



**REVIEW ARTICLE**

## Hydroponic Agriculture an Innovative Approach to Intensify Sustainable Food Production

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### ABSTRACT

As global food systems confront the converging pressures of population growth, climate change, soil degradation, and urban expansion, hydroponic agriculture has emerged as a transformative alternative to conventional farming. By eliminating the need for soil and enabling precise environmental and nutrient control, hydroponic systems offer superior efficiency in water and land use, higher yields per unit area, and year-round production. This review synthesizes current knowledge on the classification of hydroponic systems, agronomic and environmental benefits, integration into sustainable and circular food systems, economic feasibility, and barriers to adoption. It explores hydroponics' role in controlled environment agriculture (CEA) and its application in both commercial and small-scale urban farming. The article identifies key challenges energy demands, technical complexity, nutrient management, and policy gaps and outlines research priorities for microbial interactions, sustainable substrates, and life cycle assessments. It concludes by positioning hydroponics not as a universal solution, but as a strategic innovation for intensifying food production in water-scarce, land-limited, and climate-sensitive environments. Through inclusive design and integrated policy support, hydroponic agriculture can significantly contribute to building more resilient, circular, and sustainable food systems.

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**Key words:** Hydroponics, Vertical farming, Water use efficiency, Nutrient management, Food security, Sustainability.

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### INTRODUCTION

The global food system is under unprecedented pressure. With the world's population projected to exceed 9.7 billion by 2050, the demand for food is expected to rise by over 60% from current levels (FAO, 2023). At the same time, arable land availability is shrinking due to urbanization, land degradation, and climate variability. Traditional agriculture, heavily reliant on soil, seasonal rainfall, and intensive inputs, faces mounting challenges: declining soil fertility, freshwater scarcity, pesticide resistance, and greenhouse gas emissions. These constraints have sparked a growing interest in alternative agricultural methods that can produce more food using fewer resources in environmentally sound and resilient ways.

Hydroponics, a soilless plant cultivation technique that delivers nutrients directly to plant roots through a

controlled aqueous medium, has emerged as a disruptive innovation in this context. It allows crops to grow in nutrient-rich water solutions with or without inert substrates like perlite, cocopeat, or rockwool, entirely independent of soil quality. First popularized in the 20th century for scientific and space-based agriculture, hydroponics is now increasingly viewed as a cornerstone of urban farming, climate resilient production, and resource-efficient agriculture. It is particularly suited for areas with poor or contaminated soils, limited land availability, or unreliable climatic conditions (Resh, 2022).

The hydroponic approach offers several advantages that align with the principles of sustainable intensification. These include significant reductions in water usage, often up to 90% less than conventional soil farming, as well as higher yields per unit area, faster crop cycles, and minimal pesticide usage due to the

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production closer to urban centers and reducing transportation emissions (Touliatos et al., 2023). These characteristics make it an attractive solution not only for industrial growers but also for smallholder urban farmers and development practitioners seeking to enhance local food security.

In addition to agronomic benefits, hydroponic systems hold great promise for environmental sustainability. Closed loop systems eliminate runoff, minimizing eutrophication of water bodies and conserving nutrient inputs. Integration with renewable energy sources, aquaponics (fish + plant co-cultivation), and bio-circular models further amplifies the ecological benefits. With global warming posing risks to food production through altered rainfall, rising temperatures, and pest dynamics, hydroponics offers a buffer by decoupling food production from many external climate variables (Kalantari et al., 2017).

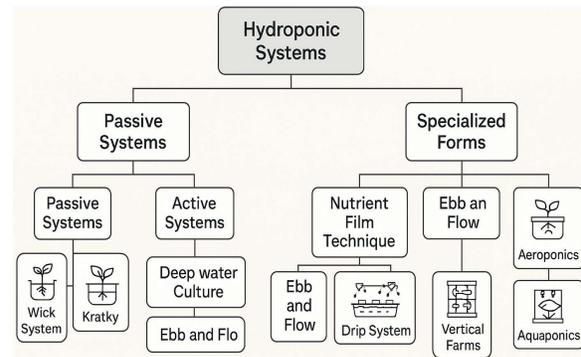
Despite its promise, hydroponic agriculture is not without limitations. High capital investment, energy demands for climate control and lighting, technical expertise, and maintenance requirements can hinder adoption, especially in low-income or off-grid settings. Moreover, the absence of soil brings new challenges in root microbiome management and long-term nutrient balance. Questions of social acceptance, food culture compatibility, and policy inclusion also remain underexplored (Santos et al., 2022). As such, hydroponics is not a universal replacement for field agriculture but a complementary and strategic innovation that can be deployed where traditional systems are infeasible or inefficient.

The aim of this review is to present a comprehensive synthesis of hydroponic agriculture as a tool to intensify sustainable food production. It begins with an overview of system typologies and technical classifications, followed by a discussion of agronomic and environmental advantages. The paper then explores hydroponics' potential within sustainable and circular food systems, assesses its economic viability, and reviews global market trends. Finally, the article critically evaluates the key barriers to widespread adoption and outlines future directions for research, innovation, and policy support. By integrating insights from agronomy, sustainability science, and food systems policy, this review positions hydroponic agriculture not merely as a technology, but as a paradigm shift in how we grow food in the 21st century.

### Hydroponic Systems and Classifications

Hydroponic agriculture encompasses a variety of soilless cultivation systems, each with distinct design characteristics, technical requirements, and crop suitability. These systems share the common principle of delivering nutrients directly to plant roots in a controlled environment, but they differ in how water, oxygen, and nutrients are managed. Understanding the classifications and operating principles of these systems is essential for optimizing production efficiency,

resource use, and system sustainability across diverse contexts (Fig 1).



**Fig 1:** A visual taxonomy of hydroponic cultivation systems, categorized into three primary types: passive systems (e.g., wick and Kratky methods), active systems (e.g., deep water culture, nutrient film technique, ebb and flow), and specialized forms (e.g., vertical farming, aeroponics, and aquaponics).

The most widely used hydroponic system is the Nutrient Film Technique (NFT). In this setup, a thin film of nutrient-rich water continuously flows through sloped channels, bathing the roots of plants such as lettuce, basil, and strawberries. NFT systems are efficient in terms of water and nutrient use and are well-suited for leafy greens with shallow root systems. However, they are vulnerable to pump failures and require precise monitoring of flow rates and nutrient concentrations (Resh, 2022). Due to their compact design and scalability, NFT systems are common in vertical farms and urban greenhouse operations.

Another prevalent method is Deep Water Culture (DWC), where plant roots are suspended in oxygenated nutrient solutions. Air pumps maintain dissolved oxygen levels, preventing root rot and supporting vigorous growth. DWC systems offer rapid growth and high productivity, especially for crops like spinach, kale, and herbs. They are also relatively simple to set up, making them popular among home growers and educational institutions (Kowalczyk et al., 2022). The main challenge with DWC is maintaining water temperature stability and preventing microbial contamination in stagnant reservoirs.

Ebb and Flow (Flood and Drain) systems operate by periodically flooding a grow tray with nutrient solution and then draining it back into a reservoir. This cycle allows roots to absorb nutrients and oxygen alternately, simulating natural wet-dry soil dynamics. Ebb and flow systems are flexible, support a wider range of crops, and are often used with inert substrates such as clay pellets or rockwool. However, precise timing and drainage design are critical to prevent waterlogging or nutrient stress (Touliatos et al., 2023).

Wick systems are among the simplest hydroponic models, relying on capillary action to draw nutrient solution from a reservoir into the growing medium through a wick. While low-cost and energy free, wick

systems have limited nutrient delivery capacity and are typically used for small-scale herb cultivation. Their passive nature makes them ideal for educational demonstrations or low-tech settings but unsuitable for commercial use or nutrient-demanding crops (Santos et al., 2022).

Aeroponics represents one of the most technologically advanced hydroponic systems. In this approach, plant roots are suspended in air and misted intermittently with nutrient solution. Aeroponics maximizes oxygen availability to roots and reduces water use further compared to other hydroponic methods. It has been employed for high value crops and seed production, as well as in space agriculture by organizations such as NASA. However, aeroponic systems require high technical expertise and are sensitive to system failures, particularly pump or nozzle clogging (Rakocy et al., 2019).

A related system is Drip Irrigation Hydroponics, where a timed drip of nutrient solution is delivered directly to each plant's root zone through emitters. This system is widely used in large-scale commercial operations, especially for fruiting vegetables like tomatoes, peppers, and cucumbers. The use of inert substrates such as cocopeat or perlite supports root anchorage and moisture retention. Drip systems offer precise control over nutrient delivery and reduce water waste, though emitter clogging and salt buildup are common maintenance issues (Jensen, 2021).

The choice of system depends on several factors including crop type, resource availability, technical skill, environmental conditions, and intended scale of operation. For example, while NFT and DWC are favored for leafy greens due to fast turnaround and small root systems, larger fruiting crops require drip or ebb and flow systems that provide more substrate volume and structural support. In low-resource or off-grid contexts, wick and passive DWC systems may offer greater accessibility, while high-tech aeroponics and automated NFT setups dominate commercial indoor farming ventures.

Most hydroponic systems can also be categorized as open-loop (non-recirculating) or closed-loop (recirculating). Open systems deliver nutrients once and dispose of the excess, potentially leading to waste and environmental contamination. In contrast, closed systems recirculate nutrient solutions, improving water and nutrient efficiency but requiring constant monitoring of pH, electrical conductivity (EC), and microbial buildup (Resh, 2022). Closed-loop hydroponics aligns better with sustainability goals but imposes higher management demands.

Another emerging classification concerns the integration of hydroponics into controlled environment agriculture (CEA) systems. These include climate controlled greenhouses, vertical farms, and indoor plant factories with artificial lighting (LEDs). In such settings, hydroponic systems are embedded within precision agriculture frameworks, utilizing sensors, IoT devices, and automated nutrient dosing systems to optimize growth

parameters. While these systems offer unparalleled yield potential and year round production, they are also the most capital and energy intensive, requiring careful cost-benefit analysis (Al-Kodmany, 2018).

### **Agronomic and Environmental Advantages**

Hydroponic agriculture offers a suite of agronomic and environmental advantages that make it increasingly relevant in the context of climate-smart and resource-efficient food production. Its appeal lies not only in its capacity to decouple plant growth from soil constraints but also in its superior efficiency in resource utilization, its compatibility with urban spaces, and its potential to reduce agricultural pollution. These advantages position hydroponics as a high potential innovation for sustainable intensification, particularly in areas where conventional farming is unviable or environmentally burdensome.

One of the most frequently cited agronomic benefits of hydroponics is its exceptional water-use efficiency. In traditional soil agriculture, a significant portion of applied water is lost to evaporation, deep percolation, or surface runoff. In contrast, hydroponic systems, particularly closed-loop recirculating designs, retain and reuse nutrient solution, resulting in up to 90–95% less water consumption per kilogram of produce (Germer et al., 2011; Resh, 2022). This makes hydroponics particularly attractive in water-scarce regions or areas prone to drought, where optimizing water productivity is paramount for food security.

Hydroponics also enhances nutrient-use efficiency by delivering precisely formulated nutrient solutions directly to plant roots. This eliminates the variability associated with soil nutrient availability and reduces nutrient losses through leaching or immobilization. Because the nutrient profile can be tailored to each crop's developmental stage, hydroponic systems support faster growth rates, shorter harvest cycles, and higher yields per unit area than conventional agriculture. For instance, lettuce yields in NFT systems have been reported to be two to three times higher than in field-grown systems under equivalent conditions (Touliatos et al., 2023). Moreover, yield stability is improved due to the controlled environment, reducing seasonal variability.

Another agronomic strength of hydroponics is the elimination of soil-borne diseases and pests, which are major limitations in field agriculture. In the absence of soil, pathogens such as *Fusarium*, *Pythium*, or nematodes are significantly reduced, minimizing the need for chemical interventions. This enables pesticide free or low input production, enhancing food safety and making hydroponic produce particularly appealing in high value markets or for consumers seeking organic or clean label products (Santos et al., 2022). Integrated pest management (IPM) in hydroponics often relies on biological control agents and environmental regulation, rather than synthetic chemicals.

In terms of land efficiency, hydroponics allows for dense planting configurations and vertical integration,

significantly increasing yield per square meter. Vertical farms and shelf-stacked systems in greenhouses can produce up to 10 times more yield per unit area than conventional farms (Kalantari et al., 2017). This is particularly important in urban and peri-urban areas, where space is limited and land costs are high. By utilizing rooftops, basements, or repurposed warehouses, hydroponic systems enable localized food production within city limits, shortening supply chains and reducing food miles.

From an environmental perspective, hydroponics reduces several key externalities associated with conventional agriculture. One of the most significant is the reduction in nutrient runoff, which is a major cause of eutrophication in freshwater and marine ecosystems. Because hydroponic systems are closed or semi-closed, and nutrient delivery is precise, the risk of nitrate and phosphate leaching is minimal. Additionally, hydroponics eliminates the need for heavy tillage, preserving soil structure and reducing erosion, even though it does not use soil itself.

Hydroponics also supports climate change adaptation and mitigation. By controlling temperature, humidity, light, and CO<sub>2</sub> concentration, hydroponic systems buffer crops from the adverse effects of extreme weather, drought, and pest outbreaks. This controlled environment makes hydroponics more climate-resilient than open-field systems. From a mitigation perspective, hydroponic systems generally have a lower carbon footprint per unit yield when powered by renewable energy and operated efficiently (Barbosa et al., 2015). Compared to conventional systems, energy intensive hydroponic systems still emit less GHG per kilogram of yield due to higher productivity and lower input demand.

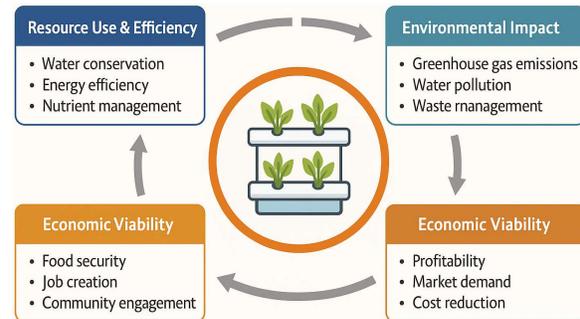
Furthermore, hydroponic systems offer scalability and modularity, allowing growers to start small and expand incrementally. Systems can be adapted for household food security, school education, small businesses, or commercial-scale production. This flexibility makes hydroponics an inclusive technology, with potential applications ranging from refugee camps and disaster zones to high-tech urban centers and commercial greenhouses.

However, it is essential to acknowledge that these agronomic and environmental advantages are highly context-dependent. For instance, energy use for lighting and climate control in indoor hydroponics can offset water and land efficiency gains if fossil fuels are the primary energy source. Nutrient management must be closely monitored to avoid accumulation of salts or nutrient imbalances, especially in closed-loop systems. Additionally, waste from growing media (e.g., rockwool) and single-use plastics can become environmental concerns if not managed properly (Gruda, 2023).

### Sustainability and Circularity Potential

Hydroponic agriculture holds substantial promise not only for increasing productivity and resource efficiency but also for contributing to broader sustainability and

circular economy goals. As global food systems aim to reduce their environmental footprints, hydroponic systems offer opportunities to redesign agricultural processes around closed-loop nutrient cycles, renewable energy integration, and waste minimization (Fig 2). These attributes are particularly relevant in urban and peri-urban settings where resource limitations and environmental concerns intersect.



**Fig 2:** A conceptual framework illustrating how hydroponic agriculture contributes to sustainability through circular resource flows.

A defining feature of hydroponics in the sustainability context is its potential to close nutrient and water loops. Unlike conventional soil-based systems where much of the fertilizer applied is lost to leaching or runoff, hydroponic systems recirculate nutrient solutions, allowing plants to absorb what they need while the remainder is filtered and reused. This not only improves nutrient-use efficiency but also prevents pollution of surrounding ecosystems (Gruda, 2023). In a well-managed closed system, up to 90% of nitrogen and phosphorus inputs can be recovered, aligning hydroponics with the principles of sustainable nutrient management promoted under international agreements such as the EU Circular Economy Action Plan and UN Sustainable Development Goals (SDGs).

Hydroponic systems can also be integrated into urban circularity strategies by reusing organic waste streams. For example, nutrients can be sourced from treated municipal wastewater, digestate from anaerobic digestion, or composted food waste, reducing dependence on synthetic fertilizers derived from finite phosphate rock or energy-intensive ammonia synthesis (Goddek et al., 2019). Although these approaches require careful monitoring to ensure food safety, advances in filtration, microbial bioreactors, and nanomaterials are making waste-derived nutrient solutions increasingly viable.

One of the most synergistic models in circular hydroponics is aquaponics, which combines hydroponics with aquaculture in a closed system where fish waste provides nutrients for plants, and the plants, in turn, help purify the water for the fish. Aquaponics exemplifies integrated resource use, reducing both water and nutrient inputs by creating a symbiotic production loop. Studies have shown that aquaponic

systems can reduce water use by 95% and fertilizer use by up to 70% compared to conventional systems (Junge et al., 2017). Although aquaponics systems are more complex to manage, they offer strong educational, ecological, and economic appeal.

Energy sustainability is another key aspect of hydroponic systems, particularly those housed in vertical farms or indoor environments that rely heavily on artificial lighting, HVAC systems, and pumps. To ensure environmental benefits are not offset by high carbon footprints, there is growing interest in integrating renewable energy sources such as solar, geothermal, or wind to power hydroponic facilities. Life cycle assessments (LCA) of hydroponic greenhouses powered by solar energy show significant reductions in greenhouse gas emissions, particularly when paired with energy-efficient LEDs and smart climate control systems (Al-Kodmany, 2018; Barbosa et al., 2015).

Furthermore, hydroponic agriculture supports the principles of localization and urban resilience, two pillars of food system sustainability. By enabling production near or within cities, hydroponics reduces “food miles,” shortens supply chains, and increases the freshness and shelf-life of perishable goods. This is particularly important in the context of pandemics, fuel price shocks, or geopolitical disruptions that affect global food trade. Urban hydroponic farms also reclaim underutilized spaces such as rooftops, abandoned warehouses, or shipping containers and transform them into productive assets, enhancing land-use efficiency and reducing urban heat islands (Specht et al., 2020).

Waste minimization and material circularity are additional sustainability levers in hydroponic systems. Innovations in biodegradable substrates, recyclable plastics, and organic nutrient formulations are reducing the environmental impact of growing media and equipment. Furthermore, efforts to integrate hydroponics into zero-waste agricultural systems are gaining traction in controlled environment agriculture (CEA) research. For instance, some operations repurpose vegetable trimmings into compost or animal feed, reducing waste while enhancing circularity (Gruda, 2023).

Despite these advantages, some sustainability trade-offs and challenges remain. Energy demand, especially for artificial lighting and climate control, is often cited as the most significant environmental concern, particularly in high-latitude regions or non-renewable energy contexts. Additionally, managing the accumulation of salts and potential buildup of contaminants in closed-loop systems requires regular monitoring and water exchanges, which may generate small volumes of effluent that must be safely discharged or treated. Moreover, the production and disposal of synthetic substrates such as rockwool and plastic net pots still represent a waste management challenge, though alternatives such as hemp fiber, coconut coir, and biodegradable biopolymers are emerging.

In terms of systems thinking, hydroponics performs best when designed as part of integrated urban food

energy water systems. For example, coupling rooftop hydroponics with rainwater harvesting and solar panels maximizes environmental co-benefits while minimizing inputs. Similarly, integrating hydroponic farms with urban composting and bioenergy facilities can create synergistic waste-to-resource loops. These models exemplify the “nexus approach”, which seeks to optimize interdependent systems for overall sustainability rather than isolated efficiency gains (Weidner & Yang, 2020).

### **Economic Viability and Market Trends**

While hydroponic agriculture offers strong agronomic and environmental benefits, its broader adoption depends heavily on economic viability and market dynamics. For hydroponics to be scalable and sustainable, it must demonstrate profitability, resilience to market fluctuations, and alignment with consumer demand. As such, evaluating cost structures, return on investment, and emerging market trends is essential to understand hydroponics not only as a technology but as a viable business model across different geographic and socioeconomic contexts.

One of the most frequently cited challenges in hydroponic production is the high initial capital investment. Setting up a commercial hydroponic farm requires infrastructure for water delivery, nutrient dosing, lighting (in indoor systems), structural support, sensors, and climate control. These setup costs can range from \$100 to \$500 per square meter depending on system complexity and regional conditions (Touliatos et al., 2023). Advanced systems such as vertical farms or containerized units with full LED lighting require even higher upfront investments, often deterring smallholder adoption.

In addition to capital expenses, operational costs—including energy, labor, nutrient solution inputs, seedling propagation, and maintenance—are substantial. In indoor farms, energy for lighting and climate regulation can account for 50–70% of total operating costs (Kalantari et al., 2017). Nevertheless, these costs are offset by higher crop yields, shorter production cycles, and premium pricing of pesticide-free, fresh, and locally grown produce. A well-managed hydroponic lettuce system, for instance, can produce up to 10 harvests per year with yields exceeding 3–4 times those of conventional field farming (Barbosa et al., 2015).

Return on investment (ROI) in hydroponics is highly variable, depending on factors such as crop selection, market access, system efficiency, and scale. Leafy greens, herbs, strawberries, and tomatoes are among the most profitable crops in hydroponic systems due to their short cycles, high market value, and consumer familiarity. Specialty crops like micro-greens, edible flowers, or medicinal plants can command higher margins but require niche marketing. On average, ROI periods range between 3–7 years, with faster recovery in urban or peri-urban markets where produce can be

sold directly to consumers, restaurants, or retailers (Jensen, 2021).

Hydroponic systems also benefit from their spatial flexibility and land-use efficiency, allowing producers to establish farms in high-value urban real estate, rooftops, or repurposed buildings. In cities where conventional agriculture is impractical, hydroponic farms reduce transportation and storage costs, ensuring fresher produce and increasing competitiveness. The rise of direct-to-consumer models, farmers' markets, and subscription services has further strengthened the business case for hydroponics in localized food systems.

On the global scale, hydroponic agriculture is part of the rapidly growing Controlled Environment Agriculture (CEA) market, which includes vertical farming, aquaponics, and greenhouse cultivation. According to recent market analysis, the global hydroponics market was valued at over USD 9 billion in 2023 and is projected to reach USD 19 billion by 2028, growing at a CAGR of 16–20% (MarketsandMarkets, 2023). Growth is driven by urbanization, consumer demand for pesticide-free and traceable produce, climate instability, and innovations in agri-tech.

Technology integration and automation are key enablers of profitability in large-scale hydroponics. Systems equipped with AI-powered monitoring, IoT sensors, and automated nutrient dosing significantly reduce labor costs and improve consistency. In high income countries, tech firms and agri-startups are partnering to develop turnkey hydroponic solutions tailored for both commercial and community farming. These trends are supported by venture capital, public-private partnerships, and green infrastructure initiatives.

Nevertheless, profitability is not uniform across geographies. In developing regions, barriers such as limited access to financing, low awareness, inadequate extension services, and unreliable energy supply hinder widespread adoption. Innovative financing models such as micro-leasing, performance-based subsidies, and cooperative investment platforms are being tested to de-risk hydroponics for small and medium scale growers (Dey et al., 2021). In countries like Kenya, India, and Indonesia, donor funded programs and startups are promoting low-tech hydroponic kits for urban youth, schools, and refugee settlements, indicating hydroponics' potential for inclusive development.

Consumer trends also play a decisive role in market viability. Rising concerns over food safety, pesticide residues, carbon footprint, and freshness are pushing

consumers toward local, sustainably grown produce. Hydroponically grown crops especially those labeled as organic or pesticide free often fetch premium prices in retail outlets and upscale restaurants. Traceability, clean-label certifications, and digital engagement through QR codes or farm tours enhance consumer trust and brand differentiation (Specht et al., 2020).

However, consumer perceptions are mixed, particularly regarding nutritional quality, environmental impact, and taste. While most studies indicate that hydroponically grown vegetables are nutritionally comparable or superior to their soil-grown counterparts, public acceptance varies by culture, familiarity, and food tradition. Transparent communication, education, and alignment with food values are thus essential for expanding market share.

### Challenges and Research Needs

Despite the numerous benefits of hydroponic agriculture, several technical, socioeconomic, and policy-related challenges hinder its broad adoption and long-term sustainability. As hydroponic farming expands from niche technology into mainstream agricultural discourse, these challenges must be critically addressed through research, innovation, and institutional support. This section outlines the key barriers and areas where further investigation and development are needed (Table 1).

One of the most persistent barriers is the high dependency on energy, particularly in controlled environment agriculture (CEA) systems such as indoor farms and vertical hydroponic setups. Lighting, heating, ventilation, and air conditioning (HVAC) systems often rely on electricity derived from fossil fuels, significantly affecting the carbon footprint and operational cost of these farms. While renewable energy integration has shown promise, it requires considerable capital and technical coordination (Barbosa et al., 2015). Research is needed to enhance energy efficiency, develop low-energy climate control systems, and improve the cost-performance ratio of LED lighting technologies tailored to plant physiology.

Closely related is the nutrient management challenge. Unlike soil systems, where microbial communities and soil buffering capacity modulate nutrient dynamics, hydroponic systems require precise control of nutrient concentrations, pH, and electrical conductivity (EC). Nutrient imbalances or contamination can lead to rapid plant stress and yield loss. Furthermore, managing micronutrients and preventing

**Table 1:** Barriers to Hydroponic Adoption and Corresponding Research/Policy Needs

Barrier	Type	Key Challenge	Research/Policy Priority
High Energy Use	Technical	HVAC and lighting costs	LED optimization, solar integration
Nutrient Imbalance	Agronomic	Salt accumulation, micronutrient gaps	Automated dosing, rootzone sensors
Substrate Waste	Environmental	Rockwool disposal, non-renewables	Bio-based biodegradable media
Knowledge Gaps	Socioeconomic	Lack of training for smallholders	Digital extension, curriculum dev.
Policy Ambiguity	Institutional	No zoning or subsidy clarity	Recognition in agri/urban policy

salt accumulation in closed systems remains complex, particularly in recirculating designs (Resh, 2022). There is a pressing need for automated nutrient delivery systems, real-time sensors, and decision-support tools that can optimize nutrient use while reducing labor and error.

Another challenge is the limited understanding of root microbiome interactions in hydroponic systems. While soil-based agriculture benefits from diverse microbial consortia that support plant growth and disease resistance, hydroponic systems often lack such microbial complexity. This leaves crops more susceptible to waterborne pathogens such as *Pythium*, *Fusarium*, and *Phytophthora* (Lee et al., 2020). Future research should focus on microbial inoculants, probiotic consortia, and biocontrol agents that can be introduced into hydroponic systems to simulate the protective functions of healthy soil.

Hydroponic systems also face technical complexity and knowledge requirements that can hinder adoption, particularly in resource-limited contexts. System maintenance, nutrient calibration, disease monitoring, and troubleshooting demand skills that are often lacking among smallholder farmers or first-time adopters. This knowledge barrier is compounded by the lack of formal training programs, extension support, and standardized operational guidelines. To close this gap, curriculum development, vocational education, and digital extension platforms are needed to build technical capacity across user groups (Dey et al., 2021).

In addition to technical barriers, social acceptance and cultural perceptions remain underexplored obstacles to hydroponic adoption. In some regions, hydroponically grown food is viewed as unnatural or inferior due to its detachment from soil a deeply symbolic and cultural element in agriculture. Concerns about taste, nutrition, and sustainability are often fueled by misinformation or lack of transparency. Social science research is needed to better understand consumer attitudes, develop effective communication strategies, and explore the intersection of food values, identity, and trust in new agricultural technologies (Specht et al., 2020).

Economic scalability also presents a challenge. While hydroponic systems can be profitable, their success is often contingent on proximity to high-value urban markets, premium pricing, and reliable energy and water access. In rural or low-income areas, the cost of infrastructure, replacement parts, and skilled labor can be prohibitive. Additionally, limited access to credit, subsidies, or insurance mechanisms further constrains investment. Governments and financial institutions must explore inclusive business models, such as cooperatives, leasing, or public private partnerships, to democratize access to hydroponics and reduce entry barriers (Jensen, 2021).

Policy and regulatory gaps add another layer of uncertainty. In many countries, hydroponic farming is not explicitly addressed in agricultural policies, land-use

planning, or food safety standards. This results in ambiguity regarding organic certification, zoning regulations, and eligibility for subsidies or technical support. Policymakers need to recognize hydroponics as a legitimate and strategic component of national food systems, incorporating it into climate adaptation, urban agriculture, and innovation policies. Legal clarity and incentive structures will be essential to foster responsible expansion.

From a research perspective, there are still knowledge gaps in optimizing system design, improving substrate sustainability, and integrating circular economy principles. Common substrates like rockwool and perlite are non-renewable and often non-biodegradable, raising concerns about waste and environmental impact. Ongoing efforts to develop biodegradable, compostable, or locally sourced substrates such as hemp fiber, coconut coir, or biochar must be accelerated (Gruda, 2023).

Finally, more robust life cycle assessments (LCA) and cost-benefit analyses are required to evaluate hydroponics in different contexts. Most existing LCA studies focus on lettuce or leafy greens in high-tech settings; fewer analyses are available for diverse crops, hybrid systems (e.g., aquaponics), or decentralized models in the Global South. Comparative studies with conventional agriculture under variable climatic and socioeconomic scenarios will help guide evidence-based decision making.

### Conclusion and Future Directions

Hydroponic agriculture represents one of the most promising innovations in modern food production, offering a compelling response to the urgent challenges of land degradation, water scarcity, climate variability, and urbanization. By decoupling crop cultivation from soil and enabling precise control over environmental and nutritional parameters, hydroponics delivers significantly higher resource-use efficiency, yield per area, and spatial adaptability than conventional farming systems. It has become central to the emerging paradigm of controlled environment agriculture (CEA) and is increasingly embedded in urban food systems, vertical farming, and circular economy models.

This review has highlighted the agronomic, environmental, and socioeconomic benefits of hydroponics from improved water and nutrient use, to year-round productivity, reduced pesticide reliance, and minimized land requirements. It has also detailed how hydroponic systems can advance sustainability through closed loop nutrient management, integration with renewable energy, and alignment with circular economy principles. Furthermore, market trends indicate rapid growth, driven by consumer demand for clean, fresh, and traceable produce, as well as technological advancements that support automation and monitoring.

However, the review also identifies several critical limitations. High capital and energy costs, knowledge

intensive management, vulnerability to nutrient imbalances and pathogens, and policy ambiguities remain major barriers to broader adoption particularly in resource-limited or decentralized contexts. Additionally, questions of social acceptance, cultural fit, and long-term environmental impacts of substrates and materials require further exploration. These constraints underscore the need for holistic system design, context sensitive implementation, and inclusive investment strategies.

Future directions must focus on four priority areas. First, advancing energy efficient and modular system architectures to reduce costs and increase scalability. Second, enhancing biological and ecological integration particularly through microbial management and sustainable substrate development. Third, building capacity and democratizing access through training programs, localized innovation, and smallholder friendly models. Fourth, embedding hydroponics into national food and climate policies, urban planning frameworks, and green infrastructure funding.

In conclusion, hydroponics is not a panacea but a powerful complement to traditional agriculture capable of intensifying sustainable food production in both urban and rural settings. When integrated with renewable energy, waste reuse, and community engagement, it becomes more than a production method: it evolves into a model of resilient, localized, and regenerative food systems. With continued research, innovation, and policy support, hydroponic agriculture has the potential to play a pivotal role in feeding a growing population while safeguarding planetary health.

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