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Revolutionizing Agriculture: A Review on Benefits and Potential of Hydroponics Technology

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ABSTRACT

The global population is increasing and half of the arable land may become unsuitable for farming, making hydroponics an increasingly popular alternative worldwide. Cultivating crops without soil is becoming more popular through the use of hydroponics, which involves using a nutrient solution and precise climate control. This technique has the potential to revolutionize agriculture in both developed and developing countries. Hydroponic farming provides several advantages over traditional agriculture practices with higher yields. Furthermore, because hydroponic systems are maintained in controlled environments, it allows for cultivation throughout the year regardless of outdoor conditions. It offers high outputs using less space by extending farms vertically. Numerous studies have been carried out using hydroponic systems to examine how plants react to both biotic and abiotic stress factors. Hence, hydroponics is a promising technology due to its low operational costs despite the high initial capital expenditure, making it an attractive alternative for farming globally.

Key words: *Hydroponics, Deep Water Culture (DWC), Nutrient Film Technique (NFT), Drip Irrigation, Ebb and Flow, Aeroponics, Aquaponics, Biotic stress, Abiotic stress*

Introduction

It is estimated that the global population will increase to 9.7 billion by the year 2050. According to estimates, approximately half of the arable land worldwide will become unsuitable for farming (U. Nations, 2017). Modern farming methods heavily depend on soil and water, which leaves them exposed to erratic weather conditions. This implies that there is a need to modify and improve the economic policies of agriculture. The urgency for food production is undeniable, as it is predicted to increase twofold in order to fulfill the growing demand (The Sahara Forest Project, 2009).

Soil is the primary used growing medium for plants, as it offers essential nutrients, water, air, and stability for successful growth. Unfortunately, soil can be limited by factors such as unsuitable composition, erosion, inadequate drainage, inappropriate pH levels, and the presence of disease-causing organisms and nematodes (Dholwani *et al*., 2018). To overcome these barriers to plant growth in agriculture, the hydroponics system was introduced. Hydroponics is a technique for cultivating plants without soil, where nutrient-rich solutions are used instead. Unlike traditional farming methods that rely on soil for nutrients, hydroponics involves providing plants with water-based solutions that contain the necessary nutrients (Khan *et al*., 2020). The roots of crops are supplied with nutrient solutions that have a balanced pH and EC and contain the specific nutrients needed for their growth. These solutions are delivered in a soluble form that can be easily absorbed by the roots, and the entire process is carried out in a controlled environment (Pretty, 2020)

Professor William Gericke is credited with coining the term in the early 1930s. The largest market for hydroponics is in Europe, with France, the Netherlands, and Spain being the top 3 producers, followed by the US and the Asia-Pacific region. This technique is gaining popularity worldwide, and it is estimated that the global hydroponic market will experience a growth rate of 18.8% between 2017 and 2023, resulting in a market size of USD 490.50 million by 2023 (Jan *et al*., 2020)

Hydroponic systems are not widely used by Indian farmers due to a lack of knowledge and skills required to operate them. One of the main challenges is the low literacy rate among farmers. In order to address this issue, it is important to provide guidance and training to as many farmers as possible (Solanki *et al.,* 2017). Those with less fragmented land can take advantage of hydroponic culture in greenhouses to increase crop productivity. Additionally, in the event of crop loss due to natural disasters, farmers can have an alternative option to grow organic and pesticide-free vegetables to sustain themselves and contribute to the country's economic growth (Solanki *et al*., 2017)

Hydroponics is an advantageous technique in food production due to its ability to easily modify the hydroponic solution's composition. This can lead to improved efficiency of nutrient acquisition by the plants through physicochemical phenomena and nutrient interactions. Consequently, hydroponics has been proven to improve both the quality and quantity of plant production. Moreover, hydroponics is highly efficient and offers a wide range of benefits, including environmental benefits, by utilizing nutritional and water resources more effectively. Overall, hydroponics is a promising cultivation method with significant potential and numerous advantages (Sathyanarayana *et al*., 2022)

History

Hydroponics has been practiced for thousands of years, with evidence of its use found in the Hanging Gardens of Babylon nearly two millennia ago (Krumrei, 2019). The term "hydroponics" originated from the Greek words, "hydro," meaning water, and "ponos," meaning labor (Khan *et al*., 2020). While the technique has been in use for a long time, modern researchers are increasingly utilizing it to deepen their understanding of plant growth processes. Specifically, they are studying how plants absorb nutrients and the various roles each nutrient plays in their development. This increased use of hydroponics is allowing scientists to gain more insights regarding the flora and their functionality, which can inform more effective farming practices and crop production methods that are both sustainable and efficient (Krumrei, 2019). This method becoming increasingly popular in the space program as a way to provide astronauts with a healthy diet and remove harmful CO_2 from the air inside Spacelab. NASA has conducted extensive research on hydroponics for its Controlled Ecological Life Support System (CELSS), which aims to create a self-sustaining ecosystem for long-term space missions. As a result, companies around the world are investing in hydroponic technology to establish and expand this method of growing plants (Sathyanarayana *et al*., 2022).

Why use hydroponics?

Hydroponics provides several advantages over traditional farming, and as people become more aware of these benefits, more individuals may choose to adopt hydroponic techniques for their agricultural needs.

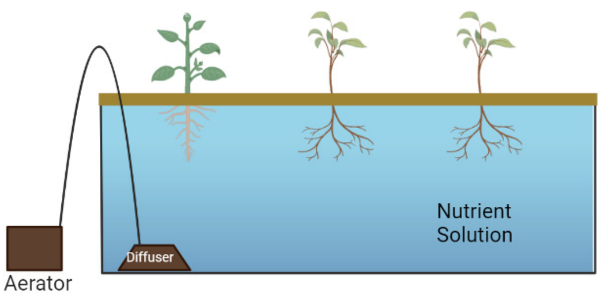
According to the UN reports on global population, hydroponic systems have shown a 20% to 25% increase in yield compared to traditional agriculture methods, with productivity rates being 2 to 5 times higher. The controlled environmental conditions in hydroponic systems also allow for better management of the effects of climate change on crops, without compromising annual crop production (Verma *et al.,* 2020). It requires only 5% of the water and a smaller area of land to produce the same amount of crops as traditional agriculture (Al Shrouf, 2017).

It provides the advantage of a shorter harvest period since plants grown in hydroponic systems have direct access to water and nutrients, eliminating the need for extensive root systems to search for nutrients. This leads to healthier and fuller plants, and they grow in about half the time compared to traditional agriculture (Turner, 2012).

Types of hydroponics system

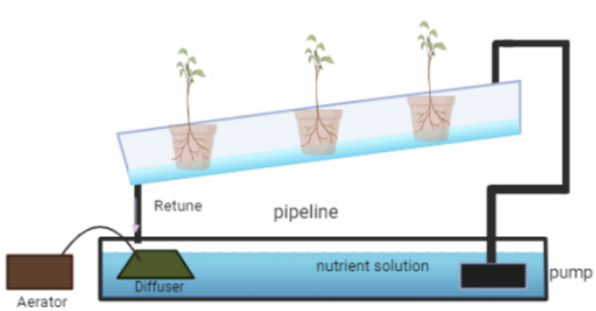
Deep Water Culture (DWC)

One type of hydroponic technique utilized by many is the Deep Water Culture (DWC). This method involves supplying plants with nutrient solutions directly to their roots, which are always submerged in the solution. DWC hydroponics can be done indoors or in a box, using TL lamps instead of natural sunlight (Nursyahid, *et al*., 2021). The Hydroponics bucket system is a well-known example, plants are positioned in net pots, and their roots are suspended in a nutrient solution, which helps them grow quickly and abundantly. However, it is crucial to keep a close eye on the levels of oxygen, nutrients, pH, and salinity to prevent the growth of unwanted algae and molds in the reservoir (Jan *et al*., 2020).



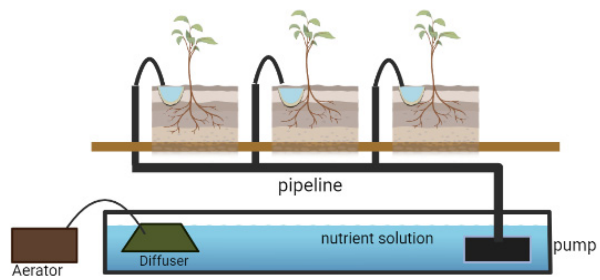
Nutrient Film Technique

In this cultivation method, the plant roots are placed in channels, also known as gullies, through which a thin layer of nutrient solution passes. This keeps the roots moist but not waterlogged. The nutrients are mixed in a primary reservoir and continuously flow through the system, delivering a consistent feeding rate of one liter per minute to the plants. Automation can be employed to regulate aeration in the system. The key concept of NFT (Nutrient Film Technique) is the recycling of nutrient solutions for growing crops (Mohammed *et al*., 2016).Compared to the floating root system, NFT uses less nutrient solution, but it requires more energy and components to function properly. The surplus solution is directed back to the storage tank via gravity, and the flow of nutrient solution can be either continuous or intermittent (Velazquez-Gonzalez *et al*., 2022)



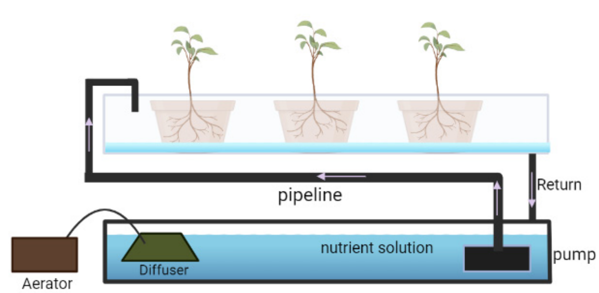
Drip Irrigation

Drip systems are a simple and widely used technique in which a pump on a timer provides a slow and steady supply of nutrient solution to each plant's base individually. This method works effectively with growing mediums that retain water well, such as coco coir, and peat moss. It is a low-maintenance and high-yielding system when functioning correctly, but the drip lines may become obstructed, leading to dry plants. For these systems, synthetic nutrients are preferable because organic substances clog the lines more quickly (Yuvaraj *et al*., 2020). It is used commonly utilized for growing tomatoes and peppers (Macwan *et al*., 2020)



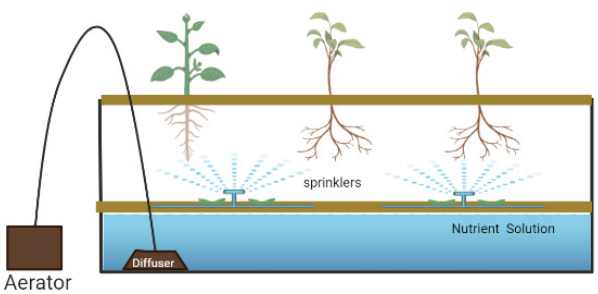
Ebb and Flow system

The Ebb and Flow System, also known as the flood and drain system, is an affordable option for setup and upkeep, which has contributed to its widespread adoption. This system ensures an even distribution of nutrient solution to all plants (George *et al*., 2016). In the Ebb and Flow System, water and nutrient solution are pumped from a reservoir to grow plants, and they remain there for a specific duration to nourish the plants. However, this method is prone to root rot, algae, and mold growth, making it necessary to modify the system by adding a filtration unit. Additionally, the system can be computerized for automation (Macwan *et al*., 2020).



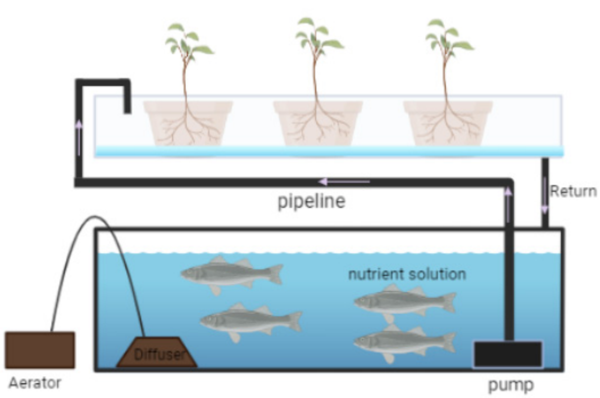
Aeroponics

The Cabot Foundation Laboratories developed an aeroponics system between 1973 and 1974. This system involves cultivating plants by exposing their roots to a nutrient mist (Zobel *et al*., 1976). The term "aeroponic" is derived from the Latin words "aero," meaning air, and "ponic," meaning work, and refers to the process of cultivating plants in an air-based medium.Aeroponics is a technique for growing plants without soil or water as a medium (Lakkireddy *et al*., 2012). This method involves maintaining essential growth parameters, such as temperature, pH, humidity, and electrical conductivity of a nutrient solution, to promote plant growth (Kaur and Kumar, 2014).



Aquaponics

Aquaponics is a method of integrated multi-trophic food production that combines a recirculating aquaculture system (RAS) with a hydroponic unit. This system involves the cultivation of plants and fishes together in a mutually beneficial manner (Getachew *et al*., 2018). In an aquaponics system, the plants absorb nutrients from the water, while the microbial processes of nitrification and denitrification occur. This allows for the recycling of water from the fish tank, creating a balanced micro-ecosystem (Macwan *et al*., 2020). As a result of the continual circulation and nutrient exchange in the water system between plants and fish, there is no requirement for the application of artificial pesticides or herbicides to support plant growth (Janni *et al*., 2022).



Growing media for hydroponics

Different types of growing media are used in hydroponic systems to support plant growth and root development. The primary function of the growing media is to provide aeration and support to the root system. There are several options for growing media that can be used in hydroponics some of the important media are

Expanded clay: Highly effective, with excellent capillary action and reusable clay pebbles.

Rockwool: Rockwool is produced by melting rocks and then spinning the molten material into fibers. These fibers are compressed to form sheets of inert mineral material that possess excellent water and air-holding properties (Tripathi *et al*., 2022).

Perlite: The water retention capacity of a growing medium is influenced by its irregular surface structure. To improve aeration and drainage, perlite is commonly incorporated into the growing media (Tripathi *et al*., 2022).

Vermiculite: Light and has a high water-holding capacity.Vermiculite is commonly added to the sowing medium and soil mixture to provide coverage for germinating seeds Tripathi *et al*., 2022).

Coconut fiber: Nursery plant production often utilizes coconut husks as a growing medium. These husks are ground and compressed for transportation and sale. While coconut husks offer an excellent substrate for effective air and water exchange by the plant roots, similar to composted pine bark, they can also bind nitrogen, leading to increased production costs (Tripathi *et al*., 2022).

Sand: Suitable sand particle size ranges from 0.5 mm to 2.5 mm

Crushed granite: Screened crushed granite with a particle size of 2 mm is commonly used, but it has a low water retention capacity (Nana Lal Mali *et al*., 2021)

Nutrients required

The quality and yield of crops in hydroponic systems are directly affected by the nutrient solution. This solution typically consists of aqueous solutions containing essential elements in organic or inorganic forms. There are 17 essential elements that are necessary for proper plant growth, including carbon, oxygen, hydrogen, phosphorus, nitrogen, potassium, calcium, sulfur, magnesium, iron, zinc, copper, manganese, boron, chlorine, nickel and molybdenum (Salisbury, 1992). The most important elements found in the nutrient solution include nitrogen, phosphorus and potassium as well as calcium magnesium and sulfur which require supplementation with micronutrients. These elements have a significant impact on plant growth and ultimately affect crop yield. If any of these essential elements are absent from the growth medium it can adversely affect all aspects of plant development (Barman *et al.*, 2016)

pH range of solutions

Optimal pH levels in the nutrient solution are important for plant growth and nutrient uptake. However, plants can affect the pH of the solution as they develop. Therefore, external monitoring and control is necessary to ensure productivity. Nonetheless, minor fluctuations of up to 0.1 pH units can be deemed insignificant. The ideal pH range for many plant species is typically between 5.5 and 6.5 units, which is suitable for most common plants, but some more tolerant species can thrive at higher or lower pH levels. It's crucial to acknowledge that different plant species have distinct pH requirements leading to significant variability (Sonawane, 2018).

Pros and cons of Hydroponics

Increased earning or income generation

Hydroponic systems have been used commercially in various places, including Thailand, where expensive vegetables are grown using this technology. Although the initial setup costs for hydroponic systems can be high, it is justified since the crops produced using this method fetch a higher price. This has opened up opportunities to grow crops locally, without harming the environment, while making better use of natural resources and reducing hunger (Butler and Oebker, 1962).

Year Round Production

Hydroponic cultivation relies on precise management of agro-climatic factors, such as light, relative humidity, and temperature, which enables year-round crop cultivation, including off-season cultivation. Typically, short-duration crops are mainly usedin hydroponic cultivation. In a hydroponic system, the amount of nutrients given to plants can be precisely controlled, resulting in reduced costs for fertilization (Putra and Yuliando, 2015). Additionally, since it is a closed system, nutrients are not lost through water runoff. In fact, an efficient hydroponic farm uses only 25% of the fertilizer required by a traditional open agricultural system. This prevents eutrophication, which is caused by the accumulation of fertilizer and plant nutrients leaching into river water, leading to the overgrowth of aquatic plants, such as algae (Sonawane, 2018).

Reduced space requirement

Vertical farming enables high outputs to be generated using less space. Hydroponic farms can be extended vertically, even in places such as marginal lands, warehouses, and water-scarce areas. This can be achieved by placing racks or tiers of plants vertically and providing each tier with equal care and facilities, such as UV light and other necessary resources (Goenka, 2018)

Improved rate of growth

Providing a plant with precisely what it requires, at the right time, can result in healthy growth that is genetically optimal. Hydroponic cultivation makes this possible by creating an artificial environment within four walls, with the addition of light and air conditioning. This environment is tailored to suit the specific needs of different plants, resulting in better outcomes in terms of taste, freshness, and color (Qureshi *et al*., 2017). Hydroponic cultivation provides complete control over the nutrients that plants receive. Prior to planting, growers can determine the specific requirements of a particular crop and provide the plants with the necessary nutrients in precise amounts (Dubey and Nain, 2020). When fodder is grown hydroponically, it tends to be juicier, more appealing to the taste, and richer in nutrients compared to conventionally grown fodder. This, in turn, leads to increased production of milk and meat (Ramteke *et al*., 2019).

The conservation of water through the recycling and reuse of water

The hydroponic system is known for its water conservation and recycling capabilities, as well as its ability to remediate water. It has been shown to offer advantages in terms of lower water requirements, which makes it easier to manage external factors. Studies have shown that the use of water and fertilizers in hydroponic cultivation has decreased significantly, with a reduction of up to 10 times in water usage and up to 40% in fertilizer usage as compared to conventional cultivation systems (Kaintura *et al*., 2020)

Reduce pesticides

According to Resh and Howard, the use of pesticides in hydroponic systems can be minimized while achieving increased yield and water conservation. Additionally, plants grown in hydroponic systems tend to grow faster and produce higher yields compared to those grown in soil. Furthermore, hydroponic methods are capable of providing the right proportion and sufficient nutrient content to meet the plants' needs (Resh and Howard, 2012).

Improved vegetable production

Vegetables grown hydroponically are of excellent quality and need little cleaning. Soil preparation and weeding can be greatly decreased or eliminated altogether. By providing an ideal growing environment, it's possible to produce large amounts of vegetables on a small plot of land. This method is especially valuable in regions that face environmental challenges like extreme cold, heat, or desert conditions since the plants have access to all the necessary nutrients and water at all times (Prakash *et al*., 2020). It requires only 5% of the water and a smaller area of land to produce the same amount of crops as traditional agriculture (Al Shrouf, 2017). The WUE values for tomato production in the San Joaquin Valley of California varied depending on the irrigation method used. Flood irrigation had a WUE range of 10-12 kg m-3, sprinkler irrigation had a range of 11-19 kg m-3, and drip irrigation had a range of 19-25 kg m-3. In contrast, greenhouse tomato production in the Netherlands and France using open hydroponic irrigation systems achieved higher WUE values at 45 kg m-3 and 39 kg m-3 respectively, without reusing any water. Closed irrigation systems with water recirculation also showed high WUE values with 66 kg m-3 achieved in the Netherlands and 25 kg m-3 to 30 kg m-3 in Spain and Italy's warmer climates (Al Shrouf, 2017).

Cost of production

Hydroponics is a promising technology due to its low operational costs compared to traditional farming, despite the high initial capital expenditure. Hydroponics employs advanced control devices that reduce labor and maintenance expenses (Lages Barbosa *et al*., 2015). According to a 1996 study by UNDP, hydroponic celery had total expenses of $2.31 per square meter and net income of $28.55 per square meter (UNDP 1996). Other studies have also shown that hydroponics cultivation yields greater profits than the cost of cultivation for growing crops. For instance, while setting up a hydroponic tomato farm may be costly, the operational expenses are notably lower, including polybags, coco pear, nutrients per cropping cycle, seeds, electricity, and employee salaries at approximately 15.1 lakh/year. Despite these costs, revenue from hydroponic tomato farming can reach about 30 lakhs/year (Swain *et al*., 2021).

Cons of hydroponics

Despite the potential advantages of hydroponic systems in urban environments, they have not become widely adopted due to various limitations. These limitations include:

Initial cost

Protected cultivation in greenhouses often involves the use of hydroponic systems, allowing for precise control over growth conditions like temperature, humidity, gas composition, and light. Unfortunately, these systems can be quite costly to set up, making them a challenge for farmers in developing countries who may be unwilling to invest due to the risks involved (Kaintura *et al*., 2020).

Supervision

Expert supervision is necessary for hydroponic systems, as it involves individuals with knowledge of different factors such as plant growth selection, habits of the selected plants, climatic needs or adaptations of the crop, and pollination requirements (Shinde *et al*., 2021).

High Disease risk

Hydroponically grown crops can be more susceptible to disease infections if proper care is not taken. In an open system, where the nutrient solution and water drain away freely, the risk of disease infection is considerably lower because the crop roots are less prone to attack. However, in a closed system, excess drain continuously flows through the roots of the plant in a circular pattern, which can make the crops more susceptible to disease infections. If there is any trace of a disease-causing pathogen in the system, the whole plant may suffer a severe infection attack (Jensen, 2013).

Difficulties arising from abiotic stresses

In hydroponics, it is simple to subject both shoot and root tissues to abiotic stresses because they can be accessed quickly (Geary *et al*., 2015). Abiotic stresses affect the composition of plants, with temperature being a primary factor that influences nutrient uptake and metabolism (Gent *et al*., 2016). A decrease in specific leaf area, total reduced nitrogen, and nitrate content in lettuce occurs when temperatures are cooler while warmer temperatures increase dry matter, sugar, malic acid, and potassium content in lettuce tissues (Gent *et al*., 2016). Although improper nutrient supply can have positive or negative effects on plants, salinity is a major limiting factor for plant growth in hydroponics. Salinity reduces root water uptake due to osmotic effects which leads to water stress. Surprisingly, hydroponic salinity positively affects tomato fruit quality but negatively impacts plant growth and fruit production (Zhang *et al*., 2016). In addition, increasing light intensity and continuous light duration enhances oxidative stress as seen by the production of reactive oxygen species (ROS) and lipid peroxidation (Zha *et al*., 2019).

Difficulties arising from biotic stresses

Hydroponic systems provide an ideal environment for various types of pests, making pest infestations more likely compared to traditional soil-based cultivation. Controlling pests in hydroponics requires a diverse range of methods tailored to specific pests. Therefore, it is important to have knowledge about pests and the appropriate measures to control them. In hydroponics, pest control procedures are not fundamentally different from those used in soil-grown plants to prevent insect infestations. Regular monitoring of pests is crucial in hydroponics, identifying harmful pest incidences that require economic control measures (Sathyanarayana *et al.,* 2022). In hydroponics systems, the growth of algae is heavily reliant on the presence of nutrients and light, specifically in recirculating systems like the nutrient film technique. Algae can create various issues, such as interference with water supply, competing with plants for nutrients intake, and some kinds of algae produce harmful substances that may impede or stop crop growth. In summary, algae's existence usually has unfavorable impacts on crop productivity in hydroponics systems (Sathyanarayana *et al.*, 2022).

Future aspects

The world's population is expanding at an unprecedented rate, which is resulting in a decrease in the amount of arable land available for farming. As a result, farmers are facing challenges in increasing the productivity of their land per unit area. This could lead to increased food costs in the future due to the high demand and limited supply (Mattice and Brown, 2010).The issue of a decreasing amount of farmland and an increasing demand for food could potentially be resolved by hydroponics. Research indicates that implementing hydroponic methods may result in yields 20-25% higher than traditional soil cultivation. Furthermore, tomatoes grown through hydroponics can produce over twice the amount as soil-based systems over several years due to improved nutrition and management, along with less time between crop turnovers. Another benefit is that commercial hydroponic growing techniques necessitate fewer chemicals for root zone sterilization and pest control compared to conventional soil-based cultivation (Mattice and Brown, 2010).

In conclusion, the use of hydroponics in farming is gaining recognition as a feasible method to grow different kinds of crops and has the potential to help feed a large part of the world's population. In nations like India, where cities are expanding quickly, adopting soilless farming techniques like hydroponics has become necessary to ensure food safety and high-quality yields. However, for commercial hydroponic farms to succeed and cost-effective hydroponic technologies to be developed, government and research institutions must play an active role.

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