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Review Article

Hydroponics and Aquaponics: Future Prospects in Urban Agriculture

Manjeet Kaur[1*], Seema Mahlawat[2], Naval Kishore Meena[3], Lucy Kumari[4], Anuj Kumar[5]
[1]Ph.D. Scholar, Department of Vegetable Science, College of Agriculture, Hisar CCS HAU
[2]Assistant Professor, Department of Botany, Pt NRS Govt. College, Rohtak
[3]Ph.D. Scholar, Department of Horticulture (Fruit Science), RCA, MPUAT, Udaipur
[4]Ph.D. Scholar, Department of Horticulture, Pg College of Agriculture,
Dr Rajendra Prasad Central Agriculture University Pusa Bihar
[5]Assistant Professor, Faculty of Agriculture Science, Mandsaur University, Mandsaur, (M.P.)
*Corresponding Author E-mail: seema.mahlawat@gmail.com

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ABSTRACT

Rapid urbanization and the growing global population have intensified the demand for sustainable food production systems within urban environments. Hydroponics and aquaponics have emerged as innovative soilless cultivation technologies that offer significant potential for urban agriculture. This review examines the fundamental principles, types, advantages, and limitations of hydroponic and aquaponic systems, with a focus on their application in urban settings. Hydroponics enables plant cultivation in nutrient-rich water solutions without soil, while aquaponics integrates aquaculture with hydroponics in a symbiotic closed-loop ecosystem. Both systems demonstrate substantial water savings of up to 90% compared to conventional agriculture, higher crop yields per unit area, and year-round production capability. The integration of emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), and vertical farming further enhances the efficiency and scalability of these systems. Despite challenges including high initial capital costs and energy consumption, hydroponics and aquaponics represent promising pathways toward achieving food security and environmental sustainability in cities worldwide.

Keywords: *Hydroponics; Aquaponics; Urban Agriculture; Soilless Cultivation; Sustainable Food Production.*

INTRODUCTION

The global population is projected to reach 9.7 billion by 2050, with approximately 68% residing in urban areas (United Nations, 2018). This unprecedented urbanization poses severe challenges to food security, as arable land continues to shrink due to urban expansion, soil degradation, and climate change. According to the Food and Agriculture Organization (FAO, 2020), conventional agriculture accounts for approximately 70% of global freshwater withdrawals, rendering traditional farming practices increasingly unsustainable in water-scarce regions.

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In this context, soilless cultivation technologies, particularly hydroponics and aquaponics, have gained significant attention as viable alternatives for urban food production. Hydroponics involves growing plants in nutrient-rich water solutions without the use of soil, while aquaponics combines hydroponics with aquaculture (fish farming) in an integrated, closed-loop system (Goddek et al., 2019). These technologies enable crop production in controlled environments, including rooftops, basements, warehouses, and vertical farm structures, thereby transforming underutilized urban spaces into productive agricultural zones (Benke & Tomkins, 2017).

This review paper aims to provide a comprehensive overview of hydroponic and aquaponic systems, evaluate their advantages and challenges for urban agriculture, and discuss future prospects shaped by technological innovations and policy developments.

2. Hydroponics: Principles and Systems

2.1 Definition and Historical Background

Hydroponics, derived from the Greek words "hydro" (water) and "ponos" (labour), is the science of growing plants without soil by using mineral nutrient solutions dissolved in water. The concept dates back to the hanging gardens of Babylon, but modern hydroponics was pioneered by Julius von Sachs and Wilhelm Knop in the 1860s, who demonstrated that plants could thrive in nutrient solutions alone (Savvas & Passam, 2002). Over the past century, hydroponic technology has evolved from laboratory experiments to large-scale commercial operations worldwide.

2.2 Types of Hydroponic Systems

Several hydroponic systems have been developed, each suited to different crop types, scales, and growing conditions. The six major types include (Resh, 2022):

Table1. Major types of hydroponic systems and their descriptions

System Type	Description
Nutrient Film Technique (NFT)	A thin film of nutrient solution flows continuously over plant roots in sloped channels, providing constant nutrient and oxygen supply. Widely used in commercial lettuce and herb production.
Deep Water Culture (DWC)	Plant roots are fully submerged in an aerated nutrient solution. An air pump provides oxygen through air stones. Ideal for fast-growing leafy greens.
Ebb and Flow (Flood and Drain)	Nutrient solution periodically floods the grow tray and then drains back to the reservoir, mimicking natural irrigation cycles. Suitable for a wide variety of crops.
Drip System	Nutrient solution is delivered to each plant through individual drip emitters, offering precise control over water and nutrient delivery. Common in commercial greenhouses.
Wick System	The simplest passive system where nutrient solution is drawn from a reservoir to the growing medium via capillary wicks. Best suited for small herbs and non-fruiting plants.
Aeroponics	Plant roots are suspended in air and periodically misted with nutrient solution. Provides maximum oxygen exposure, promoting rapid growth rates and high yields.

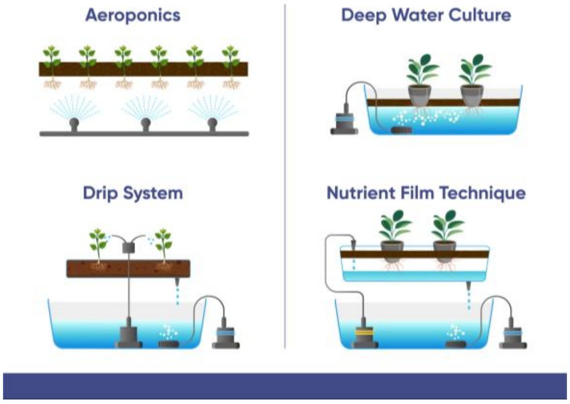

Figure1. Types of hydroponic systems: Aeroponics, Deep Water Culture (DWC), Drip System, and Nutrient Film Technique (NFT) (Source: Ponics Life, 2022)

3. Aquaponics: Principles and Components

3.1 Definition and Working Mechanism

Aquaponics is an integrated food production system that combines aquaculture (the raising of aquatic animals such as fish) with hydroponics (soilless plant cultivation) in a symbiotic recirculating environment. In this system, fish produce ammonia-rich waste, which is converted by nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*) into nitrates, a form of nitrogen readily absorbed by plants. The plants, in turn, filter and purify the water, which is then recirculated back to the fish tanks (Goddek et al., 2019). This closed-loop nutrient cycling minimizes waste, eliminates the need for synthetic fertilizers, and creates a nearly self-sustaining ecosystem.

3.2 Key Components

A functional aquaponic system comprises three biological components working in synergy: (a) **Fish** – Tilapia, catfish, and trout are commonly raised species due to their hardiness and adaptability to recirculating systems; (b) **Plants** – Leafy greens such as lettuce, basil, spinach, and herbs thrive best in aquaponic conditions due to their lower nutrient demands; and (c) **Bacteria** – Nitrifying bacteria in the biofilter serve as the biological bridge converting toxic ammonia into plant-available nitrates (Somerville et al., 2014).

3.3 Types of Aquaponic Systems

Three primary aquaponic configurations are widely employed: (1) **Media Bed Systems**, where plants grow in inert media (gravel or expanded clay) that also serves as a biofilter; (2) **Deep Water Culture (DWC/Raft Systems)**, where plants float on polystyrene rafts above oxygenated nutrient-rich water; and (3) **Nutrient Film Technique (NFT)**, where a thin stream of nutrient water flows through narrow channels housing plant roots (Lennard & Goddek, 2019).

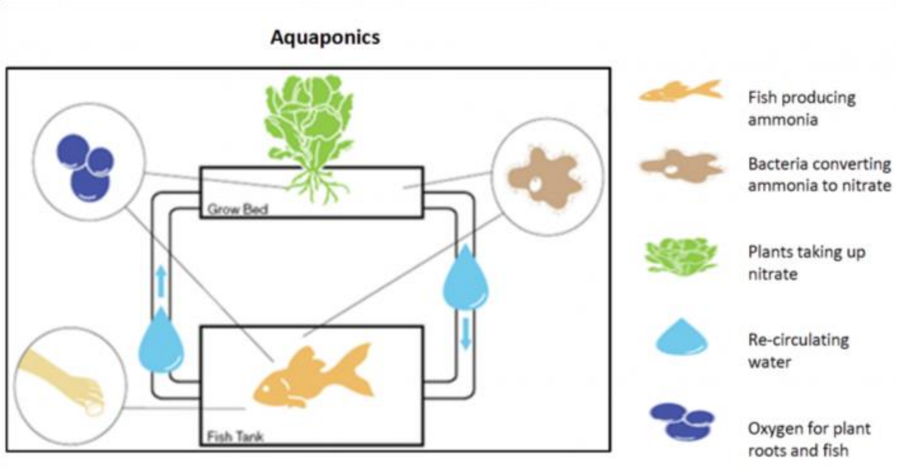

Figure2. Schematic diagram of an aquaponics system illustrating the nitrogen cycle: fish produce ammonia, bacteria convert it to nitrates, plants absorb nutrients, and clean water recirculates (Source: ISB Systems Education Experiences)

4. Advantages of Hydroponics and Aquaponics in Urban Agriculture

4.1 Water Conservation

Both hydroponics and aquaponics demonstrate remarkable water efficiency. Hydroponic systems use up to 90% less water than conventional soil-based agriculture because nutrient solutions are recirculated within the system, minimizing losses from evaporation, runoff, and deep percolation (Barbosa et al., 2015). Barbosa et al. (2015) reported that hydroponic lettuce production required only 20 ± 3.8 L/kg/year compared to 250 ± 25 L/kg/year for conventional field-grown lettuce in Arizona. Similarly, aquaponic systems consume up to 90% less water than traditional farming due to continuous recirculation between fish tanks and plant beds (Goddek et al., 2019).

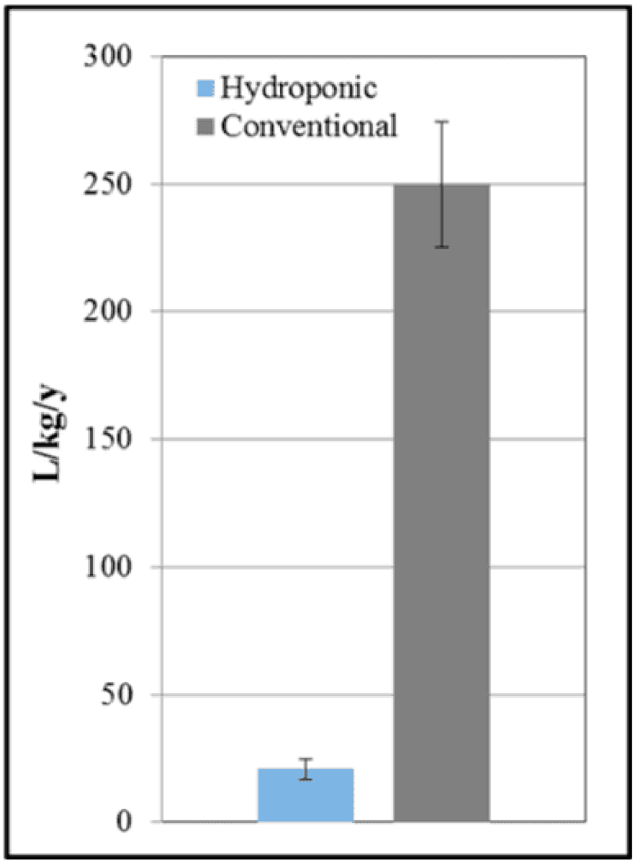

Figure3. Comparison of water use (L/kg/year) for lettuce production: Hydroponic (~20 L/kg/y) vs. Conventional (~250 L/kg/y) (Adapted from Barbosa et al., 2015)

4.2 Higher Yields and Space Efficiency

Hydroponic systems can produce 11 times higher yields per unit area compared to conventional farming methods (Barbosa et al., 2015). When combined with vertical farming approaches, production density increases even further, with some urban vertical farms producing up to ten times the yield per acre compared to traditional methods (Benke & Tomkins, 2017). This space efficiency makes hydroponics and aquaponics particularly suitable for densely populated urban areas with limited land availability.

4.3 Year-Round Production and Reduced Chemical Use

Controlled environment agriculture (CEA) enables year-round crop production independent of seasonal and climatic variations. The enclosed nature of these systems significantly reduces pest and disease pressure, thereby minimizing or eliminating the need for synthetic pesticides and herbicides (Kozai et al., 2016). In aquaponics, the sensitivity of fish to chemical toxins inherently prevents the use of synthetic inputs, resulting in organically produced crops (Somerville et al., 2014).

4.4 Environmental Sustainability

Urban hydroponic and aquaponic farms reduce food miles by producing food closer to consumers, thereby decreasing transportation-related carbon emissions. These systems also eliminate agricultural runoff, a major source of water pollution in conventional farming, and contribute to urban greening and biodiversity conservation (Despommier, 2010). The World Economic Forum (2023) reported that vertical farming systems can reduce water usage by up to 98% compared to open-field agriculture.

Figure4. Commercial vertical hydroponic farm demonstrating year-round indoor crop production in a controlled environment (Source: Eden Green Technology)

5. Challenges and Limitations

Despite their considerable advantages, hydroponics and aquaponics face several challenges that limit widespread adoption. **High initial capital costs** represent the most significant barrier, as setting up controlled environment facilities, lighting systems, pumps, and monitoring equipment requires substantial investment (Kozai et al., 2016). **Energy consumption** is another critical concern; Barbosa et al. (2015) found that hydroponic lettuce production required 82 times more energy than conventional methods, primarily due to artificial lighting, climate control, and water pumping systems.

Additional challenges include the need for **technical expertise** in system management, nutrient balancing, and water quality monitoring. In aquaponics, maintaining the delicate equilibrium between fish health, bacterial populations, and plant nutrient requirements demands skilled operators (Goddek et al., 2019). Furthermore, the **limited crop variety** currently suited to these systems (primarily leafy greens and herbs) restricts their ability to fully substitute conventional farming. **Regulatory and policy gaps** also present hurdles, as many urban jurisdictions lack specific frameworks for soilless food production (Reinhardt et al., 2019).

6. Future Prospects and Technological Integration

The future of hydroponics and aquaponics in urban agriculture is closely linked to the integration of emerging technologies. The **Internet of Things (IoT)** enables real-time monitoring and automated control of critical parameters such as pH, electrical conductivity, dissolved oxygen, temperature, and nutrient concentrations, significantly reducing labour requirements and optimizing resource use (Khan et al., 2025). **Artificial Intelligence (AI)** and machine learning algorithms are being developed to predict crop growth patterns, detect diseases early, and optimize environmental conditions for maximum yield (Sharma et al., 2024).

The expansion of **vertical farming** technologies is accelerating the adoption of hydroponic systems in high-rise urban structures, transforming buildings into productive farmland. The integration of **renewable energy sources**, particularly solar and wind power, is addressing the energy challenge by reducing operational costs and carbon footprints (Benke & Tomkins, 2017). Furthermore, innovations in **LED lighting technology** with spectrum-specific wavelengths are enhancing photosynthetic efficiency while reducing electricity consumption (Kozai et al., 2016).

The global aquaponics and hydroponics market is experiencing robust growth, with the media-filled grow bed segment projected to reach USD 1.0 billion by 2030 at a compound annual growth rate (CAGR) of 13.5% (Research and Markets, 2024). Government initiatives, community-supported agriculture (CSA) programmes, and educational institutions are increasingly promoting these technologies as key components of smart and sustainable city planning. Projects like Gotham Greens (USA), Sky Greens (Singapore), and ECF Farms (Germany) exemplify the commercial scalability and viability of urban soilless farming systems (Singh, 2017).

CONCLUSION

Hydroponics and aquaponics represent transformative technologies that address critical challenges in urban food production, including land scarcity, water depletion, and the environmental impact of conventional agriculture. Hydroponic systems offer superior water efficiency, higher crop yields, and year-round production capability, while aquaponics adds the dimension of sustainable protein production through integrated fish–plant symbiosis. Both systems are well suited to urban environments, enabling food production in compact spaces such as rooftops, warehouses, and vertical farm structures.

While challenges related to initial costs, energy consumption, and technical complexity remain, the integration of IoT, AI, renewable energy, and advanced LED lighting is progressively overcoming these barriers. As global urbanization intensifies and climate change disrupts traditional agriculture, the role of soilless cultivation systems in ensuring food security and environmental sustainability will become increasingly vital. Continued investment in research, favourable policy frameworks, and public awareness campaigns are essential to realizing the full potential of hydroponics and aquaponics as cornerstones of future urban agriculture.

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