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Hydroponic Cultivation of Spices and Aromatics: Techniques, Benefits and Challenges

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Authors' contributions

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

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ABSTRACT

The global shift towards urbanization, with 55% of the population residing in urban areas and an anticipated rise to 68% by 2050, presents challenges to traditional farming. The increasing world population, further intensifies the strain on available agricultural land due to urban expansion.

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Climate change combines with these issues, make conventional cultivation more challenging. Alternative agricultural practices, such as hydroponics, gain significance in addressing these concerns. Aromatic and spices have been used for centuries for their medicinal and culinary properties. They contain various essential oils, flavonoids, and other phytochemicals responsible for their distinctive flavour and aroma, as well as their health benefits. The rising global demand for natural products from herbs and spices has led to its market growth. Hydroponics, a technology for cultivating plants in nutrient solutions with or without an artificial medium such as sand, gravel, vermiculite, rockwool, peat moss, coir or sawdust, offers a promising solution. This paper explores the potential of hydroponic cultivation for planting material production, enhancing the yield, nutritional composition, essential oil content and medicinal properties of various spice and aromatic crops, including black pepper, saffron, ginger, garlic, coriander, mint, celery, fenugreek, parsley, thyme, rosemary, green mustard, basil and others. The main challenges in hydroponic production of these crops include high initial investment, precise monitoring and lack of technical knowledge. Hence by reviewing recent literature, this paper aims to provide insights into the classification of hydroponics and its different techniques, benefits and challenges of hydroponic cultivation, various growing media and nutrient solutions used, types of hydroponics utilized and their purposes in the production of diverse herbs and spices. Embracing hydroponic techniques could contribute to sustainable agricultural practices, particularly in urbanized environments where traditional farming faces constraints.

Keywords: Urbanization; climate change; hydroponics; herbs; spices; sustainable agriculture.

1. INTRODUCTION

As of today, 55% of the global population resides in urban areas, a figure projected to rise to 68% by 2050 (UN 2018). Additionally, the world's population is anticipated to increase by nearly 2 billion persons in the next 30 years, from the current 8 billion (mid-November 2022) to 9.7 billion in 2050 and could peak at nearly 10.4 billion in the mid-2080s (UN 2022). The land available for agriculture is shrinking because of urbanisation and the allocation of land for domestic as well as other needs. Additionally, climate change makes farming more challenging. To overcome this, alternative agricultural practices need to be strengthened, with hydroponic cultivation becoming increasingly important in this context.

Hydroponics offers several benefits, including the ability to reserve traditional farmland for major crops and save over 90% of irrigation water by using a recycled, fixed amount of water. It can be run in various places, such as balconies, rooftops, greenhouses, and lands unsuitable for conventional farming. Fertilizers are applied in precise quantities based on plant needs. In hydroponic cultivation, it is easier to manage plants and to conduct the required protection operations against various pests. Additionally, hydroponics allows for year-round cultivation, as climate conditions can be controlled in greenhouses. Since plant roots do not need to reach for nutrients, planting density can also be increased (El-Kazzaz and El-Kazzaz 2017).

Aromatic plants and spices have long been valued for their medicinal and culinary uses, as they contain essential oils, flavonoids, and other phytochemicals that give them their unique flavour, aroma, and health benefits. The demand for spices and herbs is rising in both developed and developing nations, driven by increasing consumer interest in their potential health benefit (Nguyen et al. 2019). The market for essential oils is also steadily increasing, because of their use in products like air fresheners, lotions, and other items. The most commonly traded essential oil compounds include menthol, menthone, carvone, eugenol, and linalool (Khaliq and Mushtaq 2023). Aromatic plants are rich sources of antioxidants and natural antibacterial agents, making them valuable for the food industry, while spices are aromatic substances of plant origin used to season dishes (Vikou et al. 2023). In this context, promoting hydroponic cultivation can help boost the yield, nutritional value, and essential oil content, as well as the antioxidant and medicinal properties of certain spices and aromatic plants.

2. HYDROPONICS

Hydroponics is a method of growing plants in nutrient solutions with or without the use of an artificial medium, such as sand, gravel, vermiculite, rockwool, peat moss, coir, or sawdust, to provide mechanical support (Jensen 1997). The term hydroponics comes from the Greek words "HYDRO" (water) and "PONOS" (labour), meaning "water working." This system is scientifically feasible because soil is not required for photosynthesis. The fundamental requirements for any hydroponic system include maintaining optimal levels of electrical conductivity (EC), pH, temperature as well as proper aeration. Additionally it is important to take into account the buffering effect of water and nutrient solution on the growing medium, and to provide all essential micro and macronutrients to the plants (Hasan et al. 2018). A typical hydroponic system consists of several key components, including a growing tray, reservoir, timer, controlled submersible pump, delivery system, air pump, air stone for oxygenating the nutrient solution, and grow lights (for indoor hydroponics) within the required range (Sathyanarayana et al. 2022). The basic plant requirements in any hydroponic system are as follows (El-Kazzaz and El-Kazzaz 2017).

1. **Growth demands:** Various factors, including nutrition, light, temperature, air, pH, and salinity, influence plant growth, regardless of whether they are cultivated in soil or soilless systems. While sunlight and air are accessible in outdoor settings, indoor systems require sufficient light sources, such as fluorescent lights, metal halide lamps, or sodium vapour lamps.
2. **Nutrient solution:** The availability of well-balanced nutrient solutions suitable for all stages of plant growth.
3. **Water quality and disinfection:** Water used in hydroponics should be of high quality and free from pathogens. A drawback of closed systems is the potential for rapid spread of soil-borne pathogens through the recirculating nutrient solution. To eliminate these pathogens, various disinfection methods can be employed, including ozone treatment, UV disinfection, heat treatment, slow sand filtration, electrolyzed water, hydrogen peroxide, membrane filtration, and chlorination.

2.1 Benefits and Challenges of Hydroponic Cultivation

The key advantages of hydroponic cultivation include a lower occurrence of soil-borne pathogens and diseases, no need for soil disinfection or treatment, precise control over environmental factors, higher yields, improved product quality, increased water and nutrient efficiency, and year-round production (Hasan et al. 2018). Hydroponics is ideal for areas with limited or contaminated land, allowing for higher planting density and eliminating the risk of weed infestation (Dubey and Nain 2020). It also requires less space compared to traditional farming and reduces the use of harmful plant protection chemicals (Khan et al. 2020). The benefits of this method will contribute into global sustainability by minimising the impact on ecosystems, reducing pollution, and mitigating climate change. It will also reduce the impact of climate change and pollution on food production, freeing up huge areas that are currently under pressure from human activity and allowing them to regenerate. This, in turn, will reduce the overall ecological effect (Sousa et al. 2024). A study of Romanian consumer's attitudes towards hydroponic farming found that their knowledge of the quality and safety of the produce significantly influences their frequency of consumption. Freshness and quality were major determinants in purchase decisions across demographics, followed by environmental sustainability, health benefits, and price. The majority of participants were confident in the extended shelf life of hydroponically cultivated products (ŢĂLU 2024).

A research was conducted to investigate the benefits and challenges faced by hydroponic farmers in Tanzania and Uganda in order to increase the adoption of this technology in East Africa and throughout Africa. The results reported that hydroponics is a climate-smart farming technology that generates high yields in minimal space, has no soil-borne pests and diseases, and allows farmers to adapt to changing climatic conditions. On the contrary, more than half of respondents reported high investment costs and a lack of expertise about hydroponics as the key constraints. More research is needed to explore ways to reduce the high expenses associated with the technology, such as using organic fertilizers, non-automated green houses, and locally available materials that can be used for hydroponic farming (Gumisiriza et al. 2022). Thus, the main limitations of hydroponics are the high initial investment, the need for advanced technical knowledge, and the requirement for precise monitoring for adjusting the pH and EC (Hasan et al. 2018). Some diseases, such as fusarium and verticillium, can spread quickly through the system, and algal growth presents an additional challenge (Khan et al. 2020, Sathyanarayana et al. 2022). Clogging of the system and adjusting of pH level can be challenging while using organic nutrient solution in hydroponics.

Overcoming these challenges and limitations will be critical for making hydroponics a more accessible and sustainable approach. Hydroponic systems must be upgraded, simplified, and automated so that they are accessible to a wider range of users. Efforts should be made to make residential hydroponic systems more affordable and technologically accessible to the general public. Hydroponics on a small and medium scale can improve food security and strengthen local economies, even encouraging self-employment or profitable commercial ventures (Sousa et al. 2024). The technological limitations are one of the main obstacles in implementing domestic hydroponics, necessitating the adoption of new platforms such as the Internet of Things (IoT). IoT-based hydroponic systems can help to control variables like pH, electrical conductivity, temperature, lighting and nutritional composition (Velazquez-Gonzalez et al. 2022, Kannan et al. 2022). Electricity remains as a determining factor in the operating costs of hydroponic systems, but its impact can be reduced if it is carbon neutral (for example, wind and solar energy) (Romeo et al. 2018). The risk of water borne diseases and algal growth can be controlled by using clean water and adopting various water disinfection methods.

3. CLASSIFICATION OF HYDROPONICS

Hydroponic systems are categorized into passive and active types. In passive systems, plant roots remain in contact with the nutrient solution while being supported by the suspension method, making these systems simple to set up. An example of a passive system is the wick system. On the other hand, active systems use an electric pump to deliver nutrient solutions to the plant roots and rely on gravity to drain any excess solution, which can then be recycled and reused. Examples of active systems include the Nutrient Film Technique (NFT), Deep Flow Technique (DFT) and Ebb and flow system (Macwan et al. 2020).

Hydroponic cultivation can be classified based on the type of substrate and container, the method of nutrient delivery to the plant, and drainage. The two main types are solution culture or liquid hydroponics, and solid media culture (also known as aggregate systems).

1. Solution culture or Liquid hydroponics: Solution culture, or liquid hydroponics, involves growing plants in a fully liquid medium contained within pipes or appropriate containers (Hasan et al. 2018). This method can be further divided into circulating systems (closed systems) and non-circulating systems (open systems).

Circulating methods (closed system): In this method, the nutrient solution is circulated through the plant root system, where an excess solution is collected, replenished, and reused (Hussain et al. 2014). Techniques within this system are the Nutrient Film Technique (NFT), Deep Flow Technique (DFT) and Ebb and flow system.

Non-circulating method (open system): In this system, the nutrient solution is utilized only once and is not recirculated. When its nutrient concentration reduces or when there are changes in pH or electrical conductivity (EC), it is replaced (Hussain et al. 2014). The different techniques, such as root dipping technique, floating technique and capillary action techniques, fall under this method. In the root dipping technique, plants are cultivated in small pots filled with a growing medium, with the bottom 2-3 cm of the pots submerged in a nutrient solution. The root dipping method is straightforward, cost-effective, and easy to set up. The floating technique involves using shallow containers about 10 cm deep where plants are placed in small pots and secured to a styrofoam sheet or a similar lightweight material, allowing them to float on the nutrient solution in the container (Hasan et al. 2018). The capillary action technique uses pots with holes at the bottom, filled with an inert medium where seeds or seedlings are planted. These pots are placed in shallow containers containing a nutrient solution, which is absorbed into the inert medium through capillary action. Proper aeration is crucial in this method (Hussain et al. 2014).

2. Solid media culture (Aggregate systems)

The chosen growing medium should be flexible, easily crumbled, capable of retaining both water and air and allow for efficient drainage. Additionally, it should be free from toxic substances, pests, disease-causing microorganisms, and nematodes. The medium must be thoroughly sterilized before use (Hussain et al. 2014).

Hanging bag technique: In this verti-grow technique, 1-meter long, cylindrical UV-treated polythene bags (white on the outside, black inside) are filled with sterilized coconut fibre. These bags are sealed at the bottom and attached to small PVC pipes at the top, then suspended vertically from overhead support above a nutrient solution collection channel. Seedlings or planting materials, placed in net pots, are inserted into holes along the sides of the hanging bags. A micro sprinkler inside the top of each bag pumps nutrient solution, which drips down, moistening the coconut fibre and plant roots. Excess solution drains through holes at the bottom of the bags and is collected in the channel below, flowing back to the nutrient solution tank. This system is ideal for growing leafy vegetables, strawberries, and small flower plants (Hussain et al. 2014).

Grow bag technique: This technique utilizes grow bags made from UV-stabilized polyethylene sheets, measuring 1 meter in length, 15-20 cm in width, and 8-10 cm in height, to cultivate plants. The bags can accommodate single or paired rows of plants. Fertigation is carried out using specialized stake drippers connected to poly tubes and lateral pipes (Hasan et al. 2018).

Trench or trough technique: In this method, plants are grown in trenches or troughs constructed from UV-stabilized PVC/HDPE sheets, bricks, concrete, or other locally available materials (Hussain et al. 2014). These trenches or troughs are filled with inert organic, inorganic, or mixed materials, with a depth ranging from 30 to 60 cm based on the crop type. Fertigation is managed using specialized stake drippers connected to poly tubes and lateral pipes. Proper drainage is essential and can be ensured through holes or separate drainage pipes (Hasan et al. 2018).

Pot technique: This method uses pre-made plastic pots for plant cultivation, which are filled with inert organic, inorganic, or mixed materials. Fertigation is managed using specialized single or multiple outlet stake drippers connected to poly tubes and lateral pipes (Hasan et al. 2018).

3.1 Different Techniques of Hydroponic System

Anyone can create their own design tailored to their specific needs and the type of plants they wish to grow based on the primary goal and the purpose of the hydroponic system (El-Kazzaz and El-Kazzaz 2017). The following are different systems of hydroponics which are mainly used.

1. Nutrient film technique (NFT): In this technique, plant roots are exposed to a thin film of nutrient solution, approximately 0.5 mm thick, flowing through the channel. This design allows the roots to access oxygen from the surrounding air, as they are not fully submerged in the solution (Dubey and Nain 2020). Developed in the mid-1960s in England by Dr. Alen Cooper, this method is also referred to as gutter hydroponics (Macwan et al. 2020, Shinde and Marathe 2021). The system works by pumping nutrient solution from a holding tank through irrigators at the top of each sloping pipe. The excess solution is collected at the bottom and recycled back into the tank, creating a continuous flow (El-Kazzaz and El-Kazzaz 2017). Channels are typically made from flexible PVC or plastic sheets, with seedlings anchored in pots containing growing media. These channels, which are between five and ten meters in length, are set at a slope of 1 in 50 to 1 in 70, with a flow rate of two to three litres per minute (Hasan et al. 2018). While NFT systems do not require a timer for the submersible pump, they are highly vulnerable to power outages or pump failures, as the roots can dry out quickly without a continuous flow of nutrients (Hussain et al. 2014). This technique is particularly suitable for plants with small root systems, such as lettuce, strawberries, and herbs (El-Kazzaz and El-Kazzaz 2017).

2. Deep flow technique (DFT): It is a hydroponic system where a nutrient solution, 2-3 cm deep, flows through PVC pipes. Plants are placed inside plastic pots, which are positioned at regular or desired intervals along the pipes. These main and sub-main pipes are fixed on raised platforms. The PVC pipes can be arranged either in a single horizontal plane or in a multi-level zig-zag vertical layout (Hasan et al. 2018). As the recycled nutrient solution flows back into the stock tank, it becomes aerated. The pipes are typically sloped at a gradient of 1 in 30 to 40 to ensure a smooth flow of nutrient solution. Painting the PVC pipes white can help to reduce the heating of the nutrient solution (Hussain et al. 2014).

3. Ebb and flow system: This system which is also known as the flood and drain system, is an affordable type of hydroponic setup. It consists of two containers, the top one holds plants in pots with substrate, while the bottom one contains the nutrient solution. Nutrients are pumped in large volumes into the top container, flooding it to a level determined by an overflow pipe, with excess solution recirculating back to the bottom container. The pump operates intermittently, typically running for 30 minutes and switching off for 15 minutes, allowing the grow tray to flood periodically. When the pump is off, the nutrients drain out of the tray through the pump line, providing oxygen to the roots. For this reason, an air stone is not essential in ebb and flow systems. This setup is especially suitable for plants with large root systems (El-Kazzaz and El-Kazzaz 2017). However, issues like root rot, algae, and mould are common, making it necessary to incorporate a filtration unit in modified versions of the system (Macwan et al. 2020).

4. Deep water culture (DWC): Plants are suspended on a floating platform above a bath of hydroponic nutrient solution, with oxygen supplied continuously by an air pump. This system can be easily set up in various containers, such as glass basins, fish ponds, plastic or ice boxes, concrete basins, or basins covered with polypropylene sheets. Since the plants are always in contact with the nutrient solution, they are not at risk of damage in the event of a power outage or air pump failure. DWC is particularly well-suited for growing plants like lettuce, strawberries, and herbs (El-Kazzaz and El-Kazzaz 2017).

5. Wick system: This is the simplest type of hydroponic setup (El-Kazzaz and El-Kazzaz 2017). In this system, nutrient solution reaches the plant roots through capillary action, with the wick serving as the connection between the potted plant and the nutrient solution in the reservoir. It's especially useful in areas where electricity is unavailable or unreliable. The water supply to the plant can be adjusted by using a larger or wider wick, or multiple wicks. This system works well for small plants, herbs, and spices but is less effective for plants that require a large amount of water (Gaikwad and Maitra 2020).

6. Drip system: The drip system consists of at least two containers, with plants placed in the top container and the nutrient solution in the bottom one. A pump delivers the nutrient solution to drips located at the base of each plant, and an aquarium air stone oxygenates the water. The nutrients filter down to the plant roots and then may or may not return to the bottom container. Both the water and air pumps typically run continuously in this system. It is particularly well-suited for plants with large root systems (El-Kazzaz and El-Kazzaz 2017). A key advantage of the drip system is its ability to withstand short-term power or equipment failures, while also conserving more water compared to other systems. However, it can be expensive and complex to set up, as the nutrient solution supply needs to be timed (Macwan et al. 2020). There are two types of drip systems in hydroponics: recovery and non-recovery. In a recovery system, the nutrient solution is collected and recycled continuously, while in a non-recovery system, the solution is not recycled but drained out after use (Dubey and Nain 2020).

4. NUTRIENT SOLUTIONS FOR HYDROPONICS

A nutrient solution must contain all the 17 essential elements for plant growth and development, as these nutrients are irreplaceable and vital for completing the plant's life cycle (Hussain et al. 2014). If the system experiences a water shortage, the concentration of nutrients can increase, potentially harming the roots and affecting their function. To prevent this, it is important to add fresh, filtered water to restore the nutrient solution to its original concentration. Additionally, maintaining the root zone temperature between 20 - 22°C is crucial. If the nutrient temperature is too high, it can lead to issues such as yellowing, falling flowers, damaged fruits, and stunted growth (El-Kazzaz and El-Kazzaz 2017). Therefore, the success of a soilless cultivation relies heavily on a strict nutrient management program. Properly controlling factors like pH level, temperature, and electrical conductivity, along with timely replacement of the nutrient solution, are essential for thriving soilless cultivation (Hussain et al. 2014).

The optimal pH range for nutrient solutions in soilless cultivation is between 5.8 and 6.5. Deviating from this range can lead to nutrient deficiencies or toxicity symptoms, depending on the specific crop. Similarly, the ideal electrical conductivity (EC) for hydroponic nutrient solutions is between 1.5 and 2.5 dS m^{-1}. If the EC is too high, osmotic pressure can inhibit nutrient absorption, while a lower EC can negatively affect plant health and yield. As plants absorb nutrients and water, the EC of the solution fluctuates. To maintain balance, fresh water should be added if the EC is too high, or nutrients should be added if it is too low (Hussain et al. 2014).

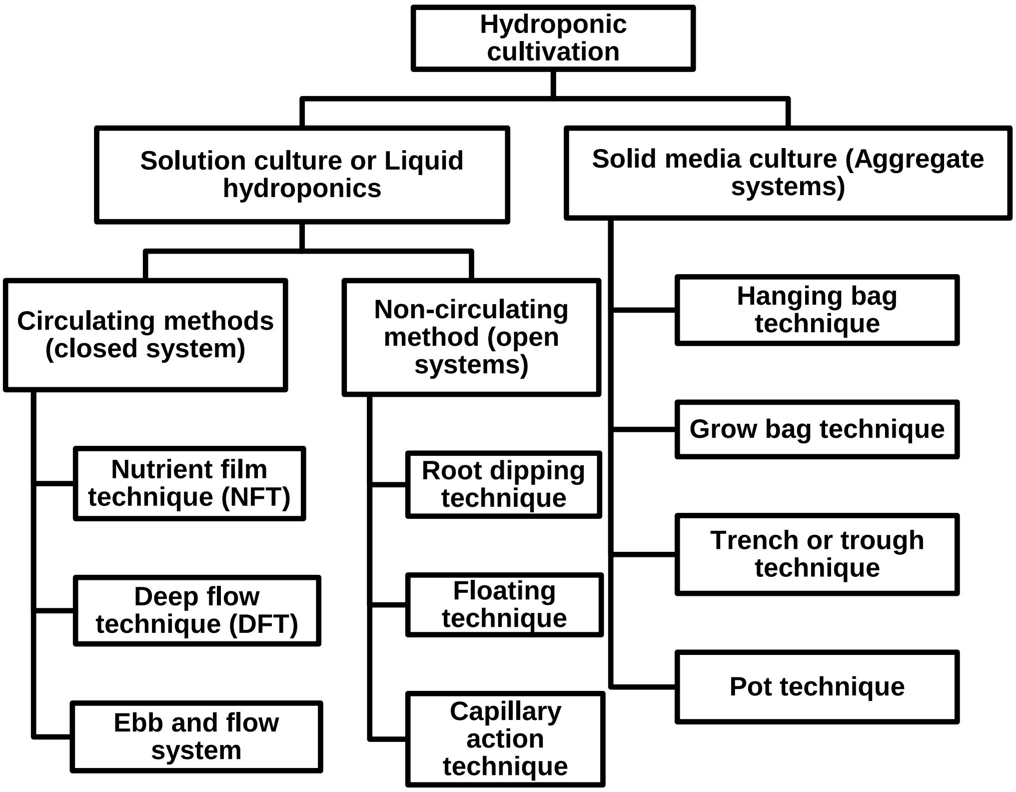

Fig. 1. Classification of hydroponics based on the type of substrate and container, the method of nutrient delivery to the plant, and drainage.

There are several standard nutrient solutions used in hydroponics, such as the Hoagland and Arnon solution, Cooper solution, Steiner solution, and Albert medium. Commercial hydroponic fertilizers contain all the macro and micronutrients necessary for plant growth, with recommendations based on the electrical conductivity (EC) and pH levels of the nutrient solution (Brechner et al. 1996). The Hoagland solution, developed by Hoagland and Arnon (1950), is a well-known hydroponic nutrient solution that provides all essential nutrients for plant growth. Its composition per litre of solution includes KNO_3 (5 ml of 1 M), $Ca(NO_3)_2{\cdot}4H_2O$ (5 ml of 1 M), KH_2PO_4 (1 ml of 1 M), $MgSO_4{\cdot}7H_2O$ (2 ml of 1 M), micronutrients (1 ml of stock solution), and Fe-EDTA (1–5 ml of 1000 mg L^{-1}). The micronutrient stock solution contains H_3BO_3 (2.86 g), $MnCl_2{\cdot}4H_2O$ (1.81 g), $ZnSO_4{\cdot}7H_2O$ (0.22 g), $CuSO_4{\cdot}5H_2O$ (0.08 g), and $MoO_3{\cdot}H_2O$ (0.02 g) per liter (Hoagland and Arnon 1950). Alternatively, liquid organic nutrient solutions can be used in hydroponics as a chemical-free option derived from organic sources that are safe for health (Upendri and Karunarathna 2021). These organic solutions can be made from a variety of animal, plant, or algae-based substances, including manure extracts, fish products, vinasses, corn steep liquor, vermicompost tea, and algae extracts (Park and Williams 2024).

5. GROWING MEDIA FOR HYDROPONICS

In soilless cultivation systems, the growth medium serves as a substitute for soil. Its primary functions are to provide oxygen to the roots, ensure that water and nutrients reach the roots, and offer stability to plants to prevent them from toppling over (El-Kazzaz and El-Kazzaz 2017). Hydroponic substrates are classified into two types: fibrous and granular. Fibrous substrates can be either organic or inorganic, while granular substrates are typically inorganic (Sathyanarayana et al. 2022).

Table 1. Classification of materials used as substrate

Substrate	Characteristics	Examples
Organic	This category consists of natural organic substrates, including organic residues, by-products, and waste materials of organic origin, typically derived from agriculture or industrial by-products from the wood industry.	Peat, coconut fibre
Inorganic	This category encompasses both natural materials and mineral products that are produced through industrial processes.	Sand, pumice, vermiculite, perlite, clay pellets, rockwool, zeolites
Synthetic	This category includes both ion-exchange synthetic resins and low-density plastic materials.	Expanded polystyrene, polyurethane foam

Table 2. Different substrates used in hydroponic systems

Substrate	Characteristics
Coco-Coir	Coco coir is a fully organic medium made from shredded coconut husks. It combines the water retention properties of vermiculite with the air retention qualities of perlite, providing protection against root diseases and fungi (Hussain et al. 2014). Additionally, coco coir is pH neutral and promotes good aeration for the roots (Gaikwad and Maitra 2020). Also referred to as coir pith, coir meal, coir dust, and coco peat, it consists of the dust and short fibers extracted from the mesocarp of the coconut (Joshi et al. 2022).
Peat Moss	It retains moisture in growing mediums (Hussain et al. 2014).
Composted organic waste	In the past 40 years, the use of composted organic waste in soilless growth media has grown significantly. Composts have been shown to inhibit pathogens, enhancing their economic value (Joshi et al. 2022).
Rice Hulls	This material is a by-product of the rice industry. Although it is organic plant material, it decomposes very slowly, similar to coco coir, which makes it suitable for use as a growing medium in hydroponics (Gaikwad and Maitra 2020).
Fibre from wood	The effectiveness of substantially processed wood fibre as a growing medium has been thoroughly investigated, revealing that it has enhanced total porosity and air-holding capacity (Joshi et al. 2022).
Sand	Sand is a widely used growing medium in hydroponics. It is often blended with vermiculite, perlite, and/or coco coir, all of which contribute to moisture retention and improve aeration for the roots (Gaikwad and Maitra 2020).
Perlite	Perlite is the most commonly used medium in containerized soilless culture systems. These lightweight granules are derived from a silicone mineral that forms in volcanoes (Hussain et al. 2014). Perlite can be used on its own or combined with other growing media (Gaikwad and Maitra 2020). It retains more air than water and has a neutral pH, exceptional wicking ability, and high porosity (Macwan et al. 2020).
Vermiculite	This substance includes both potassium and magnesium. It retains a significant amount of water and helps with drainage and aeration, although it is less durable than other mediums like sand and perlite (Hussain et al. 2014). Vermiculite is a silicate mineral that expands when subjected to extreme heat. It is lightweight and often floats (Gaikwad and Maitra 2020).
Rockwool	Rockwool is the most widely used growing medium in soilless cultivation. It is a sterile, porous, and non-degradable medium made mainly from granite and/or limestone. Rockwool absorbs water readily. Before use, it should be pH balanced by soaking it in pH-balanced water (Gaikwad and Maitra 2020).
LECA (Light Expanded Clay Aggregate)	LECA baked clay pellets, are suitable for hydroponic systems and they are inert, pH neutral and do not contain any nutrient value (George and George 2016).
Oasis Cubes	They are made from an open-cell material, allowing them to absorb both water and air. Unlike rockwool cubes, oasis cubes are less prone to becoming waterlogged (Gaikwad and Maitra 2020).

6. IMPORTANCE OF HYDROPONICS IN SPICES AND AROMATICS

Hydroponics plays a crucial role in the cultivation of spices and aromatics by enhancing both yield and product quality. This method allows for better control over pests and pathogens, ensuring the production of healthy planting materials such as corms and cuttings that are free from contamination. Additionally, hydroponics shortens the growing period and promotes the greater accumulation of medicinal components in spices and aromatics. It also improves the essential oil yield and quality by increasing the concentration of the major constituents present in the essential oil. Furthermore, hydroponics enables off-season production of various herbal and leafy spices, as well as aromatic herbs.

6.1 Hydroponics in Spices and Aromatics

Stem cuttings are the planting material for black pepper; however, soil propagation exposes the stems and developing roots to soil-borne pathogens, which can compromise plant quality. High-quality rooted cuttings supports faster and more effective establishment of black pepper plants. Hydroponic farming provides an excellent platform for producing quality rooted cuttings. A research study evaluated seven nutrient media compositions, finding that Hoagland solution supplemented with potassium silicate at 0.005 mM (T4) and salicylic acid (SA) at 2 mM (T6) promoted faster root growth and initiation. Silicon fertilization plays a regulatory role in nutrient uptake, while SA enhances cellular auxin synthesis at the root tip, aiding the development of adventitious roots. Stem cuttings without roots at planting showed greater increases in root numbers and extension due to their enhanced ability to absorb water and nutrients (Babirye et al. 2021).

Saffron, one of the most expensive spices globally, is propagated vegetatively using corms, as the cultivated plants are sterile auto-triploids (Nardi et al. 2022). Its cultivation faces several challenges, including limited cultivable land in high-altitude, cold climates and the labour intensive process of harvesting and handling. Additionally, the low multiplication rate of cormlets and susceptibility to fungal infections further reduce saffron productivity. Hydroponics offers a promising alternative to traditional open-field cultivation, potentially increasing saffron yields and lowering production costs. This method also supports sustainable production by providing pathogen-free stock corms. However, for hydroponic saffron production to be effective, the system and growth conditions must be carefully optimized (Dewir et al. 2022). In a study on comparison of saffron production in nutrient film technique (NFT), peat moss-perlite substrate cultivation, and soil cultivation, high germination rates for saffron was found in all the three techniques. Despite lower flower productivity in NFT, it produced the highest quality corms, with 100% commercially viable and the heaviest corms. This was due to NFT's efficient water use and continuous nutrient supply (Razan et al. 2023).

Fig. 2. Hydroponic (Deep water culture) production of high quality rooted cuttings of black pepper (Babirye et al. 2021)

In an experiment, saffron corms were sprouted by gradually lowering the temperature from 14°C to 8°C and cultivated hydroponically in perlite or volcanic rock for 24 weeks using ebb-and-flow or continuous immersion systems. They concluded that large corms grown in volcanic rock-based aerated continuous immersion hydroponics produced optimal yields of saffron stigmas and daughter corms (Dewir et al. 2022). The flowering potential of saffron corms across various weight groups in hydroponic conditions were evaluated and it was found that corms weighing less than 4 g generally lacked the ability to flower. However, corms weighing between 4-8 g appeared to produce more flowers in controlled environments compared to natural environments (Fallahi 2022). A research work was undertaken to compare the yield of saffron corms in protected soil cultivation and protected soilless cultivation utilising "Radon grow" as hydroponic nutrient media and a soilless substrate of peat and crushed silica in a 1:1 ratio. The study concluded that protected soilless culture outperformed protected soil-based cultivation in terms of foliage, root, mother and daughter bulb growth, as well as biomass accumulation (Maliqa et al. 2023).

High-quality ginger is typically grown in highlands using shifting cultivation to avoid issues with infertile soil and soil-borne diseases that can harm rhizomes and reduce yields. However, this method is unsustainable, as it leads to land erosion in the highlands. Hydroponic systems offer a promising alternative, addressing land availability challenges while also increasing production yields, enhancing productivity, and shortening the growing cycle (Chong et al. 2023).

The effects of soilless substrates, such as coir dust and burnt paddy husks, on ginger growth using a drip irrigation system were studied. They found that substrates with 70-100% coir dust significantly improved growth and increased rhizome yield by up to 36%. The higher porosity of coir dust made it the most effective medium for ginger cultivation (Suhaimi et al. 2012). An experiment investigated the effects of hydroxyapatite nanoparticles (HANPs) on ginger growth in hydroponics, using a modified Hoagland solution with varying HANP concentrations (200, 500 and 1000 ppm) and the results showed that 200 ppm HANP significantly increased leaf number, chlorophyll content, and photosynthetic rate compared to the control. Regular use of the modified Hoagland solution provided adequate nutrients, promoting steady growth throughout the cultivation period (Chong et al. 2023).

Garlic, a member of the Liliaceae family, is widely used as both a spice and medicinal herb in many countries. One of its key bioactive compounds, ajoene, is formed through the enzymatic conversion of alliin into allicin by alliinase. Ajoene is known for its numerous health benefits, including anti-thrombosis, anti-tumor, anti-leukemia, and cholesterol-lowering effects, as well as its anti-fungal, antimicrobial, antioxidant, and antiviral properties (Naznin et al. 2018). There are two forms of ajoene: E-ajoene, the more stable cis isomer, and Z-ajoene, the trans isomer (Naznin et al. 2010). Hydroponic cultivation of garlic promotes faster growth and a higher accumulation of these medicinal compounds compared to traditional soil cultivation (Naznin et al. 2018).

A floating technique hydroponic system for garlic cultivation resulted in higher fresh weights and ajoene concentrations in the bulbs, roots, and leaves compared to soil-grown plants. The garlic plants in hydroponic culture were also more vigorous and healthier (Naznin et al. 2009). A research was done on how different levels of dissolved oxygen, achieved through various aeration methods, affected garlic growth and ajoene concentrations in floating technique hydroponics using a modified Hoagland nutrient solution. The treatments included no aeration (control), 12 hours of aeration in the dark, 12 hours in the light, and 24 hours of continuous aeration. The findings indicated that garlic plants with higher dissolved oxygen levels exhibited better growth rates and increased ajoene content (Naznin et al. 2010).

Excessive use of nitrogenous fertilizers increases the nitrate concentrations in plant tissues while simultaneously reducing ascorbic acid levels. Therefore an experiment was done on the effects of three nitrogen concentrations (90, 180, and 270 ppm) on the growth, yield, and chemical characteristics of three celery cultivars (Utah, President, and Montery) in a floating hydroponic system. The results showed that an intermediate nitrogen level of 180 mg L^{-1} significantly improved plant height, number of leaves per plant, fresh weight, and total yield. Increasing nutrient concentration led to higher nitrate levels in leaf tissues, but these levels remained below the limits set by the European Community (Abd-Elkader and Alkharpotly 2016). An investigation on the effects of vermiwash and vermicompost derived from neem (*Azadirachta indica*) and lime (*Citrus aurantifolia*) on celery growth in a hydroponic system, found that vermiwash and vermicompost from lime leaves significantly promoted plant growth, resulting in taller and wider celery plants. These amendments provide sufficient macro and micronutrients and release nutrients slowly for better accessibility (Ansari et al. 2019). Hydroponic systems resulted in higher crop productivity for celery compared to soil-less and soil medium (Kumar and Agarwal 2024). A recent study compared fenugreek cultivation in NFT hydroponics and conventional systems. The results revealed that while the crops in the hydroponic system had a pale yellowish-green color, indicating micronutrient deficiencies, the NFT hydroponic system still produced slightly better crop growth and longer average root lengths than the conventional system (Begum et al. 2022).

Higher growth and production of coriander in DFT hydroponics were achieved with a recirculation interval of 0.25 hours compared to longer intervals of 12 and 24 hours. Adjusting the recirculation intervals is crucial for maintaining an optimal oxygen supply to the nutrient solution (da Silva et al. 2020). Two coriander cultivars, Verdao and Tabocas, were grown in both adapted DFT systems using pipes (with depths of 0.02 m and 0.03 m) and conventional DFT systems using wooden tanks (with depths of 0.013, 0.017, and 0.025 m). Results showed that Verdao was more productive, and the smallest nutrient solution depths performed similarly to larger ones, indicating that smaller depths are feasible and contribute to water and fertilizer savings (da Silva et al. 2023). An experiment demonstrated that varying concentrations of amino acid solutions (0, 100, and 200 ppm) influenced the growth, elemental content, and essential oil composition of hydroponically grown coriander under broad-range red and blue (BRB) light and white light. This amino acid solution rich in aspartic acid and other amino acids, at 100 ppm concentration, particularly under BRB light, led to significant improvements in plant morphology, chlorophyll, carotenoids and the diversity of functional groups. It also promoted the synthesis of more aromatic monoterpenes, highlighting the potential of amino acids to modulate essential oil composition based on specific formulation needs (Sowmya et al. 2023).

The growth, essential oil quality and content of thyme in a greenhouse hydroponic system (Drip system) were evaluated under varying planting densities (14, 28, and 71 plants m^{-2}) and nutrient solution concentrations (Steiner- 100% and 50%). Optimal growth was achieved with a 100% Steiner solution and a density of 28 plants m^{-2}. The hydroponic system produced 18.45 kg m^{-2} of fresh thyme annually, a 386.8% increase compared to the 3.79 kg m^{-2} yield from open-field cultivation (Guerrero-Lagunes et al. 2011). An investigation was done to observe the relationship between plant density and total dry biomass production in hydroponically grown rosemary. Among the three densities tested, the highest biomass production was achieved at a population density of 8 plants m^{-2}, outperforming the higher densities of 16 and 24 plants m^{-2} (Luna-Maldonado et al. 2016). Hydroponic growing of parsley using Hoagland solution (T1) in a DFT system significantly improved plant morphology, physiological performance and myristicin content in essential oil of parsley compared to the Thakur nutrient solution (T2). Parsley treated with T1 also showed higher growth in leaf, stem and root biomass and increased antioxidant potential (Rattan et al. 2022).

Fig. 3. Celery under hydroponic culture (Kumar and Agarwal 2024)

Fig. 4. Coriander grown in NFT hydroponic system

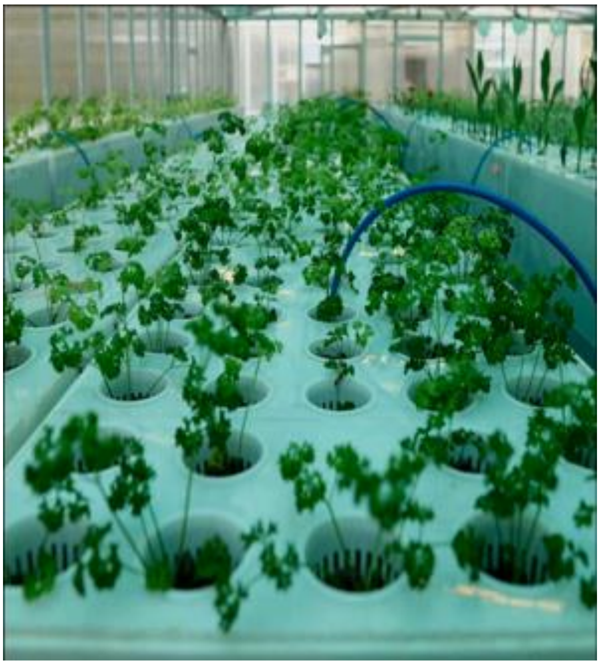

Fig. 5. Parsley in Deep flow technique hydroponic system (Rattan et al. 2022)

The green mustard plant (*Brassica juncea* L.), a vegetable that typically grows in sub-tropical climates, is also well-suited for tropical regions (Faruq et al. 2021). Its leaves are frequently used in traditional dishes from African, Indian, Asian, and African-American cuisines due to their distinct horseradish, peppery, and spicy flavor (Muthu et al. 2023). A study investigated the impact of using vegetable waste as a nutrient supplement in hydroponics on the growth of mustard greens. Six treatments were tested: P0 (control), P1 (20 ml Organic Liquid Fertilizer (OLF) + 40 ml AB mix nutrient solution), P2 (30 ml OLF + 30 ml AB mix), P3 (40 ml OLF + 20 ml AB mix), and P4 (60 ml OLF) in a wick hydroponic system. The findings indicated that P2 produced the best outcomes in terms of plant height, fresh weight and dry weight, likely due to its role in promoting accelerated cell division in the apical meristem (shoots) (Faruq et al. 2021). The growth performance of mustard greens was evaluated under wick hydroponic conditions using various nutrient sources, including Organic Liquid Fertilizer (OLF), OLF with bokashi, commercial liquid fertilizer, and pure water. Bokashi compost is one of the potential fertilizer sources for organic hydroponics. The study found that the organic liquid fertilizer from vegetable waste was as effective as commercial liquid fertilizer. Although plants in the OLF wick system showed slight yellow colour by the end of the season, no leaves were dried out, unlike those in the nutrient solution, which had bright green leaves with few dried ones. Additionally, plants treated with OLF and bokashi wilted by the eighth day due to an unsuitable pH level for mustard greens (Muthu et al. 2023).

An investigation was done on the impact of nitrogen levels on the growth, nutrient content, antioxidant activity and essential oil quality and quantity of spearmint grown hydroponically. Five nitrogen concentrations (150, 175, 200, 225, and 250 mg L^{-1}) were tested, while potassium and phosphorus levels were kept constant at of 325 mg L^{-1} K and 50 mg L^{-1} respectively, based on previous studies. The study found that a nitrogen level of 200 mg L^{-1} resulted in high dry matter content in the upper plant biomass without affecting fresh weight. Higher nitrogen concentrations (>200 mg L^{-1}) reduced the levels of several micronutrients in the plant tissue. For optimal carvone content and enzymatic activity, a nitrogen level of 200 mg L^{-1} is recommended for spearmint cultivation aimed at essential oil production (Chrysargyris et al. 2017). The feasibility of commercially growing peppermint and spearmint in a floating tray system under mild salinity conditions was explored, as freshwater availability is a challenge for hydroponic production. The study tested three NaCl concentrations (0 mM, 10 mM, and 20 mM) and found that plant growth was generally unaffected by salinity, although high salinity did reduce plant height. With increasing salinity, the nutritional composition of peppermint remained stable whereas the spearmint benefited from reduced nitrate levels and increased antioxidant capacity, total soluble phenols, total carotenoids and essential oil content. Overall, both peppermint and spearmint can be successfully cultivated in floating systems with mild salinity without compromising yield, essential oil and phenolic composition (Danai-Christina et al. 2021).

A work was done to determine the effects of silicon (Si) amendments on hydroponically (using DFT) grown sweet basil (variety 'Genovese') at a constant temperature of 23°C. The study tested 0, 25, and 75 ppm Si levels, incorporated through K_2SiO_3. The results showed that higher Si levels significantly improved plant growth and survival under cold stress. After an unexpected frost during the research, basil treated with 75 ppm Si showed reduced cold injury, suggesting that Si amendments can enhance basil resilience in cooler conditions (Li et al. 2020). Basil grown in an open hydroponics was compared with that of soil to assess resilience to downy mildew, heat, and storage and shelf life performance. Hydroponically grown basil had higher antioxidant levels and better resistance to downy mildew, but it was less resilient to heat and more prone to browning during storage, leading to a shorter shelf life compared to soil-grown basil. The higher antioxidant content, while beneficial against pathogens and for health, contributed to reduced storability due to oxidation and browning (Maurer et al. 2023). An experiment compared the development and quality of basil plants grown in NFT hydroponics, Ebb hydroponics and soil-based systems. They found that basil plants produced in NFT Hydroponics had greater growth characteristics, including plant height, root length, leaf length and width, number of leaves per plant, and stem diameter (Indira and Sabitha Rani 2024).

Fig. 6. Hydroponic (Floating system) cultivation of sweet basil (Kiferle et al. 2011)

Table 3. Types of hydroponic systems utilized for spice and aromatic crops cultivation as reported in previous studies

Crop	Hydroponic system	Nutrient Solution	Growing media	Reference
Black pepper	Deep water culture	Hoagland solution and Modified Hoagland solution	Sponge cubes	(Babirye et al. 2021)
Saffron	Nutrient Film Technique	Hoagland solution	Leca stone	(Souret and Weathers 2000)
	Pot technique	Hoagland solution with different concentration of copper	Perlite	(Sorooshzadeh and Tabibzadeh 2010)
	Ebb and flow system	Commercial liquid fertilizer	Perlite Rockwool	(Dewir et al. 2022)
	Continuous Immersion system	Commercial liquid fertilizer	Perlite Rockwool	(Dewir et al. 2022)
	Nutrient Film Technique	Hoagland solution	_	(Razan et al. 2023)
	Pot technique with fertigation	Long-Ashton solution	Perlite	(Stelluti et al. 2023)
Ginger	Drip system	Formulated by MARDI (Malaysian Agricultural Research and Development Institute)	Burnt paddy husk and coco peat in various proportions	(Suhaimi et al. 2012)
	Drip system	Modified Hoagland solution	Coco peat	(Chong et al. 2023)
Garlic	NFT	Cooper solution	_	(Abou-Hadid et al. 1998)
	Floating or hanging technique	Modified Hoagland solution	Styrofoam particles	(Naznin et al. 2009) (Naznin et al. 2010) (Naznin et al. 2015) (Naznin et al. 2018)
Fenugreek	Non circulating culture	Albert's solution	Coco peat	(Tuwar and Tuwar 2018)
	Aggregate culture	Albert's solution	Coco peat	(Tuwar and Tuwar 2018)
	NFT	_	Coco peat	(Begum et al. 2022)
Celery	Floating system	Cooper solution	Perlite	(Abd-Elkader and Alkharpotly 2016)
Coriander	DFT	Nutrient solution recommended by Furlani et al. (1999) for leafy vegetables	Coconut fibre	(da Silva et al. 2020)
	Adapted DFT system Conventional DFT system	Nutrient solution recommended by Furlani et al. (1999) for leafy vegetables	Coconut fibre	(da Silva et al. 2023)
	NFT	TV PLUS Mastermix	Coco-coir	(Sowmya et al. 2023)
Parsley	DFT	Hoagland solution Thakur nutrient solution	Pebbles	(Rattan et al. 2022)

Crop	Hydroponic system	Nutrient Solution	Growing media	Reference
	DFT	12N-1.8P-13.4K water-soluble fertilizer	Stone-wool cubes	(Walters and Lopez 2021)
Thyme	NFT	_	Polyurethane foam	(Udagawa 1994)
	Drip system	Steiner solution	Red volcanic sand	(Guerrero-Lagunes et al. 2011)
Rosemary	Closed hydroponic system	A standard hydroponic nutrient solution as per Rodríguez-Fuentes et al. (2011).	Volcanic rock	(Luna-Maldonado et al. 2016)
Mustard greens	Wick system	Organic liquid fertilizer (OLF)	Rockwool	(Faruq et al. 2021)
	Wick system	Organic liquid fertilizer, Organic liquid fertilizer with Bokashi, AB mix	Rockwool	(Muthu et al. 2023)
Onion	Custom made hydroponics (Floating type)	_	Gravel	(Khatun et al. 2021)
	Floating type	Growth nutrient solution	_	(Mouroutoglou et al. 2021)
	Nutrient film technique,	Growth nutrient solution	_	
	Aggregate system	Growth nutrient solution	Perlite	
Dill	NFT	_	Polyurethane foam	(Udagawa 1994)
	DFT	12N-1.8P-13.4K water-soluble fertilizer	Stone-wool cubes	(Walters and Lopez 2021)
Mint	Floating tray system	_	Peat	(Danai-Christina et al. 2021)
Sweet basil	DFT	Modified Sonneveld solution	Oasis cubes	(Li et al. 2020)
Lemon balm	Ebb and flow system	70 g of Flory basis 1 along with 150 mg L^{-1} N	Wood fibre and sand	(Manukyan et al. 2004)
	Ebb and flow system	70 g of Flory basis 1 along with 150 mg L^{-1} N	Peat and wood fibre	(Manukyan 2011)
Lavender	Drip system	_	Perlite	(Chrysargyris et al. 2016)
Geranium	Pot technique	_	Perlite	(Chrysargyris et al. 2021)

Lemon balm (*Melissa officinalis* L.), a perennial herb from the Lamiaceae family with a lemon-like scent, is traditionally used in Europe to treat neurogenic disorders, insomnia, and stress due to its sedative and spasmolytic effects. Its essential oil also has antibacterial and antioxidant properties (Son et al. 2021). The antioxidant activity, total phenol, and flavonoid content of lemon balm grown in various media under hydroponic conditions were examined. The study found that different culture media, with distinct physical and chemical properties, influenced the plant antioxidant levels. Peat moss substrate significantly enhanced the antioxidant properties of lemon balm compared to other media [58].

7. CONCLUSION AND FUTURE PROSPECTS

As the global population increases and arable land diminishes due to poor land management practices, there is a shift towards innovative technologies like hydroponics and aeroponics to expand crop production channels. The excessive use of pesticides and insecticides is contributing to soil infertility, further driving the movement towards soilless farming. Additionally, agriculture primarily relies on river water, but industrialization has led to pollution from toxic waste, contaminating these water sources with heavy metals and toxins. Consequently, the availability of water for conventional farming is diminishing, necessitating a transition to hydroponics, which uses 80-90% less water. Hydroponics is viewed as the future of agriculture, offering a sustainable and eco-friendly approach to enhance crop yield and quality, thereby supporting food security. Although the initial capital costs for setting up hydroponic systems pose a challenge, these costs are expected to decline over time, making hydroponics a more feasible option in the long run. Additionally, hydroponics could play a crucial role in the future of space exploration, as we haven't yet found any soil that can support life in space, and transporting soil via shuttles is impractical. Furthermore, hydroponics provides an excellent platform for biological research, facilitating the analysis of interactions among various factors that influence plant growth.

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

Abd-Elkader, D. Y., & Alkharpotly, A. A. (2016). Effect of nitrogenous concentration solutions on vegetative growth, yield and chemical characters of celery (*Apium Graveolens* L.). Journal of Plant Production, 7(11), 1201-1206. Available: https://doi.org/10.21608/jpp.2016.46970

Abou-Hadid, A. F., El-Shinawy, M. Z., & Omer, E. A. (1998). Cultivation of garlic in nutrient film technique (NFT). Egyptian Journal of Horticulture, 25(3), 271-280.

Ansari, A. A., Raghubeer, H., & Jaikishun, S. (2019). The effect of vermiwash and vermicompost produced from leaves of *Azadirachta indica* and *Citrus aurantifolia* on the growth parameters of celery through hydroponic system. International Journal of Tropical Drylands, 3(1), 11-16. Available: https://doi.org/10.13057/tropdrylands/t030102

Babirye, K., King, J. H. P., & Ong, K. H. (2021). Producing black pepper (*Piper nigrum* L. cv.'Kuching') rootstock in a deep-water culture hydroponic system. Borneo Journal of Resource Science and Technology, 11(2), 88-97. Available: https:doi.org/10.33736/bjrst.3367.2021

Begum, A. A., Rao, B. M., Gowd, M. H. P., & Ismail, T. (2022). Design and evaluation of low-cost rectangular framed hydroponic system in leafy vegetables. The Pharma Innovation Journal, 11(12), 2391-2393.

Brechner, M., Both, A. J., & Staff, C. E. A. (1996). Hydroponic lettuce handbook. Cornell Controlled Environment Agriculture, 834, 504-509.

Chong, W. X., Kiew, W. Y., Low, Y. C., Lim, T. H., & Tan, H. Y. (2023, February). The effects of hydroxyapatite nanoparticles on the growth and yield of ginger (*Zingiber officinale* Roscoe) from seedling to tillering stage. In IOP Conference Series: Earth and Environmental Science (Vol. 1139, No. 1, p. 012005). IOP Publishing. Available: https://doi.org/10.1088/1755-1315/1139/1/012005

Chrysargyris, A., Nikolaidou, E., Stamatakis, A., & Tzortzakis, N. (2017). Vegetative, physiological, nutritional and antioxidant behavior of spearmint (*Mentha spicata* L.) in response to different nitrogen supply in hydroponics. Journal of applied research on medicinal and aromatic plants, 6, 52-61. Available: https://doi.org/10.1016/j.jarmap.2017.01.006

Chrysargyris, A., Panayiotou, C., & Tzortzakis, N. (2016). Nitrogen and phosphorus levels affected plant growth, essential oil composition and antioxidant status of lavender plant (*Lavandula angustifolia* Mill.). Industrial Crops and Products, 83, 577-586. Available: https://doi.org/10.1016/j.indcrop.2015.12.067

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. Available: https://doi.org/10.3390/agronomy11061237

da Silva, M. G., Costa, I. P., Alves, L. S., Soares, T. M., & Gheyi, H. R. (2023). Coriander cultivation under different nutrient solution depths in hydroponic systems: a comparison between conventional DFT and adapted DFT with PVC pipes. Water Resources and Irrigation Management-WRIM, 12(1-3), 29-43. Available: https://doi.org/10.19149/wrim.v12i1-3.3077

da Silva, M. G., Soares, T. M., Gheyi, H. R., Costa, I. P., & Vasconcelos, R. S. (2020). Growth, production and water consumption of coriander grown under different recirculation intervals and nutrient solution depths in hydroponic channels. Emirates Journal of Food and Agriculture, 32(4), 281-294. Available: http://doi.org/10.9755/ejfa.2020.v32.i4.2094

Danai-Christina, A., Eirini, S., Pavlos, T., Paschalina, C., & Stefan, M. (2021). Improvement of the quality in hydroponically grown fresh aromatic herbs by inducing mild salinity stress is species-specific. Folia Horticulturae, 33(2), 265-274. Available: https://doaj.org/toc/2083-5965

Dewir, Y. H., Alsadon, A., Ibrahim, A., & El-Mahrouk, M. (2022). Effects of growing substrate, mode of nutrient supply, and saffron corm size on flowering, growth, photosynthetic competence, and cormlet formation in hydroponics. HortTechnology, 32(2), 234-240. Available: https://doi.org/10.21273/HORTTECH04980-21

Dubey, N., & Nain, V. (2020). Hydroponic—the future of farming. International Journal of Environment, Agriculture and Biotechnology, 5(4). Availabe: https://dx.doi.org/10.22161/ijeab.54.2

El-Kazzaz, K. A., & El-Kazzaz, A. A. (2017). Soilless agriculture: A new and advanced method for agricultural development: An introduction. Agricultural Research Technology Open Access Journal, 3(2), 63-72. Available: http://doi.org/10.19080/ARTOAJ.2017.03.555610

Fallahi, H. R. (2022). Evaluation of flowering potential of saffron corms in different weight groups under hydroponic conditions. Journal of Saffron Research, 10(2), 344-331. Available: https://doi.org/10.22077/jsr.2022.5324.1187

Farrokhi, E., Samadi, A., & Rahimi, A. (2021). Investigation of antioxidant activity, total phenol and flavonoid content of lemon balm (*Melissa officinalis* L.) in different media under hydroponic condition. Eco-phytochemical Journal of Medicinal Plants, 8(4), 19-33.

Faruq, H., Novelia, E., Setyaningsih, M., & Nisa, R. A. (2021, April). The utilization of vegetable waste as a nutrient addition in hydroponic media for the growth of green mustard (*Brassica juncea* L.). In IOP Conference Series: Earth and Environmental Science (Vol. 755, No. 1, p. 012078). IOP Publishing. Available: https://doi.org/10.1088/1755-1315/755/1/012078

Furlani, P. R., Silveira, L. C. P., Bolonhezi, D., & Faquin, V. (1999). Cultivo hidropônico de plantas (Vol. 180). Campinas: IAC.

Gaikwad, D. J., & Maitra, S. (2020). Hydroponics cultivation of crops. Protected cultivation and smart agriculture, 279-287.

George, P., & George, N. (2016). Hydroponics-(soilless cultivation of plants) for biodiversity conservation. International Journal of Modern Trends in Engineering and Science, 3(06), 97-104.

Guerrero-Lagunes, L. A., Ruiz-Posadas, L. D. M., Rodríguez-Mendoza, M. D. L. N., Soto-Hernández, M., & Castillo-Morales, A. (2011). Thyme hydroponics crops effect (*Thymus vulgaris* L.) on essential oil quality and yield. Revista Chapingo. Serie horticultura, 17(2), 141-149.

Gumisiriza, M. S., Kabirizi, J. M., Mugerwa, M., Ndakidemi, P. A., & Mbega, E. R. (2022). Can soilless farming feed urban East Africa? An assessment of the benefits and challenges of hydroponics in Uganda and Tanzania. Environmental Challenges, 6, 100413. Available:https://doi.org/10.1016/j.envc.2021.100413

Hasan, M., Sabir, N., Singh, A. K., Singh, M. C., Patel, N., Khanna, M., et al. (2018). Hydroponics technology for horticultural crops. Tech. Bull. TB-ICN, 188(2018), 30.

Hoagland, D. R., & Arnon, D. I. (1950). The water culture method for growing plants without soil. California Agricultural Experiment Station Circular, 347, 1-32.

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. Available: http://ijagcs.com/wp-content/uploads/2014/08/833-842.pdf

Indira, D., & Sabitha Rani, A. (2024). Comparative analysis of growth parameters in hydroponic and soil-grown systems of *Ocimum basilicum* L.(Basil). Plant Science Archives, 9(2), 26-32. Available: https://doi.org/10.51470/PSA.2024.9.2.26

Jensen, M. H. (1997, May). Hydroponics worldwide. In International Symposium on Growing Media and Hydroponics 481 (pp. 719-730). Available:http://doi.org/10.17660/ActaHortic.1999.481.87

Joshi, D., Nainabasti, A., Awasthi, R. B. P., Banjade, D., Malla, S., & Subedi, B. (2022). A review on soilless cultivation: The hope of urban agriculture. Archives of Agriculture and Environmental Science, 7(3), 473-481. Available: https://dx.doi.org/10.26832/24566632.2022.0703022

Kannan, M., Elavarasan, G., Balamurugan, A., Dhanusiya, B., & Freedon, D. (2022). Hydroponic farming–A state of art for the future agriculture. Materials today: proceedings, 68, 2163-2166. Available: https://doi.org/10.1016/j.matpr.2022.08.416

Khaliq, F. A., & Mushtaq, A. (2023). The five most traded compounds worldwide: Importance, opportunities, and risks. International Journal of Chemical and Biochemical Sciences, 23(1), 185-194.

Khan, S., Purohit, A., & Vadsaria, N. (2020). Hydroponics: Current and future state of the art in farming. Journal of Plant Nutrition, 44(10), 1515-1538. Available:https://doi.org/10.1080/01904167.2020.1860217

Khatun, I., Karim, S., Das, S. K., & Hossen, R. (2021). Onion cultivation approach by custom-made outdoor hydroponics: A very first attempt in Bangladesh. Journal of Aridland Agriculture, 7, 48-51. Available: https://doi.org/10.25081/jaa.2021.v7.6518

Kiferle, C., Lucchesini, M., Mensuali-Sodi, A., Maggini, R., Raffaelli, A., & Pardossi, A. (2011). Rosmarinic acid content in basil plants grown in vitro and in hydroponics. Open Life Sciences, 6(6), 946-957. Available: https://doi.org/10.2478/s11535-011-0057-1

Kumar, H., & Agarwal, A. (2024). Comparative study of celery (*Apium graveolens*) on growth, yield and quality under different growing conditions. The Indian Journal of Agricultural Sciences, 94(7), 791-794. Available: https://doi.org/10.56093/ijas.v94i7.140506

Li, Y., Heckman, J., Wyenandt, A., Mattson, N., Durner, E., & Both, A. J. (2020). Potential benefits of silicon nutrition to hydroponically grown sweet basil. HortScience, 55(11), 1799-1803. Available: https://doi.org/10.21273/HORTSCI15320-20

Luna-Maldonado, A. I., Rodríguez-Fuentes, H., Rodríguez-Ortiz, J. C., Vidales-Contreras, J. A., Márquez-Reyes, J. M., & Flores-Breceda, H. (2016). Cultivation of *Rosmarinus officinalis* in hydroponic system. Journal of Experimental Biology and Agricultural Sciences, 4(6), 637-643. Available: http://dx.doi.org/10.18006/2016.4(Issue6).637.643

Macwan, J., Pandya, D., Pandya, H., & Mankad, A. (2020). Review on soilless method of cultivation: hydroponics. International Journal of Recent Scientific Research, 11, 37122-37127. Available:http://dx.doi.org/10.24327/ijrsr.2020.1101.5058

Maliqa, M., Junaid, N. K., Haleema, B., Arshad, H. M., Faheeem, U. K., Rohitashw, K., et al. (2023). Study of the phenology of saffron (*Crocus sativus* L.) grown in soilless media under protected environment. International Journal of Environment and Climate Change, 13(91), 819-830. Available: http://asian.go4publish.com/id/eprint/2507

Manukyan, A. (2011). Effect of growing factors on productivity and quality of lemon catmint, lemon balm and sage under soilless greenhouse production: I. Drought stress. Medicinal and aromatic plant science and biotechnology, 5(2), 119-125.

Manukyan, A. E., Heuberger, H. T., & Schnitzler, W. H. (2004). Yield and quality of some herbs of the Lamiaceae family under soilless greenhouse production. Journal of applied botany and food quality, 78(3), 193-199.

Maurer, D., Sadeh, A., Chalupowicz, D., Barel, S., Shimshoni, J. A., & Kenigsbuch, D. (2023). Hydroponic versus soil-based cultivation of sweet basil: impact on plants' susceptibility to downy mildew and heat stress, storability and total antioxidant capacity. Journal of the Science of Food and Agriculture, 103(15), 7809-7815. Available: https://doi.org/10.1002/jsfa.12860

Mouroutoglou, C., Kotsiras, A., Ntatsi, G., & Savvas, D. (2021). Impact of the hydroponic cropping system on growth, yield, and nutrition of a Greek sweet onion (*Allium cepa* L.) landrace. Horticulturae, 7(11), 432. Available: https://doi.org/10.3390/horticulturae7110432

Muthu, H. D., Izhar, T. N. T., Zakarya, I. A., Saad, F. N. M., & Ngaa, M. H. (2023). Comparative study between organic liquid fertilizer and commercial liquid fertilizer and their growth performances on mustard greens. In IOP Conference Series: Earth and Environmental Science (Vol. 1135, No. 1, p. 012002). IOP Publishing. Available: https://doi.org/10.1088/1755-1315/1135/1/012002

Nardi, L., Metelli, G., Garegnani, M., Villani, M. E., Massa, S., Bennici, E., et al. (2022). Farming for pharming: Novel hydroponic process in contained environment for efficient pharma-grade production of saffron. Molecules, 27(24), 8972. Available: https://doi.org/10.3390/molecules27248972

Naznin, M. T., Kitaya, Y., Hirai, H., & Alsanius, B. W. (2018, August). Sulfur fertilization enhances ajoene accumulation in hydroponically grown garlic. In XXX International Horticultural Congress IHC2018: II International Symposium on Soilless Culture and VIII International 1273 (pp. 217-222). Available: https://doi.org/10.17660/ActaHortic.2020.1273.29

Naznin, M. T., Kitaya, Y., Shibuya, T., & Hirai, H. (2009). Development of Hydroponic Culture System for Producing Garlic and Determination of Ajoene Concentration. Eco-Engineering, 21(4), 147-152. Available:https://doi.org/10.11450/seitaikogaku.21.147

Naznin, M. T., Kitaya, Y., Shibuya, T., & Hirai, H. (2010). Growth and ajoene concentrations in garlic plants cultured hydroponically with different aeration regimes. The Journal of Horticultural Science and Biotechnology, 85(2), 161-165. Available: https://doi.org/10.1080/14620316.2010.11512648

Naznin, M. T., Kitaya, Y., Shibuya, T., Endo, R., Hirai, H., & Lefsrud, M. G. (2015). Ground based study on culturing garlic as a source of vegetable food and medicine in space-growth and ajoene accumulation in garlic plants cultured with different CO2 regimes. Biological Sciences in Space, 29, 1-7. Available: https://doi.org/10.2187/bss.29.1

Nguyen, L., Duong, L. T., & Mentreddy, R. S. (2019). The US import demand for spices and herbs by differentiated sources. Journal of Applied Research on Medicinal and Aromatic Plants, 12, 13-20. Available: https://doi.org/10.1016/j.jarmap.2018.12.001

Park, Y., & Williams, K. A. (2024). Organic hydroponics: A review. Scientia Horticulturae, 324, 112604. Available: https://doi.org/10.1016/j.scienta.2023.112604

Rattan, S., Partap, M., Kumar, S., & Warghat, A. R. (2022). Nutrient feeding approach enhances the vegetative growth biomass, volatile oil composition, and myristicin content in hydroponically cultivated *Petroselinum crispum* (Mill.) Nyman. Journal of Applied Research on Medicinal and Aromatic Plants, 26, 100359. Available: https://doi.org/10.1016/j.jarmap.2021.100359

Razan, K., Aziz, R., Al-Maari, K., & Al-Biski, F. (2023). Studying the growth and productivity of saffron under different agriculture techniques. Iraqi Journal of Agricultural Sciences, 54(1), 242-252. Available: https://doi.org/10.36103/ijas.v54i1.1697

Rodríguez-Fuentes, H., Muñoz, S., & Alcorta-García, E. S. (2011). El tomate rojo sistema hidropónico. Editorial Trillas.

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. Available: https://doi.org/10.1016/j.procir.2017.11.048

Sathyanarayana, S. R., Gangadhar, W. V., Badrinath, M. G., Ravindra, R. M., & Shriramrao, A. U. (2022). Hydroponics: An intensified agriculture practice to improve food production. Reviews in Agricultural Science, 10, 101-114. Available: https://doi.org/10.7831/ras.10.0_101

Shinde, C. T., & Marathe, P. S. (2021). Farming without soil in today's era. Iconic Research and Engineering Journals, 4(7), 24-27.

Son, Y. J., Park, J. E., Kim, J., Yoo, G., & Nho, C. W. (2021). The changes in growth parameters, qualities, and chemical constituents of lemon balm (*Melissa officinalis* L.) cultivated in three different hydroponic systems. Industrial Crops and Products, 163, 113313. Available: https://doi.org/10.1016/j.indcrop.2021.113313

Sorooshzadeh, A., & Tabibzadeh, Z. (2010, March). Effect of copper in hydroponic solution on leaves and roots of saffron (*Crocus sativus* L.). In International Conference and Exhibition on Soilless Culture 1062 (pp. 83-88). Available: https://doi.org/ 10.17660/ActaHortic.2015.1062.10

Souret, F. F., & Weathers, P. J. (2000). The growth of saffron (*Crocus sativus* L.) in aeroponics and hydroponics. Journal of herbs, spices & medicinal plants, 7(3), 25-35. Available: https://doi.org/10.1300/J044v07n03_04

Sousa, R. D., Bragança, L., da Silva, M. V., & Oliveira, R. S. (2024). Challenges and solutions for sustainable food systems: The potential of home hydroponics. Sustainability, 16(2), 817. Available: https://doi.org/10.3390/su16020817

Sowmya, R. S., Warke, V. G., Mahajan, G. B., & Annapure, U. S. (2023). Effect of amino acids on growth, elemental content, functional groups, and essential oils composition on hydroponically cultivated coriander under different conditions. Industrial crops and products, 197, 116577. Available: https://doi.org/10.1016/j.indcrop.2023.116577

Stelluti, S., Caser, M., Demasi, S., Herrero, E. R., García-González, I., Lumini, E., et al. (2023). Beneficial microorganisms: A sustainable horticultural solution to improve the quality of saffron in hydroponics. Scientia Horticulturae, 319, 112155. Available: https://doi.org/10.1016/j.scienta.2023.112155

Suhaimi, M. Y., Mohamad, A. M., Mahamud, S., & Khadzir, D. (2012). Effects of substrates on growth and yield of ginger cultivated using soilless culture. . Journal of Tropical Agriculture and Food Science, 40(2), 159-68. Available: http://ejtafs.mardi.gov.my/jtafs/40-2/Soilless%20culture.pdf

ŢĂLU, Ș. (2024). Insights on Hydroponic Systems: Understanding Consumer Attitudes in the Cultivation of Hydroponically Grown Fruits and Vegetables. Hidraulica, (1).

Tuwar, D. A., & Tuwar, A. R. (2018). Comparison in growth of hydroponic cultivated crop plants with normal soil cultivated crop plants by using non circulating culture and aggregate culture methods of hydroponics. International Journal of Researches in Bioscience, 4(2), 266-269. Available: https://ijrbat.in/upload_papers/0803201802471362.%20Tuwar%20&%20Tuwar.2.pdf

Udagawa, Y. (1994). Some responses of dill (*Anethum graveolens*) and thyme (*Thymus vulgaris*), grown in hydroponic, to the concentration of nutrient solution. Hydroponics and Transplant Production 396, 203-210. Available: https://doi.org/10.17660/ActaHortic.1995.396.24

United Nations. (2018). 2018 revision of world urbanization prospects. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

United Nations. (2022). Population | United Nations. https://www.un.org/en/global-issues/population

Upendri, H. F. L., & Karunarathna, B. (2021). Organic nutrient solution for hydroponic system. Academia Letters, 1893, 1-10. Available: https://doi.org/10.20935/AL1893

Velazquez-Gonzalez, R. S., Garcia-Garcia, A. L., Ventura-Zapata, E., Barceinas-Sanchez, J. D. O., & Sosa-Savedra, J. C. (2022). A review on hydroponics and the technologies associated for medium-and small-scale operations. Agriculture, *12*(5), 646. Available: https://doi.org/10.3390/agriculture12050646

Vikou, C., Semassa, J., Diaconeasa, Z., Roko, G., Tohoyessou, M., Dah-Nouvlessounon, D., et al. (2023). Diversity, chemical compositions and beneficial effects of some spices and aromatic leaves consumed in Benin and in the world: Critical review. American Journal of Plant Sciences, 14(5), 569-598. Available: http://doi.org/10.4236/ajps.2023.145039

Walters, K. J., & Lopez, R. G. (2021). Modeling growth and development of hydroponically grown dill, parsley, and watercress in response to photosynthetic daily light integral and mean daily temperature. Plos one, 16(3), e0248662. Available: https://doi.org/10.1371/journal.pone.0248662

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