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Aurobinda Behera
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Anita Mohanty
All India Coordinated Research Project on Vegetable Crops, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Pradyumna Tripathy
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Sunil Kumar Dash
All India Coordinated Research Project on Vegetable Crops, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Sunita Dhar
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Disha Baisnabi
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Akash Kumar Parida
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Gracy Lakra
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Kirtika Mishra
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Sanhita Sankalini Pradhan
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Corresponding Author:
Aurobinda Behera
Department of Vegetable Science, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India

Future farming in water: A comprehensive review on hydroponics

Aurobinda Behera, Anita Mohanty, Pradyumna Tripathy, Sunil Kumar Dash, Sunita Dhar, Disha Baisnabi, Akash Kumar Parida, Gracy Lakra, Kirtika Mishra and Sanhita Sankalini Pradhan

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Abstract
Hydroponics, the science of cultivating plants without soil, is becoming increasingly relevant as urban areas face rapid population growth, limited arable land and water scarcity. This review article explores hydroponics as a promising alternative for sustainable urban farming. Beginning with the historical evolution of hydroponics, from early experiments to contemporary vertical farming methods, the paper systematically examines the various hydroponic systems and materials, including Nutrient Film Technique (NFT), Deep Water Culture (DWC), Aeroponics and other key methodologies. The review highlights distinct advantages of hydroponics such as higher crop yields, significant water savings, reduced pesticide use and efficient use of urban space. Challenges, including initial investment costs, technical complexities and energy consumption, are also discussed to provide a balanced perspective. Case studies from global pioneers such as Gotham Greens (USA), Sky Greens (Singapore) and Letcetra Agritech (India) underscore the practical success and scalability of urban hydroponics. By integrating recent FAO and UN data, this article positions hydroponics within a global context of increasing food demand, diminishing freshwater resources and shrinking arable land. The findings underscore hydroponics as a critical component in sustainable agriculture strategies, capable of substantially mitigating environmental impacts and enhancing urban food security.

Keywords: Hydroponics, urban farming, vertical farming, nutrient film technique, controlled environment agriculture, sustainable agriculture, water efficiency, food security, urban agriculture, soilless cultivation

Introduction

Historical Development of Hydroponics

Soilless culture dates back centuries, but modern hydroponics emerged in the early 20th century. In the 1860s, Knop and Sachs formulated the first standardized plant nutrient solution to grow crops without soil (OSU Extension, 2021) [11]. The term hydroponics ("water-working") was coined by plant physiologist William F. Gericke in the 1930s (Despommier, 2010) [6]. Gericke of UC Berkeley famously grew enormous tomato plants in nutrient baths, proving that all essential minerals could be delivered in water. His 1940 book *The Complete Guide to Soilless Culture* popularized the idea and promoted hydroponics as a solution to global food shortages (Despommier, 2010) [6]. Early hydroponics used simple media like sand or gravel, but the innovation of rockwool slabs (in the 1960s) allowed high-density greenhouse cultivation. NASA in the 1990s and 2000s advanced aeroponics for space and harsh environments (roots misted in air), demonstrating up to ~90% water savings (Farran & Mingo-Castel, 2006) [7]. Over time, hydroponics evolved into many system types and became integral to modern vertical farms and greenhouse operations.

Hydroponic Systems and Materials

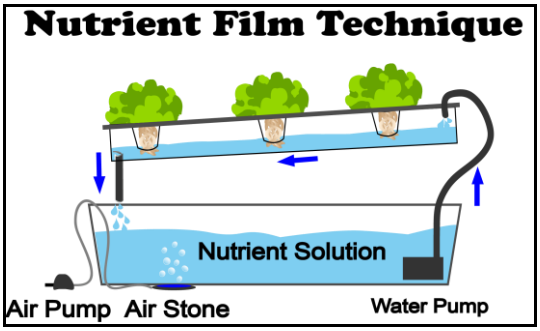
Urban farming must meet growing food demand on shrinking arable land. With the global population (~8 billion today, rising to ~9.7 billion by 2050) and per-capita farmland steadily declining, traditional agriculture faces limits. Agriculture already uses roughly 70% of global freshwater withdrawals (FAO, 2024; aquastat) [9]. Population growth, urbanization and climate pressures mean we may need 60-70% more food by mid-century (Alexandratos &

Bruinsma, 2012; Ray *et al.*, 2013) [1, 13]. Hydroponics-growing plants in water-based nutrient solutions instead of soil-offers a way to increase yields and save resources in urban settings (Bunyuth & Serey, 2024; Barbosa *et al.*, 2015) [5, 3]. In hydroponic systems, plants' roots are immersed or periodically wetted with nutrient-rich solution, often supported by an inert medium (e.g. rockwool, perlite, coconut coir). By recirculating water, these systems dramatically cut irrigation needs; studies show hydroponic lettuce can require only ~20 L/kg of water versus ~250 L/kg in the field (over 90% savings). This review covers hydroponic techniques (history, materials, system types), discusses benefits and challenges for urban farming and highlights innovations and case studies (e.g. Gotham Greens, Sky Greens, Letcetra Agritech). It also cites FAO/UN data on water, food demand and land use to frame hydroponics' relevance.

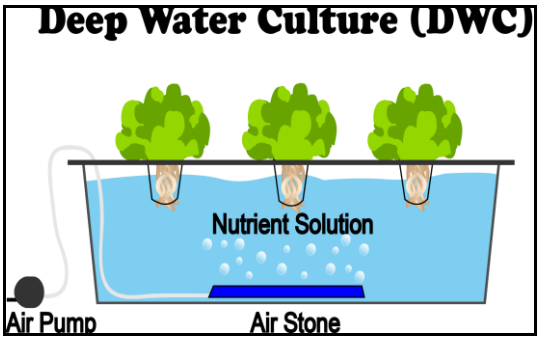
Hydroponic systems differ mainly by how nutrient solution is delivered and how roots are supported. A range of inert growing media are used: besides rockwool and perlite, organic materials like coconut coir, peat and pine bark are popular. These substrates anchor roots and retain moisture without supplying nutrients. Water-tight reservoirs and pumps circulate the nutrient solution and sensors often monitor pH, electrical conductivity (EC) and other parameters.

Key system types include

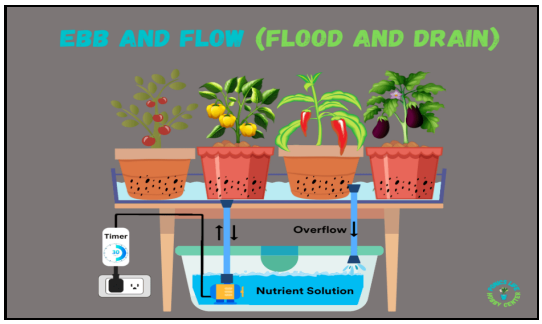
1. Nutrient Film Technique (NFT): A thin film of nutrient solution flows continuously through inclined channels, bathing plant roots. This method provides steady nutrient access and high oxygenation. It's often used for leafy greens and strawberries.



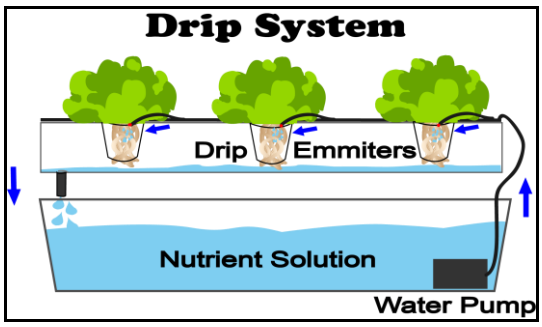
2. Deep Water Culture (DWC): Plants are held in net pots over a reservoir of aerated nutrient solution so roots dangle directly in water. DWC is simple and effective for lettuce and herbs, though it requires vigorous oxygenation.



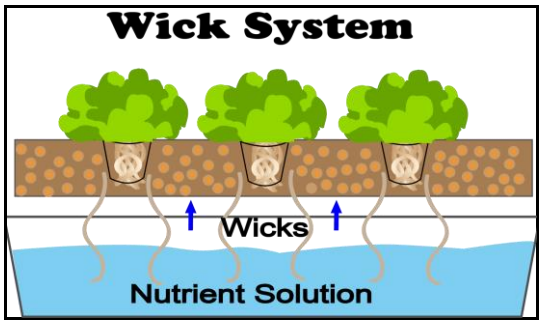
3. Ebb-and-Flow (Flood-and-Drain): Periodically floods trays of plants with nutrient solution, then lets them drain, exposing roots to air cycles. This flexible system can handle larger crops like tomatoes, peppers and cucumbers.



4. Drip (Top or Bottom Feed): Drips of nutrient solution are delivered to each plant's base at intervals. Excess solution drains back. Drip systems are common in large commercial greenhouses for vegetables and flowers.



5. Wick: A passive system where capillary wicks draw nutrient solution from a reservoir up into the plant's medium. Very simple and pump-free, but generally limited to small or low-water-use plants (seedlings, houseplants).



6. Aeroponics: Roots are suspended in air and misted with nutrient solution. This extreme CEA method maximizes root oxygenation and can cut water use by ~90% compared to field cultivation (Farran & Mingo-Castel, 2006) [7]. Aeroponics can achieve very fast growth rates, though it demands precise control.

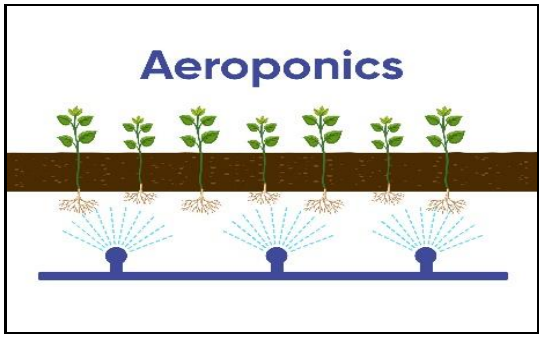


Table 1: Summarizes these hydroponic system types and their uses:

System	How It Works	Typical Crops/Notes
NFT	Thin, recirculating film of solution flows along sloping troughs over roots.	Leafy greens, strawberries. Good nutrient delivery, high O_2.
DWC	Plants float (net pots) atop a nutrient reservoir; roots immersed in solution.	Lettuce, herbs. Simple setup, requires aeration.
Ebb & Flow	Trays are periodically flooded with solution and then drained back to reservoir.	Tomatoes, peppers, cucumbers. Scalable, prevents root stress.
Drip (recirculating)	Dripper emits solution to plant base; excess drains off (or is reused).	Various vegetables (tomato, cucumber, eggplant). Efficient water use, modular.
Wick	Capillary wicks carry solution from reservoir to roots (passive flow).	Seedlings, microgreens. No pumps needed, limited scale.
Aeroponics	Roots hang in air and are misted or sprayed with nutrient solution.	Leafy greens, herbs. Highest water efficiency, tech-intensive.

Table 1. Common hydroponic system types, their operation and example uses.

Materials for hydroponics include nutrient solutions (with all essential macro-and micronutrients) and growing media. Common media include rockwool, perlite, vermiculite and coconut coir. Media must be pH-neutral, hold moisture and allow good root aeration. For example, rockwool (mineral wool) was revolutionary in the 1960s, enabling soilless greenhouse tomato culture. Nowadays, growers often mix media (e.g. perlite-coir blends) to balance water retention and drainage. Some systems (like aeroponics or DWC) don't use solid media at all, relying on mist or nutrient solution alone to contact roots.

Benefits of Hydroponics

Hydroponics offers several advantages for urban agriculture. Water efficiency is a primary benefit. Because solution is recirculated, hydroponics can reduce water use by an order of magnitude compared to conventional soil farms. In a life-cycle study, hydroponic lettuce required only ~20 L of irrigation per kilogram of produce, versus ~250 L/kg for field-grown lettuce-a >90% reduction. Similarly, vertical farms and other CEA operations claim 70-90% water savings over open-field cultivation (Mir *et al.*, 2022; Bunyuth & Serey, 2024) [10, 5]. Figure 1 illustrates this: a hydroponic system uses roughly one-tenth the water per kg of lettuce as conventional agriculture. Water savings arise because runoff and evaporation are minimized-the same solution is reused until the plants uptake the nutrients or lose water via transpiration.

Hydroponics also yields more produce per unit area. Plants can be grown in stacked layers or on rooftops, multiplying land productivity. Controlled environments enable year-round growing with optimized light, CO_2 and nutrient delivery, resulting in faster growth cycles. For example, one study reported 11-fold higher lettuce yields (per m^2 per year) under hydroponics than in open fields (41 vs 3.9 kg/m^2/year). In effect, hydroponics decouples plant growth from climate, so frequent harvests are possible. Higher densities are achievable because each plant need not develop extensive root systems searching for water-the nutrient solution meets roots at all times, shortening growth phases.

Because soil-borne pests and diseases are eliminated, hydroponic systems generally require fewer pesticides (Bunyuth & Serey, 2024) [5]. Nutrient imbalances or deficiencies are also easier to correct on the fly, by adjusting solution composition. Hydroponic produce can be very clean and pesticide-free (approved for organic labels, in many cases). These factors contribute to food safety and quality. In tightly controlled hydroponic greenhouses or plant factories, yield stability is high and quality can be premium (Gotham Greens, a leading urban hydroponic farm in New York, markets consistently fresh lettuces and herbs year-round).

Another benefit is resource localization and reduced transport. Urban hydroponic farms can be sited close to consumers (roof-top greenhouses, indoor farms, or even containerized units). This cuts food miles, preservatives and spoilage. By integrating with urban waste recycling (e.g. using captured rainwater for irrigation, or urban organic waste composted for supplementary nutrients), hydroponics can partly close resource loops. Several innovations are emerging to pair solar power or waste heat with hydroponics, further greening the systems (Bunyuth & Serey, 2024) [5].

Challenges and Limitations

Hydroponics is not without challenges. The initial investment and technical complexity can be high. Constructing a greenhouse or vertical farm with pumps, sensors, lighting and climate control requires capital. Small-scale farmers may lack access to the required equipment or knowledge. Operating costs-especially electricity for lights and pumps-can also be significant. For instance, fully indoor vertical farms rely on LED lighting and HVAC, which consume much more energy per hectare than open farms (despite water savings) (Rajaseger, 2023) [23]. Unless energy comes from renewables, greenhouse operations may have a larger carbon footprint per unit produce (Banboukian *et al.*, 2025; Barbosa *et al.*, 2015) [2, 3]. Energy efficiency is therefore a key hurdle; however, innovations in LED efficiency and solar integration are helping mitigate this.

Another concern is system failure risk. Because crops are grown in a highly controlled setting, a power outage, pump failure, or nutrient imbalance can quickly damage a whole crop. Backup systems or manual overrides are needed to prevent catastrophic loss. Managing waterborne pathogens (e.g. Pythium) requires strict sanitation, since diseases can spread rapidly through shared solution. Nutrient solutions themselves must be carefully balanced and periodically replaced or filtered to avoid accumulation of salts or by-products.

Furthermore, hydroponics traditionally excels with high-value vegetables and herbs, but cultivating large-field crops (cereals, oilseeds) is still experimental. The equipment costs make sense when crops fetch high market prices or when land is extremely scarce. In rural areas with abundant land,

adoption is slower. Finally, public acceptance and market demand for hydroponic produce can vary; education on the safety and quality of hydroponically grown food is needed to ensure consumer trust (Benke & Tomkins, 2017; FAO, 2017) [4, 8].

Innovations and Trends

Modern hydroponics increasingly leverages technology and automation. Many new systems incorporate Internet-of-Things (IoT) sensors, machine learning and robotics (Rajaseger, 2023) [23]. For example, sensors now continuously monitor pH, nutrient levels, humidity and light intensity; data analytics then optimize feeding schedules and climate parameters. Autonomous hydroponic systems can adjust inputs in real time, maximizing yield while conserving inputs.

Vertical farming is a flagship innovation in hydroponics: multi-story indoor farms stack crops to multiply output on a given footprint (Roy *et al.*, 2024) [14]. These farms use hydroponic or aeroponic growth in each layer under energy-efficient LEDs. Recent reviews note that vertical farms can save up to 70-90% of water compared to conventional farms (Mir *et al.*, 2022; Saha Roy *et al.*, 2024) [10, 14]. Aeroponic variants push this further, effectively misting roots with nutrients and using 90% less water than soil methods (Farran & Mingo-Castel, 2006; Saha Roy *et al.*, 2024) [7, 14].

Aquaponics combines hydroponics with fish farming: fish waste (ammonia) is converted to plant nutrients in a biofilter, then fed to plants; the cleaned water circulates back to the fish. This closed-loop approach can dramatically reduce fertilizer needs and produce protein + vegetables in one system. Several urban farms (e.g. Auburn University's Vertical Farms) use aquaponics to improve resource efficiency and education (and serve fish on campus dining, see Auburn Univ, 2022).

Genetic and biotechnological innovations also support hydroponics. Plant varieties can be selected or bred for hydroponic systems (compact root structure, high nutrient-use efficiency, quick growth). Controlled-environment optimized cultivars (for example, compact tomato or cucumber varieties) allow even better yields in vertical farms.

Hydroponics for Urban Food Production

Hydroponics is especially relevant to cities, where land and water are limited but demand is high. Urban agriculture can provide local, pesticide-free produce and hydroponic farms maximize what little space is available. For instance, Gotham Greens operates rooftop hydroponic greenhouses in New York and Chicago, growing thousands of tons of greens annually on closed urban sites. In Singapore (which is 100% urbanized), Sky Greens pioneered a low-energy vertical hydroponic system: rotating three-story A-frame towers that boost productivity by 5-10× per area compared to horizontal farms (Sky Greens, 2014). In India, startups like Letcetra Agritech (Goa) and FreshBox Farms (Punjab) have launched large indoor hydroponic farms since 2016, supplying cities with lettuce and herbs year-round (Singh, 2017) [15]. These projects illustrate hydroponics' ability to create "green corridors" in dense metropolises.

Urban hydroponics also integrates well with sustainable resource management. Rainwater harvesting and greywater reuse can feed nutrient solution, reducing demand on municipal supplies. Waste heat from industrial or building systems can warm greenhouses. Some farms use vertical gardens as living walls that insulate buildings while producing food. In crowded cities, even small plots (schools, restaurants, or home systems) can contribute to food security and education. Overall, hydroponics can make cities more resilient by diversifying and shortening food supply chains and by providing fresh food close to where it is eaten.

Despite the promise, urban hydroponic farming faces policy and scale hurdles. Capital costs, energy pricing and zoning laws can limit new ventures. However, governments and NGOs are increasingly recognizing hydroponics as part of climate-smart agriculture. The FAO and UN have highlighted soilless farming in discussions of sustainable intensification and water use efficiency (FAO, 2017; UN 2022) [8, 16]. In short, hydroponics is moving from pilot projects toward commercial reality, driven by innovation and necessity.

Global Context: Land, Water and Food Demand

The rise of hydroponics is set against stark global trends. Today about one-third of the world's land area is in agriculture, but most of this (nearly 3.2 billion hectares) is in pasture; only ~1.57 billion hectares are in cropland. FAO data (2024) show that from 2001-2022, total cropland grew by just ~5%, while population doubled. Cropland per person has fallen 20% (from ~0.24 to 0.20 ha per capita). Another analysis noted that per-capita arable land may drop from ~0.42 ha in 1960 to ~0.19 ha by 2050 (Mir *et al.*, 2022) [10]. In this squeeze, improving productivity on existing land is critical. (If we waited to expand arable area, it would risk deforestation and carbon emissions-a limited option.)

Meanwhile, FAO projects that agriculture must produce ~70% more food by 2050 than it did in 2005/07 to feed 9 + billion people. Demands for meat, dairy and biofuels will put extra strain. Irrigated agriculture consumes ~70% of all freshwater withdrawals worldwide and aquifers in many regions are being depleted. With climate change making rainfall and river flows less predictable, hydroponics' controlled irrigation (often recirculated in closed loops) can cut this vulnerability.

In summary, hydroponics offers a way to increase "crop per drop and crop per square meter." By boosting yields and using water more sparingly, soilless systems can help bridge the food gap without expanding farmland. While not a panacea, hydroponics can play a strong role alongside other measures (diets, waste reduction, genetic gains) in a sustainable agriculture future.

Successful organization of Urban Hydroponics

Gotham Greens (USA): Founded 2009, Gotham Greens operates multiple rooftop greenhouses in New York City and elsewhere. Using hydroponic greenhouse systems, it produces lettuce, herbs and more locally. Gotham reports yields ~100 tons per year per greenhouse and uses renewable electricity to power pumps and fans (environmental reports). Its success demonstrates how repurposed urban roofs can yield significant harvests with minimal transport and without arable land.

Sky Greens (Singapore): Launched in 2010, Sky Greens uses patented rotating A-frame towers under a greenhouse roof. Each 3-story tower holds 80 + troughs of greens; hydraulics spin the tower to distribute sunlight and solution.

Sky Greens claims 5-10× higher yield per area than horizontal farms, with very low energy input (lots of ambient tropical sunlight). This model was designed for a water-scarce city-state: water is pumped to the top and trickles down through plants, with overflow recycled, so the system needs very little makeup water. Singapore's experience shows hydroponics can overcome land constraints in dense cities.

Letcetra Agritech (India): Letcetra (based in Goa) pioneered commercial indoor hydroponic farming in India around 2016. Using Dutch-developed NFT systems and LED lights, Letcetra's first 150 m² facility grew ~1.5-2 tons of lettuce/month. Their founders highlight (Singh, 2017) [15] how hydroponics offers reliable yields during monsoons and reduces pesticide use. Today Letcetra and other Indian startups are expanding to meet growing urban demand for fresh salad greens. The Entrepreneur India profile notes Letcetra as one of four key hydroponic startups transforming Indian horticulture (Singh, 2017) [15].

Other successes include Sky Greens' example of vertical farm viability and Rooftop Farms in Bangalore (Future Farms India), Junga FreshnGreen in Hyderabad (mixed-model with aquaponics) and rooftop greenhouses like Italy's or Montreal's Lufa Farms. These case studies illustrate diverse models: rooftop sheds, converted warehouses, even shipping containers (Freight Farms in the USA). While each project is unique, common factors are integrated technology, focus on high-value crops and leveraging local advantages.

Table 2: Summary of common hydroponic system types

System	Method	Example Uses/Notes
NFT (Nutrient Film Technique)	Shallow nutrient solution flows in channels over roots.	Lettuce, herbs; very efficient nutrient delivery.
DWC (Deep Water Culture)	Roots suspended in oxygenated nutrient reservoir.	Leafy greens; simple setup, needs active aeration.
Ebb & Flow (Flood/Drain)	Trays are periodically flooded and drained.	Tomatoes, cucumbers; adaptable, moderate size.
Drip (Recirculating)	Dippers dispense solution to each plant; excess drains back.	Wide range (tomato, cucumber, berries); scalable.
Wick (Passive)	Wicks draw solution up to roots from reservoir.	Seedlings, small herbs; pump-free but low-flow.
Aeroponics	Roots misted with nutrient solution in air.	Lettuce, herbs; highest water-use efficiency, complex control.

"Modern hydroponic systems eliminate the need for soil, using nutrient solutions to meet plants' needs (Rajaseger, 2023) [23]. These systems allow precise resource use-for example, hydroponic lettuce can thrive on about 1/13th the irrigation of field-grown lettuce (20 L vs 250 L per kg)."

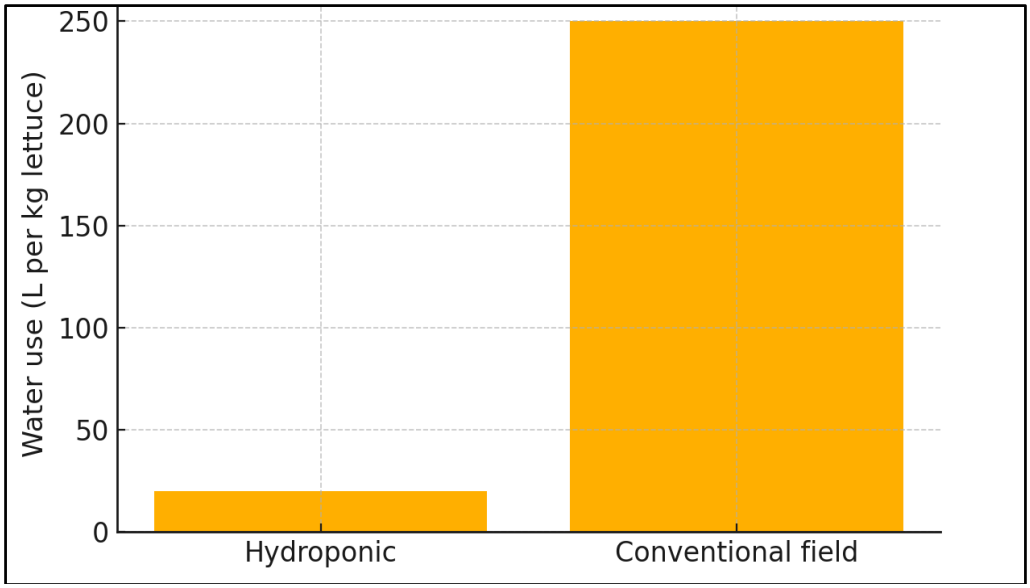


Fig 1: Water use for lettuce in hydroponic vs conventional field systems (based on Barbosa *et al.*, 2015) [3]. Hydroponics can reduce irrigation roughly 10-fold by recirculating

Conclusions

Hydroponics is maturing into a viable urban farming strategy. It addresses key challenges: minimizing water use (FAO, 2017) [8], maximizing yield on limited land and providing fresh produce near consumers. Technological advances-in lighting, sensors and system design-continue to improve its economics and sustainability (Rajaseger, 2023; Mir *et al.*, 2022) [23, 10]. At the same time, we must be mindful of energy inputs and costs, ensuring systems are as green as possible. With supportive policies, investments and consumer awareness, hydroponics can help cities contribute to food security. As FAO and UN reports emphasize, innovation in agriculture is crucial for the 21st century (FAO, 2017; UN, 2022) [8, 16]. Hydroponics-once a niche science project-is now a practical component of climate-resilient urban agriculture, promising to reshape how we farm in the coming decades.

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