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Hydroponics: A Review on Revolutionary Technology for Sustainable Agriculture

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

India's economy heavily relies on agriculture, with the majority of the population depending on it for sustenance and livelihood. However, the rapid development of regions has resulted in severe issues affecting soil quality and cultivation practices. Additionally, factors such as natural disasters, climate change, and excessive use of chemicals have further deteriorated soil fertility. The scarcity of usable water for agriculture exacerbates the problem, leading to reduced food production and widespread hunger and malnutrition. Consequently, there is a critical need to embrace agricultural technologies that can conserve water, enhance food production, and ensure its availability. "Hydroponics" is one such methodology that can be adapted to counter all these problems. Hydroponic cultivation generally yields higher-quality produce with superior taste and nutritional value compared to traditional soil-based farming methods. Hydroponics offers numerous advantages compared to conventional soil-based crop cultivation. These benefits include shorter crop growing cycles, year-round production, reduced susceptibility to diseases and pests, and the

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elimination of labour-intensive intercultural tasks such as weeding, spraying, and watering. In the future, hydroponics has the potential to emerge as a prominent method for supplying food to the global population.

Keywords: Hydroponics; sustainable agriculture; soilless farming; indoor agriculture; vertical farming.

1. INTRODUCTION

According to UN FAO estimates, the human population is expected to reach about nine billion people by 2050 which marks a milestone in human history. Global production will need to increase by around 70 % from 2007 if food demand is to be met. Also, 75 % of the world's population is expected to live in urban settlements by 2050 as the world becomes increasingly urbanised. As Plants are regarded as the 'Earth's painted canvas, breathing art into existence' and soil is an accessible medium for plant growth. They provide the plant with all the essential nutrients, water, air, etc. However, they do pose a serious threat to the plant's health. The presence of disease-causing organisms, inapt soil reaction, soil compaction, poor drainage, soil erosion, etc. are some of them.

In addition, conventional crop growing in soil (Open Field Agriculture) is somewhat difficult as it involves large space, a lot of labour, and a large volume of water. In addition, soil is not suitable for growing crops in certain urban areas and due to their unfavourable geographical or topographical situation there are shortages of fertile cultivable arable land that can be cultivated [1]. In short, hydroponics is a Greek word that comes from two words "hydro" meaning water, and "ponos" meaning labor. It is a method of growing plants in chemically inert substrates such as sand, gravel, or liquid, to which nutrients are provided but no soil is utilised [2,3]. Furthermore, the utilised water can be recovered and reused, and the nutrients can be obtained from a variety of sources, including fish excrement. It is also referred to as "Controlled Environment Agriculture" (CEA) since raising plants hydroponically requires control of environmental factors such as the intensity of light and its duration, temperature, humidity, pH of the medium, and mineral nutrients. This system helps to face the challenges of climate change and also helps in production system management for efficient utilization of natural resources and mitigating malnutrition [4]. The most advantageous factor of hydroponics is that it can be grown in areas where in-ground agriculture is not possible like in desert areas or cold regions. It also has much higher crop yields because, in a hydroponic system, plants are more densely spaced together compared to the size of land that would be needed to grow the same number of plants. But along with these it also has some disadvantages like it is quite expensive and it requires skill and knowledge to operate efficiently.

1.1 Hydroponics in Agriculture 4.0

Rapid technological progress in electronics and technology has made the agricultural sector a fast-evolving industry. By integrating machines, sensors, aerial imaging, and GPS, these innovations have transformed farming practices, such as artificial intelligence (AI), Internet of Things (IoT), and more. In order to optimise precise irrigation, pest control, plant disease identification and production management, this integration referred to as Agricultural 4.0 is intended to combine farming practices with cutting edge technology [5].

Various sophisticated technologies like robots, sensors, aerial and satellite imaging, and GPS are increasingly being utilized to enhance the entire food value chain, making farming businesses more profitable, efficient, safer, and environmentally friendly. In this context, hydroponics, a soilless method of plant cultivation, aligns perfectly with the principles of Agriculture 4.0. Major companies are leveraging breakthroughs in indoor vertical farming, artificial intelligence, and plant biology to cultivate a wide range of products [6]. With the support of advanced technologies and scientific knowledge, hydroponics has undoubtedly secured a central role in future food production systems. However, the challenge lies in making these technological advancements accessible to medium- and small-scale urban and peri-urban farming operations, where hydroponics could significantly contribute to achieving Sustainable Development Goal 11: sustainability and resilience of urban communities.

However, the adoption of the agriculture 4.0 philosophy is not a straightforward process, as there are numerous obstacles to overcome before concepts such as eco-agriculture [7], Agro-photovoltaics [8], and precision agriculture [9] become ingrained in the culture and practices of farmers worldwide. Achieving this goal requires finding common ground between agriculture and technology, where both producers and technologists understand each other's needs. Producers must comprehend the best applications of technology and demand innovations that address the real needs of the food supply and value chains, while technologists must meet producers' expectations by providing highly improved products, services, and processes to support sustainable and efficient food production in urban and peri-urban areas.

1.2 Types of Hydroponics Systems

According to growers, farmers, and researchers, the most common types of hydroponic systems and their respective characteristics [10,11,12]:

1.2.1 Deepwater culture (DWC)

Deepwater culture (DWC) is a hydroponic system where plant roots are suspended in nutrient-rich water, and the air is supplied directly to the roots through an air stone. An example of this system is the Hydroponics buckets system, where plants are grown in net pots with their roots immersed in a nutrient-rich solution. It is important to monitor oxygen and nutrient concentrations, salinity, and pH to prevent the growth of algae and mold in the reservoir [13]. DWC works well for larger fruit-producing plants, particularly cucumbers, and tomatoes.

1.2.2 Drip System

In the Drip system, plants are grown separately in a soil-less medium while the nutrient solution is stored in a reservoir. A pump delivers water or nutrient solution in the right proportion to individual plant roots through nozzles [14]. This slow dispensing of nutrients allows for the collection and recirculation or discharge of excess solutions. The Drip system enables the simultaneous cultivation of multiple plant varieties.

1.2.3 Ebb and Flow

Ebb and Flow, the first commercial hydroponic system, operates on the flood and drain principle. It consists of a grow tray and a nutrient-rich solution reservoir. Periodically, a pump floods the grow tray with the solution, which then drains slowly. Various crops can be grown in this system, but issues such as root rot, algae, and mold are common [15], necessitating the use of a modified system with a filtering unit.

1.2.4 Nutrient film technique (NFT)

The nutrient film technique (NFT), invented by Allen Cooper in the mid-1960s, is a popular hydroponic system. Nutrient-rich solution continuously flows through channels containing the plants [13]. The solution is recirculated back to the beginning of the system after reaching the end of the channel. Unlike DWC, the plant roots in the NFT method are not fully submerged.

1.2.5 Wick System

The Wick System is the simplest hydroponic system that operates without electricity, pumps, or aerators [16]. Plants are grown in a porous medium like coco coir, vermiculite, or perlite, with a nylon wick connecting the plant roots to a reservoir of nutrient-rich solution. Water or nutrient solution is supplied to the plants through capillary action. This system is suitable for small plants, herbs, and spices.

1.2.6 Aeroponics

This is a water-based system similar to NFT and doesn’t require a medium. The mineral solution is sprayed onto the plants in the form of a mist. This is difficult to set up but is beneficial in the large commercial setting.

1.3 Hydroponics in Improving Quality

Consumption of Fruits and vegetables highly decrease the rate of risk of many types of chronic disease in human [17,18]. Using green techniques like hydroponics offers the potential to enhance the levels of bioactive compounds and nutrients, such as beta-carotene and antioxidants, in vegetables, consequently improving their quality and health-promoting properties. Hydroponics is particularly advantageous in protected agriculture, as it allows for precise control over environmental factors, ensuring consistent water and nutrient conditions. Moreover, the manipulation of light and temperature within hydroponic systems can further influence the nutritional composition of fruits and vegetables, enhancing their overall nutritional quality. A significant difference has been seen in the quality of yield between hydroponically and conventionally grown lettuces [19]. The taste and acidity, carotenoids, and vitamins in tomatoes were better in hydroponic systems [20]. It was found that thirty percent more yield of tomatoes in a mixture of 80% pumice + 10% perlite + 10% peat medium in comparison to the soil [21]. Tomatoes grown hydroponically were considered softer and tastier than the traditional cultivation.

1.4 Nutrient Solution for Hydroponics

An aqueous solution consisting predominantly of inorganic ions from soluble salts of key elements that are essential for higher plants is a nutrient solution in hydroponics. The nutrient solution is an aqueous solution containing mainly macronutrients (N, P, K, Ca, Mg, and S) and micronutrients (Fe, Mn, Cu, Zn, B, Mo, and Cl). The nutrient solution must be biologically inert to avoid any biological activity that may have a detrimental effect on crops, like diseases, malnutrition, and other consequences. Bacteria can spread quickly from one plant to another if corrective efforts are not taken immediately, so the substrate must not encourage biological activity.

The electrical conductivity (EC) and pH of the nutrient solution are important parameters that need to be monitored and adjusted regularly to ensure optimal plant growth. The pH is a parameter that measures the acidity and basicity of a solution on a scale of 0 to 14 depending upon the number of ionisable H^+ and OH^- ions. The pH of the aqueous solution should lie between 5.5 to 6.5 for the proper development of crops [22]. Electrical Conductivity (EC) measures the ability of the nutrient solution to carry an electrical charge, which is directly related to the number of salts dissolved in it. The solution's electrical conductivity should be between 1.2 and 3.5 Mho for the proper development of the crops. The more salts, the higher the EC. The nutrient solution flow rate also affects hydroponic plant growth and root morphology. Researchers have tested different nutrient solution flow rates in hydroponic vegetable production using brackish water and found that 1.5 L/min and 100% ionic strength was the most effective.

1.5 Challenges in Hydroponics

The researchers discovered that wastewater exposure to air improved nitrogen removal efficiency in a hydroponic system using artificial light. Additionally, they discovered that wastewater treated with carbon dioxide prior to distillation performed the best. But the reduction of nitrogenous forms was unaffected by artificial light [23]. This hydroponic system relies on nutrient-rich fish waste to feed the plants, and the plants help to purify the water by removing toxins harmful to the fish [24]. Studies indicate that the similar yields produced by aquaponic plants and plants may be due to the presence of microorganisms that promote plant growth, particularly in peppers, tomatoes, and cucumbers. Typical hydroponics. However, given the significantly decreased nutrient levels, more research is required to fully utilize the advantages of microorganisms for all plants [25]. Vegetables can be grown using recycled hydroponics in a sustainable manner by implementing basic EC control of the nutrient solution [26]. Soilless farming is widely used in sheltered agriculture to maintain product quality, enhance the controllability of the growing environment, and remove uncertainties related to soil water and nutritional conditions. Landless techniques, like growing food on rooftops or in close proximity to cities, not only conserve water but also make it easier to produce food [27].

1.6 Future Scope of Hydroponics in India

Similar to the popularity of hydroponics on the moon, Hydroponic farming in India does not yet enjoy public acceptance. Many people in India own farms that are near the poverty line, so their lack of education, investment or willingness to get away from comfort zones is contributing to a hostile attitude towards hydroponics. Also, hydroponics is not commonly known to be used by rural farmers in India. In spite of these challenges, the prospects for hydroponic cultivation in India are positive on several grounds:

(i) Firstly, India's megacities are grappling with water scarcity, and agriculture is a major consumer of water. By transitioning from traditional agriculture to water-efficient technologies like hydroponics, it is possible to achieve more than 80% water savings. This saved water can then be redirected to the drinking water supply, addressing a pressing issue.

(ii) Secondly, a significant portion of the vegetables consumed in India contains residual chemicals, which can be harmful to health. Unlike developed countries, India lacks well-developed systems to track and monitor pesticide residue in food. As awareness of health risks grows, consumers in India are actively seeking healthier products and are willing to pay a premium for them. Hydroponically grown crops have the potential to provide chemical-free food commodities, satisfying the demand for safer products.

In general, given the growing market for organic products and an increased interest from farmers and researchers in its potential as a form of sustainable farming, it is likely that India will be able to grow hydroponic crops more widely over time. However, it will also be necessary to address the need to provide financial and technical assistance to farmers and constraints on what can be grown with hydroponic technology [28].

2. CONCLUSION

As a promising solution to address polluted soil sites and prevent further deterioration of the environment, Hydroponics is gaining ground as an essential element in promoting sustainability and environmentally friendly practices. Despite a large initial capital investment, this technology is significantly better than conventional farming due to its minimal operating costs. The cost of staff and maintenance is reduced as a result of the installation of advanced monitoring equipment. Furthermore, hydroponics has made it possible to effectively solve important food safety issues such as soil contamination and pesticide residues. The result is that in the years to come, an exponential growth of hydroponic production will take place globally.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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