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Polymer Use in Soilless Farming Systems with A Comparative Study on Hydroponics and Aquaponics

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Abstract

Hydroponics and aquaponics are innovative, sustainable agricultural methods that achieve high productivity with minimal land and water usage in controlled environments. Hydroponics, a technique that involves growing plants in nutrient-rich water solutions, utilizes various polymer-based components. Aquaponics, a symbiotic system combining aquaculture and hydroponics, also relies on polymer-based materials. These soilless techniques are crucial for producing vegetables, fruits, and other crops without relying on soil, allowing adaptability across various locations. This study compares two key methods in soilless farming: hydroponics and aquaponics, analysing their advantages and limitations relative to traditional soil-based farming. Key factors examined include technological advancements, environmental impacts, yield efficiency, costs, and specific applications of each technique. Soilless farming offers numerous benefits but is heavily dependent on specialized materials, particularly polymers, which play an essential role. This paper highlights the use of polymer films and membranes in hydroponic systems for nutrient delivery and water management, such as high-density polyethylene (HDPE) in Nutrient Film Technique (NFT) channels. Furthermore, it discusses the use of polymer-based grow media (e.g., rockwool, expanded polystyrene [EPS]) and their effects on plant growth. In aquaponics, applications include HDPE tanks for fish and polypropylene (PP) biofilters for bacteria. The study emphasizes the importance of biodegradable and surface-modified polymers for sustainable farming practices and explores the potential of novel polymeric materials to enhance efficiency and sustainability in soilless systems.

Keywords: Hydroponics, aquaponics, polymers, polymer films, polymer-based grow media, soil less farming

INTRODUCTION

Soilless farming presents an effective method for cultivating diverse crops, especially in environments where traditional agriculture is challenging due to urbanization and environmental constraints. The need for alternative farming methods has become increasingly urgent, as traditional agriculture struggles to keep up with rising demand and environmental challenges [1]. Soilless systems like hydroponics, aquaponics, and aeroponics offer viable solutions by using nutrient-rich water rather than soil to deliver essential nutrients to plants, reducing the need for arable land and minimizing water consumption. Hydroponics and aquaponics are widely used for high-efficiency food production and wastewater treatment, which further strengthens their relevance in sustainable agriculture.

In hydroponics, plants are grown in a nutrient-rich water solution, while aquaponics combines fish

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farming with plant cultivation, creating a system where fish waste is recycled as nutrients for plants [2]. The study investigates how optimizing nitrogen utilization in aquaponics can improve system efficiency by analyzing nitrogen absorption and transport.

Based on studies, hydroponic systems can serve dual purposes by producing food and treating wastewater [3]. Growing plants in nutrient-rich water without soil is a straightforward technique. Aquaponics combines fish cultivation with plant growth, creating an environment conducive to both. In this method, filtered aquaculture effluent is used to feed bacteria and plant roots in the hydroponic system. After nutrient removal, the water is recycled back into the fish tanks [4]. This analysis investigates methods to improve nitrogen utilization in aquaponics systems by studying the impacts of nitrate nitrogen from input to output, encompassing NH3 generation, nitrogen removal, nitrate absorption, and nitrogen transport [5].

Polymer Use in Soilless Farming Systems

Soilless farming encompasses various techniques for cultivating plants without traditional soil. These systems offer several advantages, including increased water efficiency, reduced disease incidence, and improved crop yields. However, their success relies heavily on the utilization of specialized materials, and polymers play a crucial role in this regard.

Polymer Films and Membranes in Hydroponics

- *Nutrient film technique (NFT) channels*: HDPE or PVC is used in NFT channels, valued for their durability, chemical resistance, and impermeability, ensuring efficient nutrient delivery and water flow.
- *Reservoir liners*: Linear low-density polyethylene (LLDPE) is commonly used as a liner in nutrient reservoirs due to its flexibility, chemical resistance, and impermeability.

Polymer-Based Grow Media in Hydroponics

- *Rockwool*: A volcanic rock material, spun into fibers, is used as a growth medium with high porosity and water retention capacity.
- *Expanded polystyrene (EPS):* Lightweight and inert, EPS provides structural root support but raises concerns over long-term biodegradability.
- *Polyurethane (PU) foams*: PU foams with open-cell structures enable good air and water permeability, supporting healthy root development. Durability and potential leaching need consideration.

Polymer-Based Tanks and Filtration Media in Aquaponics

- *Fish tanks:* HDPE tanks withstand pressurized water and resist chemical reactions, making them ideal for aquaponic systems.
- *Biofilters*: Polypropylene (PP) is used as a biofilter medium due to its high surface area, facilitating bacterial growth for nutrient conversion.

LITERATURE REVIEW

The literature reveals hydroponics and aquaponics as key solutions to modern agricultural challenges. Hydroponics, involving soilless plant growth in nutrient solutions, enables precise control of environmental conditions. Studies indicate that hydroponic systems are up to 90% more water-efficient than traditional agriculture, largely due to their closed-loop nutrient cycles that conserve water and maximize resource efficiency [6]. The method is particularly suitable for urban and vertical farming, allowing high-yield crop production in restricted spaces. However, the scalability of hydroponics remains limited by initial setup costs and complex nutrient management, though emerging technologies like automated nutrient-delivery systems and artificial intelligence are beginning to mitigate these challenges [7].

Aquaponics, which merges fish cultivation with hydroponic plant growth, offers a symbiotic system where fish waste serves as a natural fertilizer for plants. The closed-loop design of aquaponics not only conserves water but also reduces the need for chemical fertilizers, which contributes to its appeal as a sustainable agricultural method. Research highlights the system's efficiency in nutrient cycling and its suitability for regions with limited freshwater [8]. However, aquaponics requires specialized expertise to balance water quality, fish health, and plant nutrients, adding complexity to its implementation compared to hydroponics.

Polymers are essential materials in soilless farming systems, used for nutrient channels, reservoir linings, and grow media. High-density polyethylene (HDPE) and polyvinyl chloride (PVC) provide durability and chemical resistance, enhancing the longevity and efficiency of hydroponic and aquaponic systems [9]. Polymer-based grow media, such as Rockwool, EPS, and polyurethane (PU) foams, are also critical for facilitating gas exchange and water retention in hydroponics. Recent studies advocate for bio-based polymers due to their biodegradability, furthering environmental sustainability [10].

Recent advancements focus on improving nutrient cycling efficiency, integrating renewable energy, and developing bioengineered plants optimized for soilless cultivation. Together, these developments highlight the promise and remaining obstacles in scaling hydroponic and aquaponic systems for widespread agricultural use [11].

HYDROPONICS

It can be cultivated using different media and systems such as Dutch bucket, Nutrient Film Technique, wick system, Drip system, and Ebb flow system. These systems are regulated using devices like pH meters, EC meters, air stones, and air pumps, which are essential for maintaining water and nutrient levels. The disciplined resource management and efficient food production associated with hydroponic systems have led to their widespread adoption. However, despite the productivity benefits of closed-loop systems and substrate nutrition, scaling up such systems may not be cost-effective [12]. Agricultural biotechnology is advancing through the development of genetically modified plants to increase crop yield and incorporate desirable traits like year-round growth, weather resistance, and pest resistance. Hydroponic cultivation, in comparison to traditional agriculture, produces high-quality crops with a 90% increase in water efficiency [13].

AQUAPONICS

Aquaponics is gaining popularity due to the rising demand for production coupled with dwindling freshwater and phosphorous resources. It merges aquaculture (fish farming) with hydroponics (soilless vegetation cultivation), resulting in the creation of diverse methods and system designs. These designs may prioritize either fish or plant production, aligning with the growing trend and decreasing environmental impact compared to other production systems. [14]. Aquaponics operates as a symbiotic system where fish waste nourishes plants, subsequently purifying the water. Fish excrete waste (ammonia), which bacteria convert into nitrate, providing a nutrient source for plants. In turn, the plants absorb these nutrients, effectively acting as natural fertilizer, and purify the water, returning it to a clean state. [15].

HYDROPONICS ADVANTAGES

1. Plants can thrive in environments where suitable soil for traditional crop cultivation is lacking or contaminated with pollutants, rendering it non-arable.
2. Production of healthy and disease-free crops enhance biodegradability.
3. Plants cultivated in a hydroponic system can be shielded from UV radiation, similar to how they are protected within a covered structure.
4. Plants cultivated through this system develop robust and vigorous root systems, rendering them less susceptible to contaminants, diseases, and pest infestations.
5. It is feasible to produce 'off-season' vegetables when market prices are at their peak.
6. Vertical hydroponic gardening offers effective space management capabilities [16].

HYDROPONICS DISADVANTAGES

1. Constructing a hydroponics unit per unit area can be costly.
2. Understanding plant growth and principles of nutrition is crucial.
3. There is a potential for the rapid spread of root diseases.
4. Most plant varieties suitable for controlled growing conditions necessitate research and development efforts.
5. Growers must monitor plants daily because the plant's response to healthy and unhealthy food is remarkably rapid.
6. Farmers must understand climate control within the structure.

ADVANTAGES OF AQUAPONICS

1. Food fish are often mass-produced in confined or restricted locations for diverse purposes, including simplicity of management and maximizing the use of finite resources for optimal output. However, these living conditions come with their ramifications, one of which involves the removal of ammonia expelled by the fish, which is highly toxic to them. [17]
2. Aquaponics eliminates the necessity for heavy earth-moving machinery or equipment to till the soil, thereby averting the decay of soil structure and associated toxicity. [18].
3. Enhanced manufacturing economics result from the integrated farming of fish and vegetation.
4. Decreased fertilizer usage and associated costs.
5. Reduced water use
6. Cultivating fish and vegetation for personal health motivations.

DISADVANTAGES OF AQUAPONICS

1. Wastewater from aquaculture contains fish excreta and high levels of nitrogen, ammonia, and phosphorus. Given suitable conditions, the growth of blue-green algae, also known as cyanobacteria, can mitigate this issue.
2. It is a technically driven system for vegetable cultivation, necessitating skilled manpower with specific expertise to operate. These experts should possess thorough knowledge of suitable vegetables for growth and survival in a soilless environment [19].
3. Knowledge about vegetables which are not harmful for fish is a must.
4. Electricity is essential for managing the entire system. In the event of a power outage, the system ceases functioning immediately, posing risks such as rapid drying of plants and potential mortality of fish.
5. The initial capital investment required for setting up this vegetable cultivation system is significant.
6. Requires environment-controlled conditions and maintenance of cleanness.

Technical Requirements for Both Systems

pH

Most aquatic organisms thrive within a pH range of 6.5 to 9.0. Deviation of the water's pH too far from this range can result in the mortality of aquatic organisms. Additionally, pH levels influence the dissolvability and toxicity of chemicals and heavy metals in water, requiring regular monitoring and adjustment to sustain an optimal pH range.

The pH values recorded in the hydroponic system ranged from 6.26 to 7.77, falling within the typical range for such systems.[20].

EC (Electrical Conductivity)

EC value is different as per plant but in hydroponics (1.1-1.6 Ms/cm) is ideal and in aquaponics (1.2 – 1.8 Ms/cm) is required. High temperatures can lead to increased salinity and the dissolution of solid materials, negatively impacting plant growth and potentially resulting in the death of fish. Additionally, high temperatures can cause thermal shock for fish in aquaponics systems. For both systems, EC value needs to be low to control negative impact [20].

DISEASES

To mitigate the negative impact of soil-borne diseases and soil boron, hydroponics, and aquaponics, soilless farming methods are employed. These methods offer greater control over plant health compared to traditional soil farming. In hydroponics farming, precise regulation of water and nutrient levels results in accelerated growth rates. [21]. These farming methods carry a risk of aquatic pathogen occurrence, with species such as Fusarium, Pythium, and Phytophthora being particularly notable. Due to the recirculation of the same nutrients throughout the system, these pathogens can spread rapidly within minutes.

In aquaponics, the presence of dissolved biological matter may help suppress certain diseases by maintaining a microbial biome less conducive to floral pathogens. This biological matter originates from uneaten food debris, fish feces, biological flora growth media, root exudates, and flora residues. One challenge encountered in aquaponic farming systems is disease control, as pathogens possess the potential to affect both fish and vegetation.

DISCUSSION

The comparative analysis of hydroponics and aquaponics reveals distinct benefits and limitations in terms of scalability, environmental impact, and overall sustainability. Hydroponics allows for precise control over nutrient delivery, making it highly effective for high-yield, rapid-turnaround production. However, the initial setup cost and the need for continuous nutrient monitoring can be prohibitive for larger operations.[21] The increasing development of genetically modified crops designed specifically for hydroponics has helped alleviate some of these concerns, yet economic feasibility remains a consideration for large-scale implementation.

Aquaponics presents a compelling case for sustainable, closed-loop systems, as it integrates fish and plant production, reducing the need for external inputs such as fertilizers. This approach is particularly beneficial in water-scarce regions, as the water used in fish farming is repurposed for plant growth. However, aquaponics requires specialized knowledge in fish and plant care, as well as efficient energy management to sustain system functionality. The reliance on electrical power for water pumps and aeration adds a vulnerability to power outages, which can impact both plant and fish health [22].

The role of polymers in these systems is significant, given their durability, water resistance, and adaptability to various environmental conditions. However, this paper highlights an area for further research: the development of biodegradable and low-leaching polymers. By improving these materials, soilless farming can reduce its reliance on non-degradable components, supporting the broader goals of environmental sustainability.[23] Additionally, innovations in surface-modified polymers for enhanced microbial colonization in aquaponics biofilters or nutrient retention in hydroponic media could further optimize system efficiency and reduce resource input.

Future research should investigate the cost-benefit analysis of these advanced materials in commercial operations, as well as the potential for automated nutrient and water monitoring systems to reduce labor and energy costs. Overall, hydroponics and aquaponics are promising solutions for food security, and continued innovation in polymer technology could significantly enhance the viability and sustainability of soilless farming.

CONCLUSION

Hydroponics and aquaponic both are methods of a soil-less culture where in hydroponics material crops are grown on inorganic nutrients and in aquaponics, crops are grown on fish waste. In both systems, crops are growing healthy and disease-free but in aquaponics maintenance of all the factors is very necessary because fish are used here as compared to hydroponics. the comparative study between hydroponics and aquaponics underscores the distinct advantages and considerations associated with each system. Hydroponics offers precise control over nutrient delivery, leading to potentially higher yields and faster growth rates. On the other hand, aquaponics integrates aquaculture with hydroponics, creating a symbiotic relationship that fosters sustainable nutrient cycling and reduces resource inputs. Understanding the specific needs and objectives of a project is crucial in determining which system best suits individual circumstances. Both hydroponics and aquaponics represent innovative approaches to modern agriculture, offering opportunities for increased efficiency, reduced environmental impact, and enhanced food security. Aquaponics is recognized as an effective method for disease control in plants.

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