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Hydroponics and its role in Vertical Farming: Opportunities and Challenges in Pakistan

Waqi Ur Rehman[1], Muheen Akhtar[1], Arshayan Ahmad[2] and Qaiser Mahmud[3]
[1]Department of Plant Pathology, University of Agriculture, Faisalabad
[2]Department of Agronomy, PMAS Arid Agriculture University, Rawalpindi
[3]On Farm Water Management, Agriculture Department Punjab, Pakistan
*Corresponding author E. Mail: waqimirza2002@gmail.com

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ABSTRACT
The rise in global population and change in climate require innovative agricultural solutions to meet the demand of organic and nutritious food. Vertical farming based on hydroponic systems propose a promising solution to sustainable agriculture by optimizing spatial usage, maximizing resource efficiency and ensuring year-round production of crops. In this review, the synergies of hydroponics and vertical farming are highlighted, the potential of vertical farming to address the challenges of agriculture sector of Pakistan such as water scarcity, climate change and rapid urbanization have been underlined and the opportunities and constrains of implementing them have been explored. The paper also represents global case studies and policy recommendations to promote the adoption of such innovation to ensure food safety and security.

INTRODUCTION

The projected rise of the global population to 9 billion by 2050 has increased the demand for sufficient nutritional and organic food production. Conventional agricultural methods are failing to meet the increasing demand due to the combined challenges of restricted arable land and the growing impacts of climate change, which adversely affect crop yields in susceptible areas such as Pakistan (Al-Chalabi, 2015; Saeed and Ahmed, 2024). These constraints highlight the immediate need for new and sustainable agricultural solutions that may address food security issues without exacerbating the depletion of natural resources.

Vertical farming has evolved as an innovative agricultural method, enabling the cultivation of crops in controlled conditions that optimize resource efficiency and reduce external dependence. Through the integration of new technologies, vertical farming enhances crop output and offers a feasible solution for sustainable agriculture in urban environments, where space is a significant limitation (Sulaiman, 2024). This analysis examines the possibilities of vertical farming, especially its integration with hydroponic systems, as a revolutionary solution for contemporary agricultural issues.

VERTICAL FARMING

Cultivation of crops vertically in stacked layers in controlled environments with reduced water consumption and by using any soilless growing media is referred as vertical farming (Al-Kodmany, 2018). The growing medium varies depending upon the specific technique used such as aeroponics or hydroponics. For instance, coco peat, a substance derived from coconut husk can be used with additional components designed to control other factors like climate conditions, humidity, temperature, light and airflow to ensure optimum growth conditions. Controlled environments also facilitate year-round crop production. VF involves different types of methods and techniques designed to optimize agricultural output in constrained spaces, frequently in urban settings such as hydroponics, aeroponics, stacked layers and aquaponics. Stacked farms rely on vertical structures involving multiple trays for the cultivation of plants, primarily sprouts. Artificial lighting, irrigation

mechanisms and nutrient delivery systems are added in structure. The primary objective of such design is to maximize the growth with minimum utilization of space.

Figure 1. Stacked farms adapted from (Shan E Ahmad, Pakistan Business Council)

In aeroponic systems, plant roots are positioned in an aerial position where a solution of water and desired nutrients is applied in a mist in a controlled environment after consistent intervals. As a result, water consumptions is significantly reduced and precise regulations of plant growth parameters are enabled.

Hydroponic vertical farms replace soil media by providing nutrient-rich aqueous solutions to plant roots directly. The varieties used in hydroponics systems are specially bred to withstand without roots getting suffocated. Substrates or growing media, such as coco peat, are frequently utilized in hydroponic systems to enhance root development; however, their use is not mandatory except larger species, those may necessitate substrate support. If the setup relies on seeds rather than seedlings, substrates are necessary to create an environment conducive to germination and root development. Common hydroponic systems are the Nutrient Film Technique (NFT), Deep Water Culture (DWC), and drip systems. Each system presents distinct advantages influenced by variables such as water management, crop type, and spatial efficiency, rendering hydroponics a flexible approach for urban agriculture and vertical farming applications. (Sandhyarani, 2021).

Aquaponic systems combine aquaculture and hydroponics for sustainable food production. Fish tanks supply nutrient-dense water that is circulated to hydroponic grow beds, facilitating nutrient absorption by plants. Plants filter water, establishing a symbiotic relationship with fish.

Different vertical farming systems exhibit distinct advantages and challenges, characterized by varying degrees of sophistication and complexity. The selection of a system is primarily determined by factors including crop type, spatial constraints, and resource limitations. This paper will focus exclusively on hydroponics, as it is the most widely practiced method, particularly in Pakistan (Shan E Ahmad, Pakistan Business Council).

Increase in demand for space efficient and sustainable agricultural practices necessitates modern innovations and vertical farming integrated with hydroponics present a viable solution. These methods enable the production of high-yield, nutrient-dense crops while enhancing resource efficiency and adapting to constraints in arable land availability. Pakistan's dense urban centres and rising demand for fresh produce highlight the potential for vertical farming, especially hydroponics, to be significantly impactful. Realizing these benefits necessitates addressing specific challenges related to infrastructure, policy, and community adoption. This review analyzes the function of hydroponics in vertical farming, the unique challenges encountered in the

Pakistani context, and the possible strategies for sustainable implementation.

Hydroponics

Hydroponics is a method of cultivating crops in mineral nutrient solution without using soil as a growing medium. The mineral nutrient can be incorporated into a plant's water supply, facilitating absorption through the root system (Pascual et al, 2018). This technology enables roots to absorb a balanced nutrient solution in water that fulfils all developmental requirements of the plant. This technique is effective in regions where environmental stressors such as cold, heat, and arid conditions pose significant challenges. This method is gaining popularity due to the absence of soil-borne diseases and insect or pest infections affecting the crops. Hydroponic systems consist of various methods aimed at enhancing the delivery of water and nutrients to plants without the use of soil. Three notable types include the Wick System, Nutrient Film Technique (NFT), and Deep-Water Culture (DWC), each designed to meet varying crop needs, resource availability, and operational scales.

Deep Water Culture

In DWC, roots of plants are constantly submerged in a nutrient enriched solution. Therefore, it is suitable for only water loving crops such as lettuce. Plants grown in DWC may subject to overfeeding conditions. These systems are often used in educational settings to demonstrate a functional model of hydroponics (Sandhayarani, 2021).

Nutrient Film Technique

NFT represents a system in which the roots of plants are suspended in a channel containing a shallow stream of nutrient solution (Resh, 2013). It is different from DWC as the nutrient solution in NFT is constantly flowing.

Wick System

The wick system represents a fundamental hydroponic configuration that functions without the necessity of moving parts or electrical components. This characteristic renders it both economically viable and appropriate for small-scale or residential applications. The delivery of nutrients to plant roots occurs through a passive wicking medium, which may include materials like cotton or nylon, facilitating the plant's absorption of nutrients according to its requirements.

Synergy of Vertical Farming with Hydroponics

Vertical farming addresses a lot of challenges faced by agriculture sector of Pakistan. One of significant challenge is water loss either during or post irrigation. Studies shows that agriculture sector of Pakistan based on conventional agricultural practices consumes 93% of fresh water and a huge portion of it is wasted. Also, a major portion of minerals are leached down by old irrigation practices. Hydroponic system allows recirculation water and ensures the delivery of nutrients directly to roots and controlled environment provided by vertical farming facilitate it resulting in a consistent crop quality as well as quantity (Al Chalabi, 2015). The efficiency and economic importance of this system also rises in areas where canal water is unavailable and water has to be pumped (Shan E Ahmad, Pakistan Business Council). Recirculating systems of water utilized by hydroponics can reduce the water consumption upto 90% as compared to consumption in traditional practices (Sandhayarani 2021). Integration of Hydroponics with vertical farming allow growers to get year-round production of fresh crops without relying on climate outside. The continuous change in climate in Pakistan has affected the growth and supply of vegetables and other crops. As a result, the market price of agriculture items has been increased in Pakistan due to increase in cost of production. The controlled environment of vertical farming ensures the optimum external factors such as light, temperature and humidity to the plants leading to a consistent supply of freshly produced crops (Shan E Ahmad, Pakistan Business Council).

Figure 2. Vertical farm integrated with hydroponics

The stacked structure of vertical farming along with integration of hydroponics not only allows to utilize maximum space and getting higher yields but also reduces the transportation cost as it can be built near cities. Reduction in transport ultimately reduces carbon footprint and increases profit by ensuring the availability of fresh produce (Despommier, 2011; Shan E Ahmad, Pakistan Business Council). Protective structures of vertical farming inhibit the access of insects and helps in disease control (Despommier, 2013). Hydroponics eliminates the chances of soil borne diseases as soil is not being used as a growing medium. Operated in controlled environment minimizes the risks of diseases and use of chemicals leading to a sustainable environment (Shan E Ahmad, Pakistan Business Council).

Challenges in Implementing Hydroponics and Vertical Farming in Pakistan

In a country like Pakistan where rapid urbanization, limited arable land and climate change are common challenges of agriculture sector, vertical farming presents innovative approaches to sustainable agriculture practices. However, it comes with several challenges to implement the vertical farming at commercial scale in Pakistan that needs to be addressed. First and foremost, implementing vertical farming at commercial scale in Pakistan will require a high initial investment. Development and maintenance of controlled environment agriculture practices and advance systems like hydroponics will require a high cost. This can act as a barrier in implementation of vertical farming for many entrepreneurs and farmers. Additionally, such advance techniques always require seamless energy that can lead to high operational costs (Panotra et al, 2024). Crop varieties used for traditional agriculture practices may not perform in hydroponic systems as they are bred to perform in soil farming. Roots of such varieties may fail to uptake the nutrient is soil less media or even get suffocated due to absence of aeration leading to death of plants. Hydroponic systems seek varieties that exhibit specific traits like optimized uptake of minerals, maximized yield and ability to grow in controlled environment (Kumar et al, 2023). Pakistan's agriculture educational institutes have always focused on traditional farming practices. This creates a huge gap in skillsets in areas of sustainable agriculture techniques. Successful implementation of modern techniques always requires trained operational staff having expertise in managing complex systems effectively (Kabir et al, 2024; Singh et al, 2024). It is crucial for industry stakeholders to develop a robust pipeline of trained personnel by collaborating with universities and training institutes. Without addressing the need of technical operators, the import of technology will have to depend on foreign personnel leading an increase in operational cost. Initiatives like vocational training programs, seminars and conferences on vertical farming, hydroponics and climate change can empower Pakistan's workforce to meet this demand (Mahmood et al, 2024; Tooy et al, 2023).

Opportunities and Future potential

Despite the implementation challenges, vertical farming and hydroponic systems present promising solutions to the problems as well as significant opportunities to the agriculture sector of Pakistan. Vertical farming systems ensure the improvement of sustainable food production by optimizing space and minimum water consumption (Gerrewey et al, 2021). In a country like Pakistan where rapid urbanization is consuming arable land and causing an escalation in soil degradation and pollution, vertical farming integrated with plant growth promoting microorganisms (PGPMs) and hydroponics can efficiently enhance crop yield, utilize urban space, reduce carbon emission and transportation cost and ensure the food security in cities (Panotra et al, 2024; Sharma et al, 2024; Dhawi, 2023). While addressing the challenges of food security in cities, investment in vertical farming can significantly increase economic opportunities for Pakistan as global market of vertical farming is projected to surpass 10.02 billion USD (Dhawi, 2023). Food quality is enhanced when crops are grown in chemical free controlled environment. Vertical farming aims to improve health by ensuring access to healthier and fresh produce (Al Kodmani, 2018). In Pakistan, the production of rice has been significantly decreased in 2024 due to sudden climate change and heat wave. The normal growth cycle of crop was disturbed as increase in temperature at the stage of panicle formation led to premature ripening. The vulnerability of traditional rice varieties has been highlighted to climatic stress (Saeed and Ahmed, 2024; USDA, 2023). As Pakistan's agriculture sector rely on water loving crops such as rice, the uneven weather pattern and diminishing water resources worsen the challenge. To mitigate the future risks, efficient water management strategies and climate resilient rice varieties are urgently needed (Watoo and Ahmad, 2024). In such a continuously variable climate, the controlled system of vertical farming integrated with hydroponic systems provide a sustainable alternative and ensures food production regardless of the weather outside (Gerrewey et al, 2021).

Case Studies

Vertical farming has shown significant improvement in environment. In Stockwholm, Sweden, a hydroponic integrated vertical farm was established that used coir as growing medium as replaced plastic pots with paper pots. This replacement shown significant decrease in acidification, abiotic resource depletion and green house gas emission (Martin and Molin, 2019). SPREAD is one of largest automated vertical farm established in 2006 in Kyoto, Japan. By recycling 98% of water and incorporating advance air conditions and LED network, it produces 30,000 heads of cabbage daily. Cost efficiency and scalability is enhanced by its focus on automation (Panotra et al, 2024; Singh et al, 2024). Pasona Urban Farm in Tokyo, Japan, is providing an aesthetic work environment by integrating hydroponics with corporate office. This vertical farm occupies 43,000 square feet and produce over 200 varieties of multiple crops including rice, fruits and vegetables (Gerrewey et al, 2021; Molin and Martin, 2019).

Data driven technologies are used in PlantLab Vertical Farm in Den Bosch, Netherlands to optimize growth conditions for fruit crops such as Bananas and Strawberries. The company reduces the water usage upto 90% and triples the growth rate by using closed-loop water conditions and LED lights respectively (Sharma et al, 2024). This farm uses multi-layered stacking and advance environment controls to grow vegetables in limited space to address the food security constrains (Gerrewey et al, 2021).

Vertical Harvest located in Jackson Hole, Wyoming, US grows tomatoes and green leafy vegetables year-round in a 13,500 square feet facility. The farm employs individuals with disabilities and supplies fresh produce to local communities to show socio-economic potential of vertical farming (Sharma et al, 2024).

Policy Recommendations and Future Control:

To encourage vertical farming and hydroponic techniques in Pakistan, government must provide facilities like tax reductions, subsidizations and grants for research and development. To ensure food safety and environmental stability, quality control specific to hydroponics and vertical farming and standardized regulations are essential (Naresh et al, 2024; Panotra et al, 2024).

Pakistan's changing climate, crop varieties and limited resources demand initiatives from research and development institutions to focus on adaptations of vertical farming and hydroponics. Collaborative projects

between universities, research institutes and private companies can speed up the innovation. Creating low-cost energy efficient systems viable for urban and peri-urban regions must be brought into light (Litvinova, 2022; Singh et al, 2024; Mapari et al, 2022).

Advance technologies like integrated hydroponics in vertical farming always require skilled workforce and professional individuals to operate efficiently. Educational institutes not only should take initiatives like vocational trainings, conferences or seminars but also should add it in to agricultural curricula. Additionally, consumers must be provided with awareness on benefits of hydroponically grown crops (Mehta, 2020; Mapari et al, 2022; Naresh et al, 2024).

Conclusion

Incorporation of vertical farming with hydroponics provides a promising solution to challenges of agriculture sector of Pakistan especially change in climate and rapid urbanization. The undeniable benefits such as reduced transportation, ensuring organic, fresh and nutritious to end consumer and higher yields with minimized environmental impact emphasize its need in Pakistan. Although it requires a huge capital and skilled workforce to implement and operate such innovative modern technologies, but it can be overcome by government support and educational reforms. The collaborations of universities, research institutes and private companies along with policy makers can pave the way to ensure food safety and security.

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