Pedneault, K., Angers, P., & Gaudreau, L. (2001). Soilless greenhouse production of medicinal plants in North Eastern Canada. Acta Horticulturae, 554, 297-303.

Duan, J. X.. Duan, Q. X., Zhang, S. F., Cao, Y. M., Yang, C. D., & Cai, X. D. (2020). Morphological, Physiological, Anatomical and Histochemical Responses of Micropropagated Plants of *Trichosanthes Kirilowii* to Hydroponic and Soil Conditions during Acclimatization. Plant Cell Tissue Organ Culture 142, 177–186.

Dysko, J., Kaniszewski, S., & Kowalczyk, W. (2015). Lignite as a new medium in soilless cultivation of tomato. *Journal of Elementology*, 20(3), 559-569.

Ellis, N. K., Jensen, M., Larsen, J., & Oebker, N. (1974). Nutri-culture Systems Growing Plants Without Soil. Station Bulletin No. 44. Purdue University, Lafayette, Indiana.

Frasetya, B., Harisman, K., & Ramdaniah, N. (2021). The effect of hydroponics systems on the growth of lettuce. IOP Conference Series: Materials Science and Engineering. *IOP Publishing*, 1098(4), 042115.

Frick, J., & Mitchell, C. A. (1993). Stabilization of pH in solid matrix hydroponic systems. *HortScience*. 28 (10), 981-984.

Gent, M. P., & McAvoy, R. J. (2011). Water and Nutrient Uptake and Use Efficiency with Partial Saturation Ebb and Flow Watering. *HortScience*, 46, 791–798.

Gi, P. S., Seon, L. B., & Ju, C. S. (1999). Effects of substrates on the growth and fruit quality of 'Mudeungsan' watermelon grown in hydroponics. Journal of the Korean Society for Horticultural Science, 40(4), 419-424.

Gillespie, D. P., Papio, G., & Kubota, C. (2021). High nutrient concentrations of hydroponic solution can improve growth and nutrient uptake of spinach (*Spinacia oleracea* L.) grown in acidic nutrient solution. *HortScienc*e, 56(6), 687-694. https://doi.org/10.21273/HORTSCI15777-21

Grattan, S. R., & Grieve, C. M. (1999). Salinity-mineral nutrient relations in horticultural crops. *Scientia Horticulturae*. 78(1-4), 127-157.

Grewal, H. S., Maheshwari, B., & Parks, S. E. (2011). Water and Nutrient Use Efficiency of a Low-Cost Hydroponic Greenhouse for a Cucumber Crop: An Australian Case Study. *Agricultural Water Management*, 98(5), 841–846.

Hansen, R., Balduff, J., & Keener, H. (2010). Development and operation of a hydroponic lettuce research laboratory. *Resource Magazine*, 17(4), 4-7.

Harris, D. (1988). Hydroponics: The Complete Guide to Gardening without Soil: A Practical Handbook for Beginners, Hobbyists and Commercial Growers. New Holland Publishers, London, MA, pp. 8–210.

Hayden, A. L. (2006). Aeroponic and hydroponic systems for medicinal herb, rhizome, and root crops. *HortScience*, 41(3), 536-538.

Hoagland, D. R., & Amon, D. I.(1950). The water-culture method for growing plants without soil. Circular - *California Agricultural Experiment Station*, 347(2), 32-37.

Hoagland, D. R., & Snyder, W. C. (1933). Nutrition of strawberry plant under controlled conditions. (a) Effect of deficiencies of boron and certain other elements, (b) susceptibility to injury from sodium salt. *Proceedings of the American Society for Horticultural Science*. 30, 288-294.

Hochmuth, G., & Hochmuth, R. (2011). Design suggestions and greenhouse management for vegetable production in perlite and rockwool media in Florida. University of Florida IFAS Extension, MA, https://doi.org/10.32473/edis-cv195-1990

Hochmuth, G.J., & Hochmuth, R. C. (2001). Nutrient solution formulation for hydroponic (perlite, rockwool, and NFT) tomatoes in Florida. Fla. Coop. Ext. Serv., Fact Sheet HS796.

Hochmuth, R., Olson, S., & Hochmuth, G. (2003). Polyethylene Mulching for Early Vegetable Production in North Florida. UF/IFAS Extension Circular. No:805.

Hussain, 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.

Islam, M. S., Ito, T., Maruo, T., Hohjo, M., Tsukagoshi, S., & Shinohara, Y. (2002). Effect of organic substrates on growth, morphological, reproductive and quality characteristics of tomato crops. Japanese *Journal of Tropical Agriculture*, 46(4), 272-278.

Jain, A., Kumari, N., & Jha, V. K. (2019). A review on hydroponic system: hope and hype. Chapter-11. *Recent advances in Chemical Sciences and Biotechnology*, pp. 143-149.

Janeczko, D. B. & Timmons, M. B. (2019). Effects of seeding pattern and cultivar on productivity of baby spinach (Spinacia oleracea) grown hydroponically in deep-water culture. *Horticulturae*, *5*(1), 20.

Jenner, G., & Starkey. N. (1980). Nutrient film technique: Practicalities of cadmium. *Plant and Soil*, 49, 333-342.

Jones, J. B. (1997). Hydroponics: A Practical Guide for the Soilless Grower. St. Lucie Press, Boca Raton, Fla.

Joseph, A., & Muthuchamy, I. (2014). Productivity, Quality and economics of tomato cultivation in aggregated hydroponics- A case study from Coimbatore region of Tamil Nadu. *Indian Journal of Science and Technology*, 7(8), 1078-1086.

Joshi, N., & Joshi, A. (2018). Green Spaces: Create your own, 1st ed, Notion Press Inc., Chennai.

Khan, F. A., Kurklu, A., Ghafoor, A., Ali, Q., Umair, M., & Shahzaib (2018). A Review on Hydroponic Greenhouse Cultivation for Sustainable Agriculture. *International Journal of Agriculture Environment and Food Sciences,* 2(2), 59-66.

Kim, H. K., Lee, J. H., Lee, B. S., & Chung, S. J. (1995). Effects of selected hydroponic systems and nutrient solutions on the growth of leaf lettuce (*Lactuca sativa* L.). *Journal of the Korean Society for Horticultural Science*, 36(2), 151-157.

Kulkarni, B. P., Mohite, A. S., Pai, S. V., & Yedake, P. R. (2017). Automation of hydroponics system. *International Journal of Science Technology and Engineering*, 3(9), 600-602.

Kumar, S., Kumar, S., & Lal, J., 2023. Assessing opportunities and difficulties in hydroponic farming. Bhartiya Krishi Anusandhan Patrika, 38(1), 56-64.

Kumar, T. V., & Verma, R. (2024). A Comprehensive Review on Soilless Cultivation for Sustainable Agriculture. *Journal of Experimental Agriculture International*, 46(6), 193-207.

Lee, S., & Lee, J. (2015). Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods. *Scientia Horticulturae*, 195, 206-215.

Lennard, M. A., & Leonard, B. V. (2006). A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an aquaponic test system. *Aquaculture International*, 14, 539–550.

Leonhart, S., Pedneault, K., Gosselin, A., Angers, P., Papadopoulos, A. P., & Dorais, M. (2002). Diversification of greenhouse crop production under supplemental lighting by the use of new cultures with high economic potential. *Acta Horticulturae,* 580, 249-253.

Levine, C. P., & Mattson, N. S. (2021). Potassium-deficient nutrient solution affects the yield, morphology, tissue mineral elements for hydroponic baby leaf spinach (*Spinacia oleracea* L.). *Horticulturae*, 7(8), 213. https://doi.org/10.3390/horticulturae7080213

Li, M., Ishiguro, Y., Otsubo, K., Suzuki, H., Tsuji, T., Miyake, N., Nagai, H., Suga, H., & Kageyama, K. (2014). Monitoring by real-time PCR of three water-borne zoosporic Pythium species in potted flower and tomato greenhouses under hydroponic culture systems. *European Journal of Plant Pathology*, 140(2), 229–242.

Logendra, L. S., Thomas, J., Gianfagna, T. J., David, R., Specca, D. R., Harry, W., & Janes H. W. (2001). Greenhouse tomato limited cluster production systems: crop management practices affect yield. *HortiScience*, 36(5), 893–896.

Maboko, M. M., & Du-Plooy, C. P. (2014). Yield of two hydroponically grown tomato cultivars as affected by transplanting stage or direct seeding. *HortScience,* 49(4), 438-440.

Maharana, L., & Koul, D. N. (2011). The emergence of Hydroponics. *Yojana,* 55, 39-40.

Majid, M., Khan, J., Shah, Q., Masoodi, K., Afroza, B., & Parvaze, S. (2021). Evaluation of hydroponic systems for the cultivation of Lettuce (*Lactuca sativa* L., var. Longifolia) and comparison with protected soil-based cultivation. *Agricultural Water Management*, 245, 106572.

Maloupa, E., Papadopoulos, A., & Bladenopoulos, S. (1993). Evapotranspiration and preliminary crop coefficient of gerbera soils culture grow in plastic greenhouse. *Acta Horticulturae*, 335, 519–525.

Martin, P. N., Gent, M. P. N., & Short, M. R. (2012). Effect on yield and quality of a simple system to recycle nutrient solution to greenhouse tomato. *HortScience*, 47(11), 1641-1645.

Mattas, K., Maloupa, E., Tzouramani, I., & Galanopoulos, K. (2000). An economic analysis of soilless culture in gerbera production. *Horticultural Science*, 35, 300–303.

Mazuela, P., Urrestarazu, M., & Bastias, E. (2012). Vegetable waste compost used as substrate in soilless culture. *Crop Production Technologies*, 179-198.

Mohamed, F. H., & Hussien, M. A. N. (2021). The Impacts of different Substrates on the Growth, Yield and Fruit Quality of Greenhouse-Grown Cherry Tomato. *Hortscience Journal of Suez Canal University*, 10(1), 73-76.

Morgan, L. (2003). Hydroponic Tomatoes, Massey University, New Zealand.

Nahalkova, J., Fatehi, J., Olivain, C., & Alabouvette, C. (2008). Tomato root colonization by fluorescent-tagged pathogenic and protective strains of *Fusarium oxysporum* in hydroponic culture differs from root colonization in soil. FEMS Microbiology Letters, 286(2), 152–157.

Naville E. H. (1913). The Temple of Deir el-Bahari (Parts I–III), Vol. 16. London: Memoirs of the Egypt Exploration Fund, pp. 12–17.

Neocleous, D., & Polycarpou, P. (2010). Gravel for soil less tomato culture in Mediterranian. *International Journal of Vegetable Science*,16(2),148-159.

Nielsen, C. J., Ferrin, D. M., & Stanghellini, M. E. (2006). Efficacy of biosurfactants in the management of *Phytophthora capsici* on pepper in recirculating hydroponic systems. *Canadian Journal of Plant Pathology*, 28, 450-460.

Niu, G., & Masabni, J. (2022). Hydroponics. In Plant factory basics, applications and advances Academic Press, 153-166.

Ortega-Martínez, L. D., Martínez V. C., Ocampo, M. J., Sandoval, C. E., & Perez, A. B. (2016). Efficiency of substrates in soil and hydroponic system for greenhouse tomato production. Revista mexicana de ciencias agrícolas, *7*(3), 643-653.

Ortega-Martínez, L. D., Sánchez-Olarte, J., Díaz-Ruiz, R., & Ocampo-Mendoza, J. (2010). Effect of different substrates on tomato seedlings growth (*Lycopersicum esculentum* Mill). Ra Ximhai, 6(3), 365−372.

Pardossi, A., Malorgio, F., Incrocci, L., Campiotti, C. A., & Tognoni, F. (2002). A comparison between two methods to control nutrient delivery to greenhouse melons grown in recirculating nutrient solution culture. *Scientia Horticulturae*, 92, 89–95.

Pisanu, A. B., Carletti, G. M., & Leoni, S. (1994). Gerbera jamesonii cultivation with different inert substrates. *Acta Horticulturae*, 361, 590–602.

Potter, D. J. (2014). A review of the cultivation and processing of cannabis (*Cannabis sativa* L.) for production of prescription medicines in the UK. *Drug Testing and Analysis,* 6, 31-38.

Prakash, S., Singh, R., Kumari, A. R., & Srivastava, A. K. (2020). Role of Hydroponics towards Quality Vegetable Production: An Overview. *International Journal of Current Microbiology and Applied Sciences,* 10, 252-259.

Prasad, A., Pragadheesh, V. S., Mathur, A., Srivastava, N. K., Singh, M., & Mathur, A. K. (2012). Growth and centelloside production in hydroponically established medicinal plant *Centella asiatica* (L.) *Industrial Crops and Products*, 35, 309-312.

Rajendran, S., Domalachenpa, T., Arora, H., Li, P., Sharma, A., & Rajauria, G. (2024). Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation. *Heliyon*, 10(5), e26823

Ramazzotti, S., Gianquinto, G., Pardossi, A., Muñoz, P., & Savvas, D. (2013). Good Agricultural Practices for Greenhouse Vegetable Crops; *FAO: Rome, Italy*.

Raviv, M., Lieth J. H., & Bar-Tal, A. (2019). Soiless culture: Theory and practice, *Elsevier, San Diego, CA.*

Resh, H. M. (2013). Hydroponic Food Production: a Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. *CRC Press, Boca Raton, Fla*.

Reshma, T. (2016). Standardization of hydroponics in tomato. MSc Thesis*. Kerala Agricultural University* 72p.

Rodriguez-Ortega, W. M., Martinez, V., Nieves, M., Simon, I., Lidon, V., Fernandez-Zapata, J. C., Martinez-Nicolas, J. J., Camara-Zapata, J. M., & García-Sanchez, F. 2019. Agricultural and physiological responses of tomato plants grown in different soilless culture systems with saline water under greenhouse conditions. *Scientific reports, 9(1), 6733.*

Romeo, D., Vea, E. B., & Thomsen, M. (2018). Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. *Procedia CIRP*, 69, 540–545.

Rouphael, Y., & Colla, G. (2005). Growth, yield, fruit quality and nutrient uptake of hydroponically cultivated zucchini squash as affected by irrigation systems and growing seasons. *Scientia Horticulturae*, 105(2), 177- 195.

Rufi-Salis, M., Calvo, M. J., Petit-Boix, A., Villalba, G., & Gabarrell, X. (2020). Exploring Nutrient Recovery from Hydroponics in Urban Agriculture: An Environmental Assessment. Resources Conservation and Recycling, 155, 104683.

Russo, G., & Mugnozza, S. G. (2005). LCA Methodology Applied to Various Typology of Greenhouses. *Acta Horticulturae*, 691, 837–844.

Saaid, M. F., Yahya, N. A. M., Noor, M. Z. H., & Ali, M. M. (2013). A development of an automatic micro-controller system for deep water culture (DWC). In 2013 IEEE 9th international colloquium on signal processing and its applications, pp. 328-332.

Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry-A review. *European Journal of Horticulture Sciences*, 83, 280–293.

Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Griessler Bulc, T., & Junge, R. (2016). Tomato productivity and quality in aquaponics: Comparison of three hydroponic methods. *Wate*r, 8(11), 533.

Shahinrokhsar, P. (2008). Influences of Irrigation schedules and substrates on fruit quality of tomato (cv Hamra) in soilless culture. In Proceedings of the International Conference on Agricultural Engineering, Hersomssos, *Crete, Greece*, pp. 175-182.

Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*, 17(4), 364-371.

Shrestha, A., & Dunn, B. (2013). Hydroponics. *Oklahoma Cooperative Extension Services*, HLA-6442.

Singh, H., Dunn, B., & Payton, M. (2019). Hydroponic pH modifiers affect plant growth and nutrient content in leafy greens. *Journal of Horticultural Research*, *27*(1), 31-36.

Singh, S. R., & Rajan, S. (2022). Vertical hydroponics: A future technology for urban horticulture. *Indian Horticulture*, 67(2), 36-39.

Sonneveld, C. & Voogt, W. (2009). Plant nutrition of greenhouse crops. Springer, *Dordrecht, Netherlands*.

Sonneveld, C., Baas, R., Nijssen, H. M. C., & DeHoog, J. (1999). Salt tolerance of flower crops grown in soilless culture. *Journal of Plant Nutrition*, 22(6),1033-1048.

Souza, S. V., Gimenes, R. M. T., & Binotto, E. (2019). Economic Viability for Deploying Hydroponic System in Emerging Countries: A Differentiated Risk Adjustment Proposal. *Land Use Policy*, 83, 357–369.

Srivani, P., Yamuna Devi, C. R., & Manjula, S. H. (2022). Prediction and comparative analysis using ensemble classifier model on leafy vegetable growth rates in DWC and NFT smart hydroponic system. In *IOT with Smart Systems: Proceedings of ICTIS 2021,* Volume 2 (pp. 795-804). *Springe*r, Singapore.

Stewart, C. L., & Lovett-Doust, L. 2003. Effect of phosphorus treatment on growth and yield in the medicinal herb *Calendula officinalis* L. (Standard Pacific) under hydroponic cultivation. *Canadian Journal of Plant Science*, 83(3), 611-617.

Subramani, T., Gangaiah, B., Baskaran, V., & Swain, S. (2020). Effect of soilless growing media on yield and quality of tomato (*Solanum lycopersicum* L.) under tropical island condition. *International Journal of Current Microbiology and Applied Sciences*, 9(5), 2084-2090.

Sundin, P., Waechter-Kristensen, B., & Jensen, P. (1995). Effects of saprophytic bacteria in the closed hydroponic culture of greenhouse crops. Acta Horticulturae, 396.

Surendran, U., Chandran, C., & Joseph, E. J. (2017). Hydroponic Cultivation of *Mentha spicata* and Comparison of Biochemical and Antioxidant Activities with Soil-Grown Plants. *Acta Physiologiae Plantarum* 39, 1-14.

Swain, A., Chatterjee, S., & Vishwanath, M. (2021). Hydroponics in vegetable crops: A review. *The Pharma Innovation Journal*, 10(6), 629-634.

Talukder, M. R., Asaduzzaman, M., Tanaka, H., & Asao, T. (2019). Electro-degradation of culture solution improves growth, yield and quality of strawberry plants grown in closed hydroponics. *Scientia Horticulturae*, 243-251.

Thinggaard, K., & Middelboe, A. L. (1989). Phytophthora and Pythium in pot plant cultures grown on ebb and flow bench with recirculating nutrient solution. *Journal of Phytopathology*, 125(4), 343–352.

Verdoliva, S. G., Gwyn-Jones, D., Detheridge, A., & Robson, P. (2021). Controlled comparisons between soil and hydroponic systems reveal increased water use efficiency and higher lycopene and β-carotene contents in hydroponically grown tomatoes. *Scientia Horticulturae*, *279*,109896.

Verma, S. (2023). Scope of hydroponic farming in India. Enter Climate. https://enterclimate.com/blog/scope-of-hydroponic-farming-in-india/

Vourdoubas, J. (2015). Overview of Heating Greenhouses with Renewable Energy Sources a Case Study in Crete—Greece. *Journal of Agriculture and Environmental Sciences*, 4(1), 70–76.

Walters, K. J., Behe, B. K., Currey, C. J., & Lopez, R. G. (2020). Historical, current, and future perspectives for controlled environment hydroponic food crop production in the United States. *HortScience*, *55*(6), 758-767.

Wang, L., Chen, X., Guo, W., Li, Y., Yan, H., & Xue, X. (2017). Yield and nutritional quality of water spinach (*Ipomoea Aquatica*) as influenced by hydroponic nutrient solutions with differen adjustments. *International Journal of Agriculture and Biology*. 19(4), 635-642.

Williams, K. A., & Nelson, J. S. (2014). Challenges of using organic fertilizers in hydroponic production systems. In XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014): 1112, pp. 365-370.

Win, K. T., Toyota, K., Motobayashi, T., & Hosomi, M. (2009). Suppression of ammonia volatilization from a paddy soil fertilized with anaerobically digested cattle slurry by wood vinegar application and flood water management. *Soil Science and Plant Nutrition*, 55(1), 190–202.

Yang, T., Samarakoon, U. C., & Altland, J. E. (2023). Comparison of growth, phytochemical content, nutrient uptake, and water consumption of lettuce under two hydroponic system designs: nutrient film technique and deep-water culture.

Acta Horticulturae, 1377, 747-754.https://doi.org/10.17660/ActaHortic.2023.1377.91

Yang, T., Samarakoon, U., Altland, J., & Ling, P. (2021). Photosynthesis, biomass production, nutritional quality, and flavor-related phytochemical properties of hydroponic-grown arugula (*Eruca sativa* Mill) 'standard' under different electrical conductivities of nutrient solution. *Agronomy*.11(7), 1340. https://doi.org/10.3390/agronomy11071340

Yanti, C. W. B., Dermawan, R., Nafsi, N. S., Bahrun, A. H., Mollah, A., & Arafat, A. 2020. Response of kale (*Brassica alboglabra* L.) to various planting media and application of liquid inorganic nutrition in DWC (deep water culture) hydroponic systems. *In IOP Conference Series: Earth and Environmental Science*, 486(1), 1-8.

Yoshimatsu, K. (2012). Innovative Cultivation: Hydroponics of Medicinal Plants in the Closed-Type Cultivation Facilities. *Journal of Traditional Medicine*, 29, 30–34.

Zekki, H., Gauthier, L., & Gosselin, A., (1996). Growth, productivity, and mineral composition of hydroponically cultivated greenhouse tomatoes, with or without nutrient solution recycling. *Journal of the American Society for Horticultural Science*, 121, 1082-1088.

Zhang, C., Xiao, H., Du, Q., & Wang, J. (2023). Hydroponics with split nutrient solution improves cucumber growth and productivity. *Journal of Soil Science and Plant Nutrition*, *23*(1), 446-455.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/129699