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Cultivating Resilience: Exploring Root Systems in Hydroponic Agriculture

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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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Review Article

ABSTRACT

Hydroponic cultivation has emerged as a promising solution to address the challenges of conventional agriculture by offering efficient resource utilization and enhanced crop yields. At the core of this innovative farming technique lies the intricate relationship between plant roots and their surrounding environment. The success of hydroponic systems hinges upon the establishment of robust root systems, which serve as the anchors of growth in soilless mediums. Roots in hydroponic systems exhibit distinctive characteristics compared to those in traditional soil-based cultivation, with adaptations tailored to optimize nutrient uptake and water absorption in the absence of soil. Understanding these adaptations is crucial for maximizing the potential of hydroponic farming and overcoming limitations inherent in conventional agriculture. Additionally, various strategies for optimizing root performance within hydroponic systems are examined. Nutrient management techniques, such as nutrient film technique (NFT) and drip irrigation, play a vital role in ensuring adequate nutrient supply to support healthy root growth and overall plant development. Manipulation of root zone environments, including pH and oxygen levels, further enhances root function and nutrient uptake efficiency. These strategies contribute to the establishment of robust root systems capable of sustaining high levels of crop productivity in

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hydroponic environments. By shedding light on the significance of robust roots as the anchors of growth in hydroponic systems, this paper aims to inspire further exploration and innovation in sustainable agriculture practices, ultimately contributing to food security and environmental stewardship. Through a synthesis of current research findings, practical insights are provided to guide future advancements in hydroponic farming, fostering a more resilient and sustainable food production system.

Keywords: Hydroponics cultivation; nutrient uptake efficiency; root development; root growth; soil based system.

1. INTRODUCTION

Aiming to feed a projected 10 billion people by 2050, agricultural development is one of the most effective ways for eradicating extreme poverty and promoting shared prosperity. Compared to other industries, the sector of agriculture expansion has the potential to improve the earnings of the poorest people by a factor of two to four. Agriculture, which accounts for 4% of global GDP and up to 25% in the least developed countries, is also critical to economic development [The World Bank, 2023]. Economic contribution of agriculture in India has gradually declined to less than 15% as a result of the rapid expansion of the industrial and services sectors; however, the importance of sector to the social and economic of the country fabric extends much beyond this figure. First, about 75% of Indian families' incomes come from rural sources. Second, around 770 million people, or nearly 70% of population of India impoverished, reside in rural areas [The World Bank, 2012]. As the food demand of world grows, it is critical to develop inventive and sustainable farming systems that can meet it without further jeopardizing it. Hydroponics gives a feasible alternative to the problematic ways of traditional agriculture practices, which may alleviate this issue [1]. Growing plants hydroponically entails substituting soil with a nutrient-rich water solution [2]. It is feasible to build the system such that the plants receive the appropriate amount of oxygen, nutrients, and water for growth. The method is based on the complex interaction of plant roots with their surroundings. Strong root systems are required for hydroponic systems to function since they serve as the foundation of growth in this soilless medium. Root is a multicellular organ with distinctive characteristics such as a protective root cap, endogenous branching, gravitropic response, and root hairs. They are essential for anchoring plants, absorbing water and nutrients from the soil, and promoting overall plant growth and development [3]. The spatial configuration of the root system, known as Root System Architecture (RSA), is important for plant productivity, as it determines the capacity of plant to exploit available resources. Additionally, the distribution and function of roots are considered the most limiting factors for plant growth in almost all natural ecosystems, and the root system plays a major role in yield and overall plant productivity. Therefore, the root system is essential for the uptake of water and nutrients, providing stability to the plant, and facilitating optimal foraging for resources in the soil [4]. In hydroponic systems, roots require oxygen to breathe. To ensure that roots receive adequate oxygen, appropriate root zone aeration is required. This fosters proper root growth and overall plant health [5]. Healthy root growth is essential for plants to thrive and produce to their full potential. In hydroponics, roots anchor and sustain the plant structure even in the absence of soil. Strong and robust roots anchor the plant in the growing medium or substrate, providing stability and the proper orientation for optimal light exposure and nutrient uptake. Temperature, substrate flow rate, ph levels, and fertilizer availability all have an impact on root growth and development. Healthy root growth is required for optimal nutrient uptake, water absorption, and overall plant vitality [6].

2. ROOT MORPHOLOGY

Root morphology refers to the external structure of plant roots, influencing above-ground growth. It comprises the radicle, primary roots, lateral roots, root hairs, and root cap. The radicle, emerging from the seed embryo, develops during germination. In gymnosperms and dicotyledons, the primary root often becomes a central taproot, possibly sprouting lateral roots [8]. Lateral roots arise from pericycle cells or apical meristem [9]. Root hairs develop on sporophyte surfaces in vascular plants [Jonas et al., 2012]. The root cap protects the proximal root meristem and guides growth in response to environmental stimuli like gravity, light, touch, temperature, humidity, and chemicals [Barlow et al., 2002].

3. LENGTH OF ROOT

Root length in plants is diverse and determined by various factors. Plant species possess different root systems, with some having deep roots penetrating soil, while others have shallow roots spreading horizontally [10]. Soil properties like texture, compaction, moisture, and nutrient availability influence root length. Roots may grow longer in loose, well-aerated soils with ample nutrients compared to compacted or nutrient-poor soils [11]. Adequate water supply is crucial for root survival, with dry soil promoting root elongation and wet soil hindering it [12]. Nutrient availability affects root growth, with roots in poor soils extending further to gather nutrients [13]. Additionally, as a plant's root system enlarges over time, its length may increase [14].

4. GROWTH OF ROOTS

In a hydroponic system, where plants are grown without soil and with their roots directly immersed or suspended in a nutrient – rich water solution. Plants in hydroponic system can be almost completely submerges in water while keeping roots healthy and white. Root growth is a particular importance as it is directly influences plant’s ability to access water, nutrients and oxygen. The growth of roots is influenced by various factors.

4.1 Nutrient Availability

Nutrient availability is vital in hydroponics, where plants solely rely on the nutrient solution. Proper balance and availability are crucial for healthy root growth and overall plant development. Monitoring and regulating nutrient levels is essential to support optimal root growth. Providing a balanced nutrient solution with the right proportions of nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients is necessary. The forms of nitrogen, like ammonium (NH_4^+) or nitrate (NO_3^-), impact plant growth, with a balanced diet including both forms being beneficial [15]. The ratio of nitrate (NO_3^-) to ammonium (NH_4^+) affects root development; for instance, tomato roots thrive with a 3:1 NO_3^- to NH_4^+ ratio, while high NH_4^+ concentrations inhibit growth [15]. Nutrient solution temperature directly affects plant oxygen use and inversely correlates with dissolved oxygen levels.

4.2 Aeration and Oxygen Level

In hydroponics, proper aeration can be achieved using an air pump and air stones. The air pump forces air through the air stones, which bubbles into the nutrient solution. The stone's porous structure allows the oxygen the pump forces through it to release air in small bubbles. Hoidal et al.,[16]. Different plant species exhibit varying oxygen radiation within their roots. For example, in corn roots, a gradient of oxygen concentration from 10% to 5% was observed from the cortex to the wake. Similarly, in castor roots, the oxygen gradient range from 21% in the exterior to 7% in the phloem [17] To address oxygen deficiencies in the root zone, various oxygenation techniques are employed, such as aeroponics, oxygenation and oxyfertigation. These techniques aim to improve oxygen availability in the root environment and minimize the risk of hypoxia, ultimately enhancing plant yield and quality [18].

4.3 Root Zone Environment

In soilless culture, nutrient solutions maintain a pH of 5 to 6 (usually 5.5) to optimize nutrient accessibility within the root environment, ideally between 6 and 6.5 [19]. Temperature variations from optimal ranges can reduce root growth rates in different plant species [20]. Root temperature significantly influences water uptake and gas exchange. Research assessed water uptake (Fig 1), O_2 reduction, and CO_2 increase rates across temperatures ranging from 8 to 28°C. Response curves showed a sigmoidal pattern, with rates declining below 12°C and increasing above 16°C [21]. Boycr (1971) noted that root systems contribute over 50% of a plant's hydraulic resistance. This study investigated how root temperature impacts water uptake rate and hydraulic resistance across root systems [22].It measured hydraulic conductance and resistance in detached roots using a pressure chamber at 200-500 kPa [23]. High pressure can alter the hydraulic properties of roots grown under normal conditions [24].

4.4 Different Growing Medium for Root Growth

Different growing mediums offer diverse properties tailored to support plant growth. Inert mediums, such as rock wool, provide structural support, while coconut coir boasts excellent water retention and aeration. Perlite and vermiculite, both lightweight materials derived from natural minerals, promote good drainage and moisture availability, albeit with varying capacities. Soilless mediums blend organic and inorganic components, offering a balanced mix of water retention, aeration, and nutrient availability. Expanded clay pellets and grow stones provide sustainable alternatives with superior water retention and aeration properties, facilitating optimal root development. Organic mediums, derived from natural sources, often supplement plants with additional nutrients. These substrates offer aeration and moisture retention properties, ensuring adequate oxygenation and hydration of the root zone. The choice of substrate can influence root growth characteristics and nutrient absorption efficiency [25].

5. AERATION CAPACITY OF ROOTS

Adequate oxygen levels in the root zone are crucial for plant growth. A study on cucumber manipulated aeration levels to observe their effects on growth and bioactivity [26]. Plant roots require oxygen to produce ATP from carbohydrates. Aerobic respiration yields 38 mol ATP per mol glucose, while anaerobic conditions yield only 2 mol ATP, hindering root health and function [27]. Roots cannot photosynthesize and must absorb oxygen from their surroundings, particularly in soil where air spaces provide oxygen. Well-aerated soil ensures oxygen availability and efficient drainage, vital for root health. Hydroponic systems rely on aeration to supply oxygen. Limited dissolved oxygen in water restricts biological processes, affecting cell growth and metabolite production [28]. Dissolved oxygen in a hydroponic solution is crucial for plant health, influenced by temperature and salinity. Higher temperatures reduce dissolved oxygen, impacting plant health sooner than other factors. Maintaining appropriate dissolved oxygen levels in hydroponic systems is essential to prevent toxic shock or nutrient lockup. Overall, adequate aeration in both soil and hydroponic systems is essential for healthy plant growth and development [5].

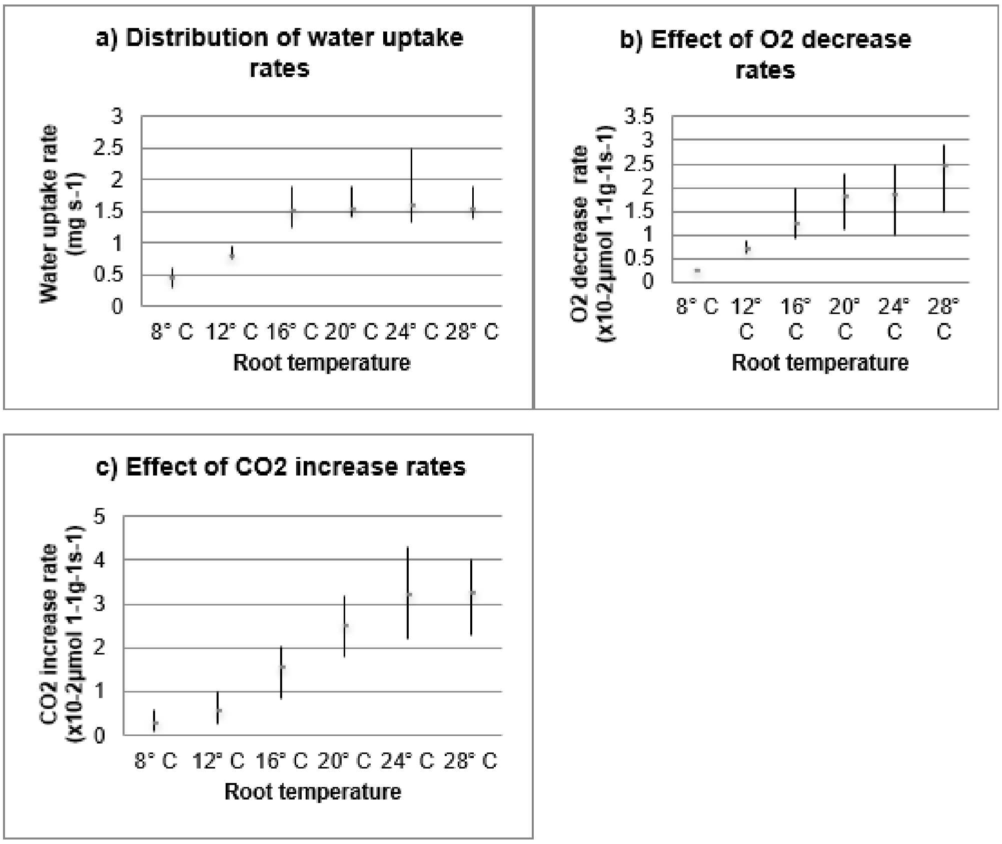

Fig. 1. The distribution of water uptake rates (a), the effects of 02 decrease rates (b) and C02 increase rates (c) on root temperature in root systems under 80 kPa suction. Mean values from 6 plants are plotted with 95% confidence interval

Source: Yoshida et al, 1989

6. NUTRIENT UPTAKE EFFICIENCY AND NUTRIENT USE EFFICIENCY OF ROOTS

In hydroponic systems, nutrient uptake efficiency is influenced by plant species [29], nutrient concentration, pH [30], root health [6], temperature [31], light intensity [32] and solution flow rate.

A study on hydroponic Swiss chard (Fig 2), investigated nutrient uptake efficiency under varying substrate flow rates. Results showed nitrogen uptake decreasing by 23.6% and 42.6% at flow rates of 6 and 8 L/min respectively. Phosphorus uptake remained stable up to 6 L/min but decreased by 41.8% at 8 L/min compared to 6 L/min. Potassium uptake increased by 34.3% from 2 to 4 L/min, but declined by 20.3% and 55.34% at 6 and 8 L/min respectively. Calcium uptake decreased by 26.2% from 2 to 4 L/min, increased by 24.2% from 4 to 6 L/min, and decreased by 36.2% at 8 L/min. Sulphur use efficiency increased by 9.2% from 2 to 4 L/min, decreased by 8.5% at 6 L/min, and significantly increased by 54% at 8 L/min [33].

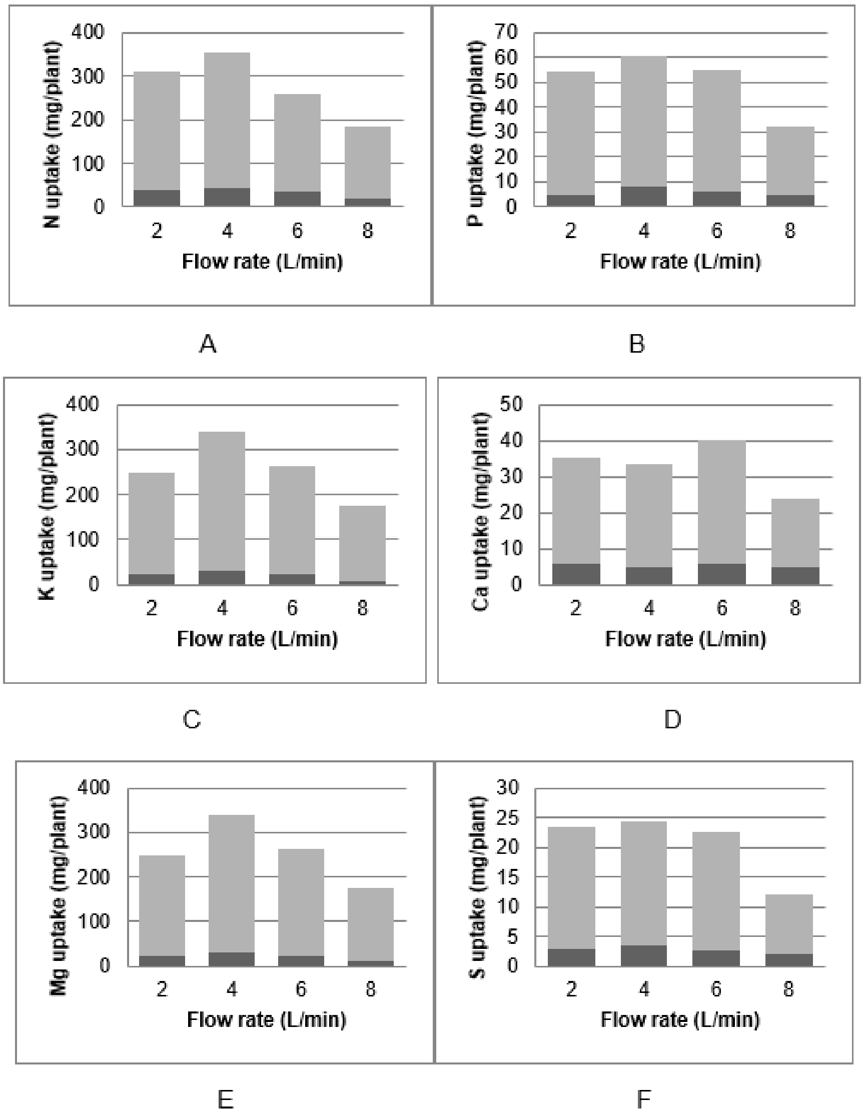

Fig. 2. Plant nutrient uptake varies with flow rate. Plants absorb a) nitrogen, b) phosphorus, c) potassium, d) calcium, e) magnesium, f) sulphur. Significant differences were observed between the bars labelled with different letters ($p < 0.05$). The data are presented as means ± standard error (n = 4)

Source: Baiyin et al., 2021

7. ROOT ZONE PROBLEMS

Root Zone problems in hydroponic systems can have significant impact on root and plant health as well as productivity. There are studies showing that the Pythium root rot, is common issue caused by various *Pythium Species* such as *Pythium ultimum* and *Pythium dissotocum.* This disease is widespread and destructive in hydroponically grown plants like cucumber, tomato, sweet pepper, spinach, lettuce and roses [34]. Root zone temperature influences the progression of Pythium root rot symptoms, with higher temperatures leading to more severe root rot in various crops. For example, in chrysanthemums, increasing the root zone temperature from 20°C to 32°C resulted in progressively more severe root rot symptoms caused by *Pythium aphanidermatum* (Fig 3). Similarly, *P. dissotocum* caused severe root disease in spinach at temperatures between 21-27°C, with even more severe symptoms observed during winter months when nutrient solution temperatures were low [35].

7.1 Mechanisms of Root Rot Caused by Pythium Species

Pythium species enter the hydroponic system through contaminated water, infected plant debris or contaminated growing media. The pathogen’s initial inoculum can include zoospores produced from sporangia formed in various resources within the crop environment. It infect plant roots through zoospores, which are attracted to root exudates and can swim in water to reach the roots [34]. Once in contact with the roots, zoospores encyst, germinate, and penetrate the root tissues to establish infection. Upon penetration, They cause damage to the root tissues through enzymatic degradation, leading to cell death and decay. This damage disrupts the normal functions of the roots, including nutrient and water uptake, and compromises the plant's overall health. As the infection progresses, symptoms of root rot become visible, including browning, rotting, and decay of the root tissues [35]. These symptoms can vary in severity depending on the specific Pythium species, host plant, and environmental conditions. Pythium root rot can spread within the hydroponic system through the movement of zoospores and mycelia, leading to widespread infection of plant roots. Factors such as temperature, nutrient availability, and root exudates can influence the rate of disease spread and severity of epidemics. The progression of root rot can weaken the plants, reduce their growth and productivity, and make them more susceptible to other stresses and diseases. The compromised root system affects the plant's ability to absorb nutrients and water efficiently, further [36]. Pathogens, nutrient temperature, fungal disease, lack of air or oxygen (often referred to as overwatering or root rot), and even pests can cause problems.

7.2 Management of Root Rot

Pythium is an organism that lives in dirt. Pythium is also a multispecies organism. Some, including *P. aphanidermatum, P. ultimum, and P. irregulare*, are extremely pathogenic. Pythium can be brought to hydroponic systems on contaminated shoes, tools, or equipment, or anywhere water can come into touch with soil, such as in outdoor retention ponds and streams. This is the reason why clean, well-filtered water is ideal for

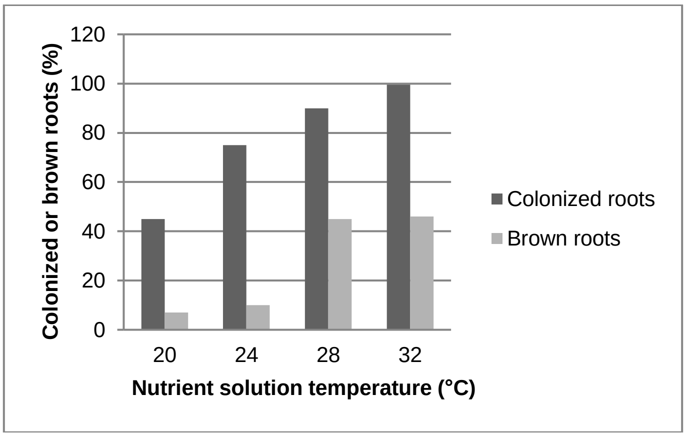

Fig. 3. The effect of nutrient solution temperature on *Pythium aphanidermatum* colonization and root browning in chrysanthemum roots 14 days after inoculation

hydroponics as it is less likely to include Pythium propagules. To preserve the health and productivity of plants in a hydroponic or aquaponic system, it is critical to follow a set of standards for preventing contamination and maintaining cleanliness. This includes putting in place safeguards to prevent germs from entering the system and frequently sanitizing all surfaces, tools, and equipment utilized inside it. Furthermore, rafts should be carefully cleansed and disinfected before reuse, and any contaminated plants should be removed and disposed immediately to minimize disease transmission. Incorporating helpful bacteria into the system can help to suppress dangerous diseases and improve plant health. It is also critical to monitor and maintain appropriate levels of fertility, dissolved oxygen, pH, and electrical conductivity in the nutrient solution. Controlling water temperature at 68-72°F (20-22°C), especially [37].

8. CONTRASTING ROOT SYSTEMS: SOIL-BASED VS. HYDROPONIC GROWTH METHODS

In soil-based systems, roots have the luxury of ample space to spread out and explore for nutrients and water. This environment encourages diverse root structures, including elongation, branching, and lateral root production [38]. Conversely, hydroponic systems confine roots to a limited root zone, potentially resulting in more compact growth patterns [39]. The physical characteristics of soil influence root architecture, leading to a more intricate and varied system. Roots in soil-based systems are exposed to a heterogeneous environment with varying soil textures, moisture levels, and nutrient distribution, prompting the development of adaptive structures like root hairs and mycorrhizal associations [40]. In hydroponic systems, the controlled environment may encourage a more standardized root architecture, as roots are not required to search extensively for nutrients [41].

Studies have shown that root length can vary between soil-based and hydroponic systems and among different crops. While hydroponic systems may promote longer primary roots, they often exhibit fewer lateral roots compared to soil-based systems [42]. For instance, research on citrus plants found that those cultivated hydroponically had longer primary roots but lower root density compared to soil-grown plants. However, root volume and surface area showed no significant difference between the two growth methods [42]. Additionally, studies suggest a positive correlation between root traits observed in hydroponic cultivation and those in traditional soil-based environments, indicating that root characteristics may be reflective across different growing methods [43].

Hydroponic systems, also known as nutrient solution cultivation, offer precise control over nutrient delivery, leading to optimized nutrient uptake and efficient root growth [Boell, 2019]. In contrast, soil-based systems require roots to physically search for nutrients in the soil, resulting in a more exploratory root architecture [Ali et al., 2023]. Furthermore, soil-based systems may face challenges such as nutrient leakage, immobilization, or competition for resources with other organisms, potentially impacting nutrient uptake efficiency [44]. To enhance fertilizer uptake and usage efficiency, nutrient management solutions must be optimized for both soil-based and hydroponic systems [Baiyin et al., 2021].

Adequate aeration is crucial for root respiration and nutrient uptake. Poorly aerated soils can lead to root suffocation and nutrient deficiencies. In soil-based systems, soil aeration is essential for microbial activity and oxidation processes [45]. In hydroponic systems, aeration ensures efficient oxygenation of the root zone, facilitating nutrient uptake and preventing root rot caused by waterborne pathogens [34]. Aeration methods such as introducing air bubbles or thin sheets of water enhance gas exchange, promoting root health and overall plant vigor [46].

Nutrient uptake and utilization efficiency may vary between soil-based and hydroponic systems due to differences in root environment and nutrient availability [46]. Hydroponic systems allow for precise control of nutrient quantities and availability, resulting in effective nutrient absorption by plants. In contrast, soil-based systems rely on microbial activity and soil properties to influence nutrient availability, potentially leading to challenges such as nutrient leakage or competition [47]. Optimization of nutrient management strategies is essential to enhance nutrient uptake efficiency in both growing methods [Baiyin et al., 2021].

Root rot is a common issue in both soil-based and hydroponic systems, albeit caused by different pathogens. In soil-based systems, root rot is typically caused by soil-borne pathogens, while in hydroponic systems, waterborne pathogens are the primary culprits [Papavizas et al., 1974]. Proper management strategies, such as sanitation practices and incorporation of beneficial microorganisms, are crucial for preventing root rot in both systems. Additionally, maintaining proper pH and nutrient levels is essential in hydroponic systems to ensure optimal root health and prevent pathogen proliferation [34,[48-52].

9. CONCLUSION

The need of robust roots in hydroponic farming and proposing answers to the pressing issues of global food crisis and agricultural sustainability. The comparison of soil-based and hydroponic systems demonstrates that hydroponics has distinct advantages in terms of disease management, nutrient delivery, and root growth optimization. Hydroponic systems can increase overall plant vitality, as well as nutrient growth and uptake efficiency, by accurately managing the parameters of the root environment. The ability of effective management approaches to address root zone difficulties like as Pythium root rot highlights hydroponics' potential to alter modern agriculture. However, additional research and technology developments are required to improve hydroponic systems for a variety of crop species and climatic situations. Furthermore, before hydroponics can be widely adopted and integrated into global food production systems, issues with initial setup costs, energy consumption, and scalability must be addressed.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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