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ADVANCEMENTS IN HYDROPONIC AND SOIL-LESS CULTIVATION OF HIGH-VALUE SPICE CROPS

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ABSTRACT
With the rising demand for sustainable agricultural practices and quality spice production, there has been a surge in the interest of hydroponic and soilless culture technologies. The cultivation of traditional spices is plagued with many problems such as soil degradation, scarcity of water, climate variability, occurrence of pests and diseases, and loss of land area suitable for their cultivation. Hydroponics provides a potential alternative that allows for precise nutrient supply, water use, environmental management and crop management. The present review presents a detailed account of the evolution, principles and the recent developments in hydroponic/soilless culture of high-value spice crops. Different types of hydroponic systems such as Nutrient Film Technique (NFT), Deep Water Culture (DWC), Ebb and Flow, Aeroponics, Wick Systems and Drip Irrigation are explained and their operational characteristics, advantages, limitations and suitability for spice crop production are discussed. The review focuses on the research findings on some significant crop species like black pepper, saffron, turmeric, ginger, garlic, fenugreek, coriander, celery, parsley with the emphasis on the growth, yield, nutrient uptake, essential oil content and accumulation of bioactive compounds under controlled cultivation conditions. In addition, the adoption of cutting-edge technologies like the Internet of Things (IoT), sensor-based monitoring and automation, artificial intelligence, and vertical farming has dramatically improved production efficiency and resource utilization. While the potential benefits are significant, there are several challenges to consider, such as nutrient management, energy use, economic viability, and system complexity. The integration into renewable energy, optimizing nutrient use for specific crops, the use of smart cultivation techniques, and the development of sustainable production systems are all areas of future research that will further boost the importance of hydroponics in climate-smart agriculture and high value spice crop production.

KEYWORDS: Hydroponics; Soilless cultivation; Spice crops; Controlled environment agriculture; Vertical farming; IoT; Sustainable agriculture.

INTRODUCTION
The soil is often the most readily available growth medium for plants. It anchors plants, supplies nutrients and other requirements (such as air and water) for plant growth (Ellis *et al.* 1974). But soils can sometimes offer significant restrictions to plant growth. Insects and disease-causing organisms, improper soil reactions, poor soil compaction, inadequate drainage, and erosion damage. Open field farming is very challenging due to requiring significant land, labour and water (Gautam *et al.* 2021).
Soilless cultivation means growing plants and providing the plant's root with nutrients, in the form of nutrient solution (Maharana and Koul 2011). Plants grow well when the roots are in contact with the nutrient solution or inert medium. Sphagnum peat, coco peat, Vermiculite, Sand, Sawdust, Vermiculite, Gravel, Rock wool, Peat moss, Perlite or Coir etc. are some of the inert media (Maharana and Koul 2011).
Hydroponics is defined as the growth of plants in controlled environments like greenhouses, vertical farms etc. The Greek terms "Hydro" and "Ponos," which stand for water and labour, respectively, are the source of the 1937 term "hydroponics." The term "hydroponicist" is used to refer to a person that performs hydroponics, and a "hydroponicum" is a building, garden or area in which hydroponics is utilized for agricultural purposes (Jones Jr 2014).
The spices are phanerogamic, angiospermic crops which produce seeds and are cultivated in specific agroclimatic regions. Spice crops were first grown in the Indus Valley Civilisation and Mesopotamian Valley Civilisation around 9000 BCE. Farmer communities in countries such as India, Turkey, Bangladesh, China, Indonesia, Pakistan, Ethiopia, Nepal, Colombia and Myanmar are actively cultivating and managing these crops. About 75% of the world's supply and output of spices comes from Indian farmers. In India, many different types of spice

crops including *Piper nigrum, Elettaria cardamomum, Cinnamomum verum, Zingiber officinale, Curcuma longa, Syzygium aromaticum, Myristica sp., Vanilla, Crocus sativus, Allium sativum* are well suited to various agroecological zones. The roots, stems, leaves, flowers and fruits are utilized in various ways, including the production of culinary powders, medicinal syrups, and pastes, as well as for use in cosmetics and disinfectants.
Piper nigrum provides 3% of Vitamin K and 13% of manganese, both vital for the body's immune system, bone health, and wound healing. *Elettaria cardamomum* promotes the production of natural antioxidants and has anti-inflammatory, anti-cancerous and anti-ulcer effects. *Cinnamomum verum* is used to regulate blood pressure, heart rate, boost immunity, digestion and circulation. *Zingiber officinale* is useful for immunity, heart related disorders and for treating nausea, motion sickness, constipation, and osteoarthritis. *Curcuma longa* can be used to treat excessive cholesterol, depression, liver disorders, and osteoarthritis. It has several vitamins, omega 3 fatty acids and curcumin which help reduce the risk of chronic diseases. *Syzygium aromaticum* contains eugenol which aids in digestion and also reduces pain and infections in the mouth, promoting oral health. *Myristica sp.* is an antioxidant, anti-inflammatory and hepatoprotective herb that prevents inflammation, alleviates joint pain. *Vanilla sp.* is beneficial for fever, spasms, blood coagulation disorders and gastrointestinal disturbance. *Crocus sativus* helps control depression, lowers inflammation, and promotes cardiovascular health (Pandey *et al*. 2025).
The spices and herbs are rising in demand by increasing the consumer's interest due to their health benefits (Nguyen *et al.* 2019). A rise in the essential oils market is also observed with most of the products being traded for its methanol, methanone, carvone, eugenol and linalool (Khaliq and Mushtaq 2023). So, hydroponic cultivation helps increase the yield, nutritional value, essential oil content, antioxidant and medicinal properties of spices (Stephen and Gopinath 2024).

EVOLUTION OF SOILLESS CULTIVATION

Historical development

Although the term soilless culture is a new one, plants growing in containers above the ground dates back many years. Temple of Deir el Bahari's wall paintings are the first document of plants grown in containers (Naville 1908). Soilless culture has been used for agricultural production by numerous ancient cultures. It is depicted in Egyptian hieroglyphic documents that date back several hundred years B.C that the growth of plants in water. The Aztecs grew a few crops on floating gardens. The hanging garden of Babylon is another good example of soilless culture (Hussain *et al.* 2014).
In 1627, the first publication of soilless culture was published by Francis Bacon in Slyva sylvarum and the water culture was put in the research spotlight. The German botanists Julius Von Sachs and Wilhelm Knop's discoveries helped in the development of the soilless cultivation technique in the years 1859-65, which became a standard research and teaching technique widely used today and also a type of hydroponics (Hussain *et al.* 2014).

Hydroponics in India

In India, Hydroponics was introduced by an English Scientist, W.J. Shalto Duglas in the year of 1946. A laboratory was established in the Kalimpong area of Darjeeling, West Bengal which is the Government of Bengal's experimental farm and also wrote a book on Hydroponics. The book was published under the name 'Hydroponics-The Bengal System' in the year of 1959. This technology has been implemented commercially by farmers of South Gujarat in 2008 (Hussain *et al.* 2014).

PRINCIPLES OF HYDROPONIC AND SOILLESS SYSTEMS

Plant nutrition in hydroponics

In hydroponics, the important nutrients are provided to the plants via the nutrient solution (Savvas and Gruda 2018). The nutrients applied for soil cultivation and hydroponics are different from one another as the plants cultivated in the soil derive their nutrients from the soil and for hydroponics, the nutrients applied are taken from the nutrient solution (EI-Kazzaz 2017). There are 17 elements that are required for growth and those essential nutrients are divided into two macro and micro nutrients (Macwan *et al.* 2020; Tembe *et al.* 2018)

Table 1: Nutrients used for hydroponics

ELEMENTS	CONCENTRATION (In ppm)
Major nutrients	
Nitrogen (N)	100-200
Phosphorous (P)	30-15
Potassium (K)	100-200
Calcium (Ca)	200-300
Magnesium (Mg)	30-80
Sulphur (S)	70-150
Minor nutrients	
Boron (B)	30.3
Chlorine (Cl)	-
Copper (Cu)	0.01-0.10

Iron (Fe)	2-12
Manganese (Mn)	0.5-2.0
Molybdenum (Mb)	0.05-4
Zinc (Zn)	0.05-0.5

Nutrient solution management

The management of nutrient solution in soilless culture is easy, but if the solution is not well managed, it may adversely affect the plants and lead to total failure. So, in this way, the tight nutrient management is the prime key of the success or failure of a soilless culture garden. The careful control of the pH, temperature and electrical conductivity of the nutrient solution and replenishing the nutrient solution as necessary will result in a successful soilless culture garden (Hussain *et al.* 2014).

pH and EC Regulation

The pH and EC are important characteristics to maintain optimal plant growth. The pH is a measure of acidity and basicity of a solution on a scale 0-14 (Kaur and Dewan 2023). The pH of nutrient solution of soilless cultivation ranges between 5.8-6.5 (Hussain *et al.* 2014). Electrical conductivity (EC) is a measure of the nutrient solution that can carry an electrical charge and is directly related to the number of dissolved salts (Kaur and Dewan 2023). The EC range for hydroponics is between 1.5 and 2.5 dS/m. Higher EC will promote restricted uptake of nutrients and lower EC will adversely affect plant health and productivity due to the osmotic pressure (Hussain *et al.* 2014).

Environmental control

To get proper growth of the plants, it is essential to maintain the environment of the hydroponic system. The temperature is an important factor of plant growth. The optimum temperature for the hydroponically grown plant is between 20-25°C during the day and 15-20°C during the night time. Temperature variations can have a significant effect on the production and quality of plants. It is crucial to use a thermometer to routinely check the temperature in order to maintain the proper temperature within the growth chamber. It is advised to utilise cooling devices, such as fans or air conditioning, to reduce the temperature if it is too high. Heating systems, however, can be used to increase the temperature if it is low. There may be a significant difference between a slight increase in temperature and a significant decrease. Ideal humidity for the plants grown hydroponically is between 40-60%. Mould, mildew and other pests can thrive in too much moisture and can be detrimental to plants. On the other hand, too low of a humidity could lead to the plants being dried out and wilted, thereby reducing growth and productivity. A hygrometer is advised that measures relative humidity of air within the growth room should be used to monitor the humidity in the room. If humidity levels are high, it is suggested to use fans or dehumidifiers to reduce the humidity. If it is low, humidifiers can be used to increase the humidity. Plants which are grown hydroponically needs artificial lights for photosynthesis and growth. It is important to consider the light's intensity, duration and wavelength when selecting a light source for a hydroponic system. LEDs, fluorescents or high-intensity discharge (HID) lights are the most common options for the light source in a hydroponic system. It is important to ensure that plants are free from pest and diseases by providing ventilation for hydroponically grown plants. To remove the excess heat and humidity exhaust fans are used to remove hot and humid air from the chamber and replace with it fresh cool air and also with the help of intake fans fresh air can be circulate in the chamber to maintain optimum CO2 level (Santosh and Gaikwad 2023).

HYDROPONIC SYSTEMS USED FOR SPICE PRODUCTION

Nutrient film technology (NFT)

A constant flow of nutrient-rich water is applied to the plant roots as part of the Nutrient Film Technique (NFT), which was developed by Allen Cooper in 1960s. This thin film allows good amount of oxygen to penetrate to the roots and also provides the required nutrients (Cooper 1979). NFT systems are widely used in commercial hydroponic systems, mostly due to their low water usage and adaptability. They are ideal for small to medium-sized plants with a short growth cycle since the shallow solution layer ensures rapid uptake of nutrients and good root growth (Jensen and Collins 1985). In order to avoid root matting and guarantee consistent nutrient distribution, recent developments in NFT systems concentrate on optimising flow rates and enhancing channel architecture (Resh 2022a). To control the growing environment accurately, several innovations have been integrated, such as nutrient level, pH and temperature sensors, and the modular systems that allow for easy system expansion (Lakhiar *et al.* 2018).

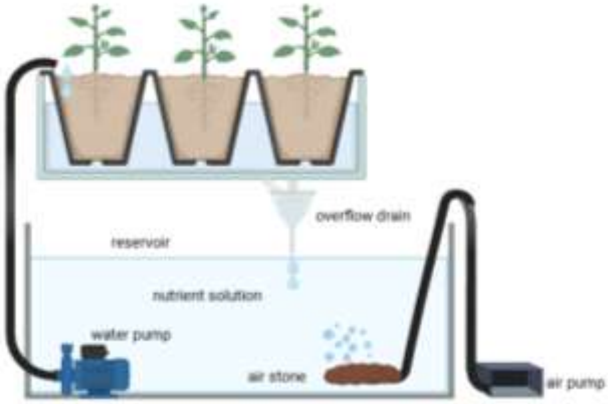

Figure 1: NFT Hydroponic system (Generated using Biorendor)

Deep water culture

Plant roots are suspended in oxygenated, nutrient-rich water in Deep Water Culture (DWC) systems. In contrast to NFT, DWC continuously supplies water, oxygen, and nutrients by maintaining a steady amount of nutrient solution (Jensen 1997). The incorporation of automated monitoring and control systems to ensure ideal nutrition and oxygen levels is one of the most recent advancements in DWC systems. Plant health and development rates have been enhanced by advances in aeration technology, such as the use of fine bubble diffusers, which have boosted oxygen dissolution in the nutrient solution (Marcelino *et al.* 2023).

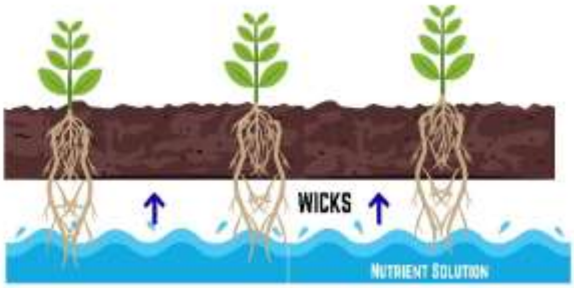

Figure 2: Deep Water Culture (Generated using Biorendor)

Ebb and Flow

The way ebb and flow systems work is that nutrient solution is periodically flooded into the grow bed and then drained back into a reservoir. During the drain phase, this cyclic process gives plants enough oxygen and the nutrients they require (Jones Jr 2014). The improvement of flooding cycle timing and control has been the main emphasis of Ebb and Flow system advancements. Precise control over flood frequencies and durations is now possible thanks to automated timers and smart controllers, maximising the utilisation of water and nutrients (Sharma *et al.* 2018). The use of sophisticated grow media that improve drainage and aeration, like expanded clay pellets and coconut coir, is one example of innovation (Resh 2022a).

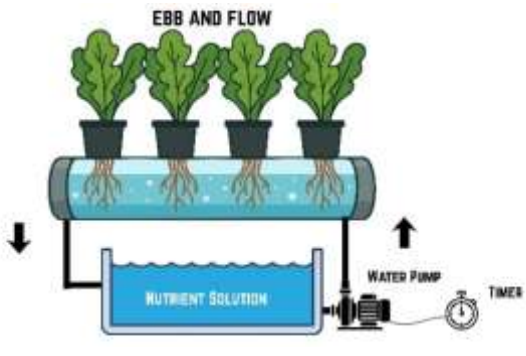

Figure 3: Ebb And Flow (Generated using Canva)

Aeroponics

In aeroponics, plant roots are suspended in the air and sprayed with a nutrient solution on a regular basis. This technique guarantees that the roots receive as much oxygen as possible while still receiving the water and nutrients they require. Aeroponics is renowned for its effectiveness and capacity to generate large yields using little water and nutrients (Lakhiar *et al. 2018)*. To enhance the nutrient absorption High – pressure misting systems and ultrasonic foggers have been developed (Soffer and Burger 1988).

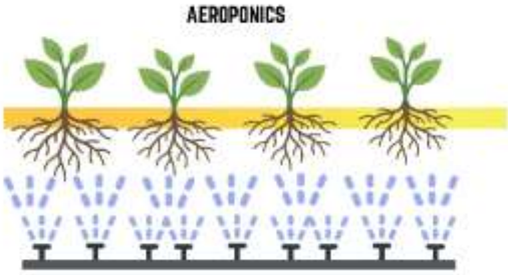

Figure 4: Aeroponics (Generated using Canva)

Wick Systems
One of the most basic hydroponic systems is a wick system, which uses capillary action to transport nutrient solution to plant roots through a wick material. These systems are perfect for novices and small-scale growers because they are passive and don't require pumps or other equipment (Resh 2022). To maximise the advantages of multiple systems, researchers are investigating the integration of wicking systems with other hydroponic techniques, such as combining wicking with NFT or DWC setups.

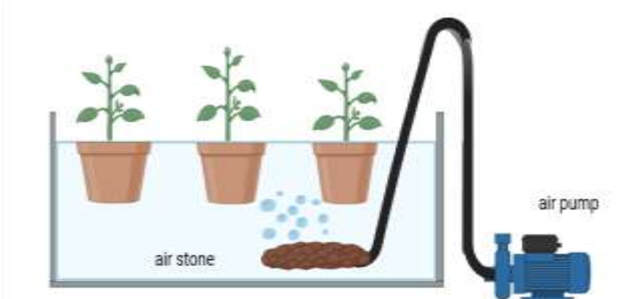

Figure 5: wick method (Generated using Canva)

Drip Systems
Drip systems use a network of tubing and emitters to feed fertiliser solution straight to each plant's base. Individual plant demands can be effectively satisfied with this exact delivery system, which also minimises water and nutrient waste (Resh 2022). The goal of drip system innovations has been to increase automation and efficiency. To avoid clogging and provide steady nutrition delivery, sophisticated emitters with programmable flow rates and self-cleaning features have been created. In order to maximise plant growth, smart irrigation controllers now incorporate sensors to track soil moisture, nutrient levels, and environmental factors. This allows them to modify the drip irrigation schedule in real time (Sharma *et al.* 2018).

Table:2 Comparison of hydroponic systems

SYSTEM	ADVANTAGES	DISADVANTAGES	SUITABLE SPICE CROPS
Nutrient Film Technique (NFT)	Water efficient Suitable for herbs and leafy plants	Not useful for large rooted plants Quick death of roots	Saffron, Garlic, Fenugreek, Coriander, Parsley
Deep Water Culture (DWC)	Simple and economical Low maintenance once set up Beginner friendly and suitable for large plants	Fluctuation of water and pH Risk of Oxygen loss	Black Pepper, Coriander, Fenugreek
Ebb and Flow System	Reusage of media helps in root growth Good amount of oxygen supply between roots	Risk of root rot is more More maintenance is required than DWC and NFT	Saffron
Aeroponics	Fast growth rates Maximum oxygen exposure to roots Less water usage than other systems	Expensive to build Difficult to maintain	Parsley, Coriander
Wick System	No need timers, pumps, electricity Very low in maintenance	Nutrient delivery is slow Wicks can dry out and also clog easily	Fenugreek, Coriander
Drip Irrigation System	Suitable for large plants Compatible with all the medias	Emitters can clog easily Time consuming	Ginger

GROWING MEDIA USED IN HYDROPONICS

In Hydroponics or soilless cultivation, growing media plays major role as a substitute for soil. It is mainly used to provide oxygen to the roots, makes sure that nutrients reach the roots and also provides stability to the plants (EI-Kazzaz 2017). Growing media are classified mainly into two viz. organic growing media and inorganic growing media (Stephen and Gopinath 2024).

Organic Growing Media

Coco peat-This media is made of shredded coconut husks. It neutralizes pH and provides aeration to the roots. **Peat moss-**Helps in retaining moisture in the growing media. **Rice hulls-**It is the by-product of rice industry. It decomposes very slowly and its functions is similar to coco peat (Gaikwad and Maitra 2020; Hussain et al. 2014).

Inorganic Growing Media

Sand-Sand is the media that is mostly used and regularly combined with vermiculite, perlite, and coco peat which improves aeration of the roots. **Perlite-** lightweight granules derived from silicone mineral which forms volcanoes. It retains more air than water and also helps in neutralizes pH and also has high porosity. **Vermiculite-**It is combination of both magnesium and potassium. It is a silicate mineral which expands during heat but light in weight. It retains good amount water and helps in aeration and proper drainage. **Rock wool-**Rock wool is the most widely used media among all which is sterile, non-degradable and porous mainly made of granite and limestone. It absorbs water easily. **Oasis Cubes-**Oasis cubes are made from an open-cell material which helps them to absorb both air and water (Gaikwad and Maitra 2020; Hussain et al. 2014; Macwan et al. 2020).

HYDROPONICS IS SPICES:

Hydroponics is essential for growing aromatics and spices since it increases product quality and yield. By controlling pests and diseases more effectively, this technique guarantees the production of contaminant-free, healthy planting materials. Hydroponics encourages the increased accumulation of medicinal components in spices while reducing the growing time. Raising the concentration of the main components found in the essential oil, it also enhances its yield and quality. Additionally, hydroponics makes it possible to produce a variety of leafy and herbal spices during the off-season (Stephen and Gopinath 2024).

Black Pepper

Black pepper is a crop that requires a lot of nutrients and is weather-sensitive, hydroponic farming appears to be a superior way to grow new plants while avoiding the negative impacts of unpredictable weather, soil nutrition, and pH fluctuations that could lower the quality of the new plant (Srinivasan *et al.* 2012). Hydroponic farming ensures that the crop production cycle begins in the absence of soil-borne pests and diseases, permits a more thorough examination of the entire root system, and makes it simpler to monitor root growth, all of which enable prompt pest control and the production of high-quality rootstock for new plants*(Amalfitano et al.* 2017; Pignata *et al.* 2017; Spehia *et al.* 2018).

In a study, black pepper stem cuttings (*P. nigrum L.* cv 'Kuching') were harvested freshly from the Malaysian Pepper Board. The deep-water culture method is used to cultivate black pepper hydroponically. Cuttings were planted in the laboratory in the growing trays with 10L of nutrient solution, EC- 1.8-2.5 mS/cm and pH- 5.8-6.3. Oxygen is given to the plants using an air pump and air stones. Seven treatments were carried out with different nutrient composition for different treatments and the experiment was done for about 4 weeks. Hoagland solution is taken as T1 and some supplements were added in other treatments. In which Hoagland solution supplemented with 0.005mM potassium silicate solution (T4) and Hoagland solution supplemented with 2mM salicylic acid solution (T6) showed faster root initiation. T1 produced the highest increase in root length accompanied by T6. The least performing nutrient solution was T5 which is the combination of T4 + 6mL of 1 M Ca $(No_3)_2.4H_20$ (Khadijah *et al.* 2021).

Saffron

Since the cultivated plants are sterile auto-triploids, saffron, one of the costliest spices in the world, is propagated vegetatively using corms. Its production is hampered by several factors, including the scarcity of arable land in cold, high-altitude regions and the labour-intensive harvesting and handling procedures. Saffron productivity is further decreased by cormlets' slow rate of proliferation and vulnerability to fungal infections (Nardi *et al.* 2022). A viable substitute for conventional open-field farming is hydroponics, which may boost saffron yields and reduce production expenses. By producing stock corms free of pathogens, this technique also promotes sustainable production. However, the equipment and growing conditions need to be carefully optimised for hydroponic saffron production to be successful (Dewir *et al*. 2022).

In a study, corms of saffron with an average of 6g ± 1 were cultivated in pots with perlite with six replications. Four types of nutrient solution were used of which three were Hoagland solutions with different concentrations of copper viz., 0, 5 and 20 µM in the form of Copper Sulphate. The experiment was carried out for about 8 weeks. Nutrient solution with 5 µM of Cu showed the highest values in leaf length, leaf dry weight and root length, contrastly the nutrient solution with 20 µM of Cu showed reduced growth in the above-mentioned parameters (Sorooshzadeh and Tabibzadeh 2010).

In another study, three different types of cultivation methods are compared which include cultivation using soil, Nutrient Film Technique (NFT) and a mixture of peat moss + perlite. Saffron corms of 12-15g about 450 nos. are taken. Hoagland solution is used as a nutrient solution. Results shown that soil cultivation has shown significant results compared to NFT and peat moss + perlite. Quality corms were produced using NFT rather than soil cultivation (Razan *et al.* 2023).

Turmeric

Turmeric (*Curcuma longa*), belonging to the family Zingiberaceae is regarded as a "golden spice" and is one of the most prized spices in human civilisation (Tudu *et al.* 2024). The ground-breaking soil-less growth method known as hydroponics, which feeds plants with carefully designed nutrient solutions, has been a game-changer for maximising turmeric production while tackling modern agricultural issues. The phytochemicals in the crop exhibit anti-inflammatory, antioxidant, antimicrobial and anticancer properties (Ramanjineyulu *et al.* 2025).
The hydroponic technique maximises curcumin production by optimising mineral nutrition through precise control over nutrient delivery (Goel *et al.* 2008). Regardless of seasonal limitations, the controlled environment eliminates soil-borne diseases, minimises the need for pesticides, and permits year-round production (Hewlings and Kalman 2017). It is especially appealing in water-scarce areas because it uses 80–90% less water than conventional farming (NCCIH., 2024). Nutrient solutions must be carefully formulated, with increased quantities of potassium and phosphorus during the rhizome growth stages. The ideal growth conditions are maintained at pH values between 5.8 and 6.2 and EC levels between 1.8 and 2.2 mS/cm. Coconut coir, perlite, vermiculite, or specialised substrate mixtures that offer sufficient aeration and root support are examples of growing media possibilities (Ramanjineyulu *et al.* 2025).

Ginger

Ginger (*Zingiber officinale*) is classified under the family Zingiberaceae used as a spice, flavouring agent and also as herbal medicine around the world (Zhang *et al.* 2021). It is thought to be indigenous to either Malaysia or India. In addition to being utilised as a spice in most Asian cuisines, ginger has a stellar reputation in traditional Chinese and Indian medicine. It possesses numerous therapeutic qualities (Rafie *et al*. 2003).

In this study, ginger was grown hydroponically in a greenhouse. Ginger pieces were treated with vitavax fungicide and it was planted. Three types of nutrient solution were used. Results shows that 7.65 lb of fresh rhizomes were produced. 62% increase in ginger yield which was proved statistically (Rafie *et al.* 2003).

Garlic

Garlic (*Allium sativum*) belongs to the family Liliaceae well known as spice crops since ancient times which has several medicinal, antiseptic and antimicrobial properties(Reuter and Sendl 1994). In this study, garlic bulbs are grown in a method called Nutrient Film Technology (NFT) in which two kinds of NFT were used. **Inorganic NFT:** Cooper solution formula was used. Different concentration(ppm) of nutrient solutions was used viz. 236N, 60P, 300k 185 Ca, 50 Mg, 68 S, 12 Fe, 0.3 B, 2Mn, 0.1 Zn. 0.1 Cu and 0.2 Mo. (NFT). **Organic NFT(ONFT):** In ONFT Grile fish (*Cyprinus carpio*) at the rate of 8 fishes/ tank was used. Results revealed that leaf area, fresh weight and diameter of the bulb were superior. The number of cloves and water use efficiency used for plating is also lower than the conventional method of planting (Abou-Hadid *et al.,* 1998).

Fenugreek

Fenugreek (*Trigonella foenum graceum*) belongs Fabaceae both seeds and leaves are used, which contain many medicinal properties. In this study, different types of hydroponic techniques were used, viz., Aggregate culture method and Water culture method and soil culture method was used as a control. In Aggregate culture sand, gravel and coconut fibre were used as a material to support the plant. In water culture, the roots are immersed in the nutrient solution. In soil culture plants were grown in soil as a control. Results shown that fenugreek grown in aggregate culture shows an average height of 15.8cm, in water culture average height was 15.6cm whereas, in soil culture the plant grows to an average height of 14.3cm. This shows that hydroponics was a successful method of cultivation compared to conventional method of cultivation (Tuwar and Tuwar 2018).

Coriander

Coriander (*Coriandrum sativum*) is one of the spice crops that belongs to the family Apiaceae, used as a flavouring and aromatic agent (Rashed and Darwesh 2015). In this study, a hydroponic system with Deep Flow Technique (DFT) was used. (Furlani et al. 1999) recommended a nutrient solution that was used in this experiment. Two types of coriander cultivars were used viz Coriander cv. Verdão and Coriander cv. Tabocas. In which cv. Verdão was more tolerant of climatic changes than cv. Tabocas (Silva 2020).

Celery

Celery (*Apium graveolens*) belongs to the family Apiaceae. Vitamins A, B1, B9, C, E, and K, as well as the minerals Ca, Mn, Mg, P, Fe, and Zn, are among the many nutrients found in celery that support a healthy body(Domagala-Swiatkiewicz and Gastol 2012; Shad *et al.* 2011). In a study, two experiments in hydroponic floating system for about 2 years 2014 and 2015. The nutrient solution utilized for the experiments was cooper solution. The nutrient solution was made in three different compositions of **N** viz 90,180,270 ppm. Celery plants were harvested after about 60 days in both the experiments. Results showed that there were significant differences in different N compositions. Intermediate nitrogen level 180mg/L showed highest values in plant height, no. of leaves/plant, plant fresh weight and also in total yield but dry weight plant showed least values. The lowest values were showed from nitrogen level 90mg/L, 270mg/L showed no significant changes (Abd-Elkader and Alkharpotly 2016).

Parsley

Parsley (*Petroselinum crispum*) belongs to the family Apiaceae. One of the main volatile substances in P. crispum essential oil, myristicin, has been found to have a number of medicinal and antioxidant qualities(Dong *et al.* 2017; Fusani *et al.* 2017; Marín *et al.* 2016). In a study, Parsley was grown in two different nutrient solutions given by Hoagland and Thakur(Hoagland and Arnon 1938; Thakur *et al*. 2019). The deep flow technique (DFT) of hydroponic system was used in the study. Parsley was also grown in pots for comparison. The experiment was carried out with three different treatments **T1-** Hoagland solution, **T2-** Thakur solution, **T3-** Tap water which was used as control. The results showed that T1 showed improved morphological attributes and physiological performances in hydroponic cultivation than pot cultivation and also more growth of leaf, stem and root were observed in T1 when grown hydroponically (Rattan *et al*. 2022).

Table 3: Types of spice crops and their hydroponic systems

CROPS	**HYDROPONICS SYSTEM**	**REFERENCE**
Black Pepper	Deep water culture	(Khadijah *et al.* 2021)
Saffron	Nutrient Film Technique	(Razan *et al.* 2023; Souret and Weathers 2000)
	Pot technique with fertigation	(Stelluti *et al.* 2023)
	Pot technique	(Sorooshzadeh and Tabibzadeh 2010)
	Ebb and flow system	(Dewir *et al.* 2022)
	Continuous immersion system	(Dewir et al. 2022)
Turmeric	Aeroponics	(Ramanjineyulu et al. 2025)
Ginger	Drip system	(Chong *et al.* 2023; Yaseer Suhaimi *et al.* 2012)
Garlic	Nutrient film Technology	(Chong et al. 2023)
	Floating or hanging Technique	(Most Tahera Naznin 2009; Naznin *et al.* 2010, 2015, 2018)
Fenugreek	Nutrient film Technology	(Begum *et al.* 2022)
	Non circulating culture and aggregate culture	(Tuwar and Tuwar 2018)
Coriander	Nutrient film Technology	(Sowmya *et al.* 2023)
	Deep Flow Technique	(Silva 2020)
Celery	Floating system	(Abd-Elkader and Alkharpotly 2016)
Parsley	Deep Flow Technique	(Rattan *et al.* 2022; Walters and Lopez 2021)

INTEGRATION OF ADVANCED TECHNOLOGIES

IoT-based nutrient monitoring

Internet of things (IoT) has great effect on hydroponics by integration of various devices and systems. Devices include smart sensors, automated controllers, cameras help to control the environment of hydroponic system monitoring and control (Hu *et al.* 2021). It also helps in data collection and analysis which is used to improve performance of the system and also predict issues of that systems issues (Liang and Shah 2023).

Sensors and automation

Light-detection resistors (LDR), soil moisture sensors (SMS), and LM35 temperature sensors (TMS) are examples of sensors that collect data on plant development, analyse it, and display it in a web application for maximum effectiveness (Chin and Audah 2017). Temperature, humidity, TDS, pH, and water level are among the environmental and nutritional variables that are monitored by sensors (Kaur *et al.* 2022).

Vertical farming

Vertical farming is a hydroponic system that uses vertical racks where multiple layers of plants are stacked on top of each other. Plants are grown in controlled environment where light, temperature, humidity and nutrients are monitored (Santosh and Gaikwad 2023). In urban settings where land is scarce, vertical farming techniques have been developed to optimise space utilisation in hydroponic systems. Compared to conventional horizontal farming, these systems can produce substantially more food per square metre by stacking growing units vertically traditional horizontal farming (Despommier 2010). Rotating towers, multi-level shelving units, and vertical wall gardens are examples of innovative vertical farming concepts that offer distinct benefits in terms of crop productivity and space efficiency (Banerjee and Adenaeuer 2014). In order to increase production and sustainability, recent advancements in vertical hydroponic systems concentrate on combining automation and smart technologies. At every level of the vertical structure, ideal growing conditions are guaranteed by automated systems for lighting, nutrition delivery, and environmental control (Kalantari *et al.* 2017).

CHALLENGES AND CONSTRAINTS

Even though there are lot of advantages of hydroponics more challenges are also there for these systems. One of the main technical challenges is managing nutrient solution and also to make sure that all the nutrients are delivered precisely to the plants. To control the nutrient delivery, pH levels and other automated systems needs high capital and is difficult to maintain and difficult to maintain (Resh 2022)

Economic challenges also play a major challenge. Initial setup cost for hydroponic system, mainly for small-scale farmers is unaffordable. Infrastructure, lighting, climate control systems, and automation technologies are among these expenses (Lages Barbosa *et al.* 2015). The economic viability of hydroponics may also be impacted by operational costs, such as energy costs for artificial lighting and climate control, especially in areas with high electricity rates (Sharma *et al.* 2018).

FUTURE PROSPECTS

Future hydroponics research is set to take advantage of new technologies that have the potential to completely transform the industry (Thapa et al. 2024). The creation of more economical and ecological materials for hydroponic systems is a potential field of study. The environmental impact and running expenses of hydroponic systems can be decreased by advancements in biodegradable and recyclable growing media as well as the use of renewable energy sources like solar power for climate control and lighting (Olle and Viršile 2013). Furthermore, developments in genetic engineering and plant breeding may result in the creation of crop types with improved growth rates, nutrient uptake efficiency, and disease resistance that are especially suited for hydroponic settings (Savvas and Gruda 2018). Using predictive models to optimise nutrient distribution and climate control, machine learning and artificial intelligence can further improve decision-making processes (Singh *et al.* 2015).

Multidisciplinary research and cooperation will be very beneficial to hydroponics in the future. To solve the intricate problems that hydroponic systems face, it is crucial to integrate knowledge and skills from disciplines including plant science, engineering, environmental science, and data science. Innovation in disease prevention, nutrient management, system design, and sustainable practices can all be fuelled by teamwork (Thapa *et al.* 2024). The advancement of hydroponic research and development can also be greatly aided by international cooperation and public-private partnerships. These partnerships can hasten the creation and commercialisation of cutting-edge hydroponic technology by combining resources, knowledge, and capital (Savvas and Gruda 2018).

With predictions of higher productivity, profitability, and resilience to climatic problems, high-value crop production has a promising future thanks to new technologies and sustainable agricultural methods. Innovation in vertical farming, hydroponics, and precision agriculture enables year-round, high-quality production (Shubhashish *et al*. 2025).

CONCLUSION

Hydroponic and soilless cultivation technologies have become a great alternative to soil-based agriculture. The increasing challenges associated with traditional farming systems, including soil degradation, water scarcity, climate variability, pest and disease incidence, and declining arable land enables the use hydroponics. Hydroponics offers a controlled production environment that enables precise management of nutrients, water, temperature, humidity, and light, which increases crop productivity.

This review highlights the historical development, principles, and various hydroponic systems employed for spice crop cultivation, including Nutrient Film Technique (NFT), Deep Water Culture (DWC), Ebb and Flow, Aeroponics, Wick Systems, and Drip Irrigation. Each system possesses unique advantages and limitations, making them suitable for specific spice crops depending on their growth habit, root architecture, and environmental requirements.

Several spice crops such as black pepper, saffron, turmeric, ginger, garlic, fenugreek, coriander, celery, and parsley have demonstrated promising responses under hydroponic and soilless cultivation systems. Research

findings indicate improvements in plant growth, root development, nutrient uptake, biomass production, essential oil concentration, and bioactive compound accumulation. In many cases, hydroponic cultivation has also reduced crop duration, improved planting material quality, minimized soil-borne diseases, and enabled year-round production.
The integration of advanced technologies including Internet of Things (IoT), sensor-based monitoring systems, automation, artificial intelligence, and vertical farming has further enhanced the efficiency and precision of hydroponic cultivation. Real-time monitoring of pH, electrical conductivity, nutrient concentrations, temperature, humidity, and water levels allows growers to optimize production and minimize resource wastage. Vertical farming approaches, combined with controlled environment agriculture, provide additional opportunities for spice cultivation in urban and peri-urban regions.
Despite these advantages, several technical and economic challenges continue to limit large-scale adoption. High initial investment costs, energy requirements, complex nutrient management, system maintenance, and the need for skilled labour remain major constraints. Furthermore, crop-specific nutrient recommendations, physiological responses under soilless conditions, energy-efficient production systems, and long-term economic feasibility require further investigation. Addressing these research gaps will be essential for developing commercially viable and sustainable hydroponic production systems for spice crops.
Future advancements in renewable energy integration, biodegradable growing media, precision nutrient management, machine learning, artificial intelligence, and genetic improvement of crop varieties specifically adapted to hydroponic environments are expected to accelerate the adoption of soilless cultivation. Collaborative efforts among researchers, engineers, policymakers, and industry stakeholders will play a crucial role in overcoming existing limitations and promoting wider commercialization.
In conclusion, hydroponic and soilless cultivation technologies represent a transformative approach for the sustainable production of high-value spice crops. Their ability to enhance productivity, improve crop quality, conserve natural resources, and facilitate year-round cultivation positions them as key components of future climate-resilient agriculture. With continued technological innovations, economic optimization, and targeted research, hydroponics has the potential to significantly contribute to global food security, nutritional quality, and the sustainable growth of the spice industry.

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