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Role of Hydroponics in Improving Water-Use Efficiency and Food Security

Ram Naresh [a*], Sagar K Jadav [b*], Monika Singh [c], Abhimanyu Patel [d], Barinderjit Singh [e], Shreedhar Beese [f] and Shivam Kumar Pandey [g]

[a] ICAR-Atari Zone III, Kanpur, India.
[b] Department of Genetics and Plant Breeding, College of Agriculture, Waghai- Dang, Navsari Agricultural University, India.
[c] Genetics and Plant Breeding, Maharishi University of Information Technology, Lucknow, India.
[d] Department of Floriculture and Landscaping, College of Horticulture and Research Station, Kunkuri Jashpur, MGUVV, Raipur CG-492001, India.
[e] Department of Food Science and Technology, I. K. Gujral Punjab Technical University, Kapurthala, Punjab, 144601- India.
[f] Department of Floriculture and Landscape Architecture, Dr. Y S Parmar University of Horticulture and forestry, Nauni Solan (Himachal Pradesh), India.
[g] Rashtriya Raksha University, India.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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**Corresponding author: E-mail: sagarjadav@nau.in;*

ABSTRACT

Hydroponic agriculture offers a soilless cultivation method that can enhance crop yields and sustainability. With decreasing arable land and water availability, hydroponics is positioned to complement conventional farming approaches to support global food security. This paper reviews the current status and future innovations in precision hydroponic technologies. Leading application crops, geographic adoption patterns, growth potential in developing countries, and technological advances are analyzed. Key challenges limiting widespread implementation are discussed, including infrastructural costs, lack of expertise, and inadequate research investments. Proposed legislation and standardization efforts in major markets are outlined. Ongoing improvements in automation, renewable energy integration, biocontrols and tailored crop varieties can further overcome limitations. The paper offers recommendations to promote hydroponics through targeted research initiatives, public incentives and localized equipment development. With appropriate regulatory support and sustained funding commitment, hydroponic systems can bolster food ecosystem resilience. The COVID-19 crisis has highlighted the interlinked risks in concentrated, centralized agriculture. More decentralized precision approaches can enhance stability. Hydroponics and vertical farming innovations can enable sustainable intensification to meet future nutritional demands. Adoption efforts to date have focused on profitable vegetable and herb markets in advanced economies, but expanding technical skills training and appropriate technologies globally would support wider implementation. With further commercial maturation and policy regulations keeping pace with innovations, hydroponics can be an integral strategy for sustainable crop production worldwide.

Keywords: Hydroponics; precision agriculture; food security; sustainable intensification; agricultural innovations.

1. INTRODUCTION

With the global population estimated to reach 9.8 billion by 2050, meeting the world's food demands represents one of the most significant challenges of the 21st century [1]. Current projections indicate that feeding this expanded population will require raising overall food production by 70% compared to current levels [2]. However, increasing agricultural output through conventional practices of expanding land under cultivation is constrained by water scarcity, soil degradation, climate change impacts, and other environmental limitations [3]. These interconnected challenges threaten future global food security and underscore the need for innovative approaches to boost crop yields in a sustainable manner [4].

Precision agriculture, defined as information-based farm management practiced at refined temporal and spatial scales [5], offers significant potential to enhance productivity while overcoming risks to long-term food production capacity [6]. By leveraging real-time data streams, advanced analytics, and emerging digital technologies, precision techniques allow for improved decision making and precise application of inputs like water, fertilizers and pesticides [7,8]. This could allow the current degraded resource base to support substantially greater output.

However, transforming farming into a high-tech, data-driven enterprise requires addressing numerous technical and economic barriers. Many promising precision innovations have failed to be widely adopted by cash-strapped farmers due to high upfront costs, lack of technical skills and inadequate infrastructure [9]. Public sector involvement is vital to incentivize technology developers and provide farmers access to precision solutions [10].

Hydroponic cultivation, the growing of plants without soil using mineral nutrient solutions in water, represents one precision approach with immense potential to expand global food supplies [11]. Although hydroponics currently accounts for a negligible share of world agricultural production, the technology offers multiple advantages over conventional practices [12]. By allowing crops to be grown in controlled settings without reliance on scarce arable land and irrigation water, hydroponic systems can sustain much higher yields with fewer inputs [13]. Shifting just a small share of field agriculture to indoor hydroponic production would greatly increase output of fruits, vegetables and herbs to meet rising consumption demands [14].

However, large-scale adoption of hydroponics also faces barriers regarding technological expertise, access to affordable equipment, availability of inputs and high energy demands [15]. Targeted research is needed to enhance efficiency, crop quality and profitability, as well as assess environmental tradeoffs [16]. Government support mechanisms will be critical in enabling rapid expansion of commercial hydroponic farms [17].

With global population size continuing to expand, failing to significantly improve agricultural productivity and resource efficiency could have dire consequences for future food availability and security [18]. Precision agriculture techniques like hydroponics offer promising pathways to sustainably enhance crop yields. But realizing this potential will require greater public and private sector coordination to promote rapid development and uptake of impactful technologies [19]. Both advanced and developing countries must prioritize investments in precision farming innovations as key strategies for achieving national and global food security objectives [20].

1.1 Water Use in Conventional Agriculture

Conventional agriculture is heavily dependent on reliable water resources for crop irrigation. However, irrigation practices often lead to significant water inefficiencies and environmentally damaging wastage. This section will examine the high water demands of traditional soil farming, issues with irrigation system performance, and the ecological impacts associated with agricultural water usage.

1.2 Water Requirements of Conventional Soil-Based Farming

Agriculture accounts for approximately 70% of global freshwater withdrawals, making it by far the largest consumer of water resources [21]. The vast majority of this water is used for crop irrigation via man-made irrigation networks or rainfall harnessing [22]. Soil-grown plants require adequate moisture in root zones to support growth and cool foliage through evapotranspiration [23]. As plants lose moisture through leaves or fail to absorb enough from the soil, crop health and yields suffer.

The precise irrigation water needs of crops depend on specific climatic variables, soil conditions, and plant biological factors [24]. However, general estimates indicate that cereal grains require 300-500 liters of water per kilogram of output, vegetables need 300-700 liters/kg, and fruit crops may require as much as 1000 liters/kg [25]. Meeting water demands to achieve target yields requires extensive irrigation infrastructure like wells, pumps, canals and sprinklers.

1.3 Irrigation Inefficiencies and Water Wastage

While irrigation enables much higher agricultural productivity, conventional application methods result in tremendous water inefficiency [26]. Surface irrigation approaches like flood and furrow irrigation fail to uniformly distribute water, resulting in overwatering in some areas and insufficient moisture in others [27]. Sprinkler methods also suffer from uneven dispersal as well as spray drift and evaporation losses exceeding 50% of water diverted from sources [28].

Excess irrigation drives widespread wasting as water percolates below root zones or runs off the field edge. Developing country farms average only 30-40% irrigation efficiency, while systems in developed nations may approach 60% efficiency at best [29]. Repetitive overwatering leaches nutrients from soil, contributes to salinity buildup, and intensifies problems like erosion [30].

1.4 Environmental Impacts of Agricultural Water Use

The utilization of vast volumes of water for irrigation depletes surface and underground water reserves faster than natural recharge in many world regions [31]. Overexploitation has caused groundwater tables to sink dramatically, drying up streams and lakes relied upon by ecosystems, agriculture and communities [32].

Chemical fertilizer and pesticide residues are commonly detected in runoff from irrigated plots, polluting rivers, lakes and coastal waters. Nutrient contamination can promote toxic algae blooms that critically alter aquatic habitats [33]. Sediments eroded from farms degrade water quality further and accumulate in hydrologic systems, damaging infrastructure.

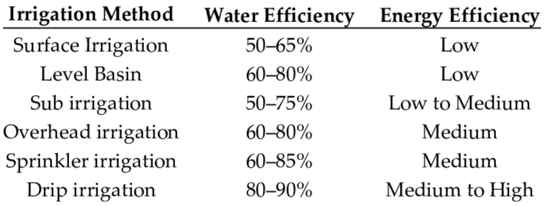
Liberal irrigation also raises local humidity levels that, paired with warm conditions, facilitate formation of ground-level ozone. Exposure to ozone decreases crop yields and destroys wild vegetation [34]. Wasteful water practices ultimately undermine the long-term viability of agriculture by eroding the quality and reliability of the very resources it depends on.

Table 1. Estimated irrigation water requirements for major food crops

Crop	Irrigation needs (litres/kg output)
Wheat	500
Rice	400
Corn	300
Potatoes	500
Tomatoes	700
Oranges	900

Source: [25]

Table 2. Relative efficiency of different irrigation methods



Irrigation Method	Water Efficiency	Energy Efficiency
Surface Irrigation	50–65%	Low
Level Basin	60–80%	Low
Sub irrigation	50–75%	Low to Medium
Overhead irrigation	60–80%	Medium
Sprinkler irrigation	60–85%	Medium
Drip irrigation	80–90%	Medium to High

Source: (29)

Table 3. Key impacts of conventional agricultural water use

Impact	Description
Depletion of water sources	Overextraction of surface and groundwater reduces future availability
Water pollution	Fertilizers, pesticides and eroded sediment discharge in runoff, reducing water quality
Salinization	Salts accumulate and degrade soil over time from excessive irrigation
Ecosystem disruption	Aquatic habitats suffer from reduced streamflows and eutrophication
Lower crop yields	Water stress and rising ozone levels decrease agricultural productivity

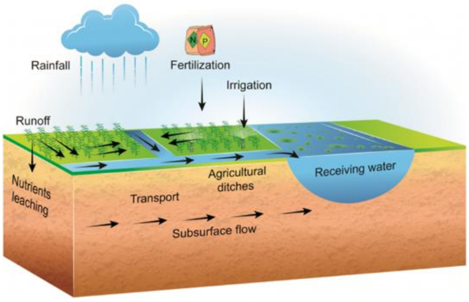


Fig. 1. Movement of agricultural pollutants with irrigation runoff
Source: [35]

Table 4. Key advantages of soilless hydroponic crop production

Benefit	Description
Higher yield	Precision input control enables greater harvests per area
Faster growth	Crops mature 30-50% quicker with optimized conditions
Less disease	Pathogens and pests have fewer infection routes
No soil depletion	Cultivation does not degrade fragile farmland over time
Less water required	Closed-loop recirculation reduces usage by up to 90%

1.5 Principles of Hydroponics

Hydroponics is the cultivation of plants without soil, instead utilizing mineral nutrient solutions in water. This technique grants growers greater control over inputs while eliminating dependence on scarce quality farmland. The following sub-sections define hydroponics, discuss its key advantages, and outline major system types.

1.6 Definition and Brief History

The term hydroponics combines the Greek words for water ("hydro") and working/toil ("ponos"), reflecting the use of water rather than land to enable and sustain plant growth [36]. While ancient civilizations likely recognized that primitive crops could grow in just water, the first recognizable hydroponic experiments began in the early 1600s [37]. Over the next few centuries, researchers developed artificial nutrient solutions to replace soil and enable robust harvests.

However, hydroponics remained restricted to small-scale applications until the 20th century advent of plastic covering materials, advanced greenhouse engineering and monitoring technologies [38]. Over the past half-century, commercial use of various hydroponic techniques has accelerated. Still, it occupies a negligible share of global agricultural production thus far.

1.7 Elimination of Soil and Enhanced Control

Hydroponics diverges completely from soil-based cultivation by eliminating root contact with traditional potting or farming earth mixtures. Instead, plant roots are suspended directly in an oxygenated, mineral-rich solution or enclosed in porous substrate materials that act as growth mediums while maintaining constant moisture conditions [39]. This liberates agriculture from dependence on arable land while granting growers heightened command over variables affecting development.

Pre-formulated nutrient solutions deliver ideal quantities of elements like nitrogen, phosphorus and potassium tailored to specific crops. Growers also carefully regulate irrigation, lighting, temperature, humidity and other environmental conditions within containment units to optimize outputs [40]. Automated hydroponic setups continuously monitor and respond to changing moisture, oxygen and nutrient levels in circulated water to attain stabilization at setpoints [41].

2. NUTRIENT FILM TECHNIQUE, DEEP WATER CULTURE, AND OTHER METHODS

Many different hydroponic configurations have been developed to anchor root structures and facilitate exposure to nutrient-dense irrigated flows. These include [42]:

- **Nutrient film technique (NFT):** Roots grow directly into a thin constantly recycled stream of water.
- **Deep water culture:** Plants fixed in inert grow medium material with lower stems/roots submerged.
- **Wick system:** Absorbent wicks deliver nutrient solution from reservoirs up to rooted growth mediums.
- **Ebb and flow:** Intermittent flooding of grow beds that then fully drain.
- **Aeroponics:** Plants suspended with roots misted in air rather than submerged.

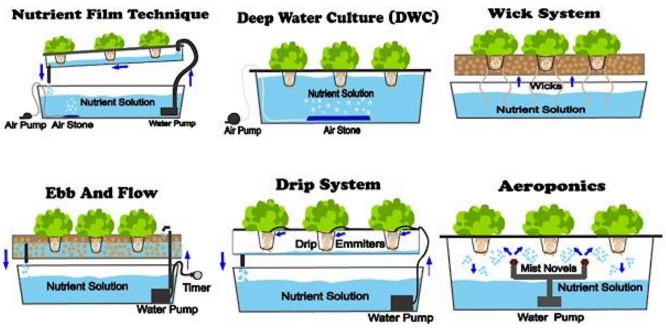


Fig. 2. Common types of hydroponic systems
Source: [43]

Configuration selections balance factors like space constraints, labor requirements, crop types, flexibility for scaling, and installation/operating expenses [44]. Commercial hydroponic greenhouses commonly utilize NFT for leafy greens and herbs, deep water culture for tomatoes and peppers, and vertical grow towers for vines [45]. Advancements like intelligent sensor networks, automation, and remote analytics tools continue to expand options and optimize outputs.

2.1 Water-Use Efficiency in Hydroponics

Hydroponics is the method of growing plants without soil, using mineral nutrient solutions in a water solvent. Terrestrial plants have adapted over millions of years to acquire nutrients from soil through their roots. However, soil also brings challenges in the form of weeds, pests, pathogens, reduced oxygen levels, and suboptimal nutrition [46]. Hydroponics allows crops to grow without the restrictions of soil while receiving perfectly tailored nutrition.

One of the main advantages of hydroponics is greatly improved water-use efficiency compared to conventional agriculture. As water resources face increasing scarcity globally, water-efficient farming practices are essential for future food security. This article will analyze the factors that give hydroponics higher water-use efficiency and reduced ecological footprints.

2.2 Greatly Reduced Water Needs

Hydroponics requires far less water input than soil-based farming. It has been estimated that hydroponics uses 10 times less water than conventional agriculture to produce the same yields [47]. For example, producing 1 kg of tomatoes takes 214 liters of water in soil, but only 20-40 liters in hydroponic systems [48]. There are several reasons hydroponics can thrive on a fraction of the water:
No water is lost to soil absorption and evaporation. Up to 80% of water applied in open field irrigation is lost to evaporation or drainage beyond the root zone before plants can absorb it [49]. Hydroponic systems recirculate unused nutrient solution. Precise moisture control prevents overwatering. Sensors monitor moisture levels and feed schedules can be adjusted to provide water on demand. This avoids water waste through drainage. Higher yields are achieved per liter of water input. With optimized growing conditions and accelerated growth rates, hydroponic systems make more efficient use of the water and nutrients supplied. Minimized ecological footprint. By recirculating and reusing solution, hydroponics systems discharge little to no agriculture effluent into the environment compared to soil farming.

2.3 Precision Moisture Control and Recirculation

Hydroponic systems give growers an unprecedented degree of control over moisture levels. Nutrient solution delivery can be carefully regulated to satisfy transpiration demands without overwatering. Common techniques include [50]:

- Drip irrigation to root systems.
- Intermittent misting of plant foliage.
- Raising seedlings on moisture-wicking mats.
- Subirrigation benches with controlled water levels.

Sensors help monitor moisture needs, enabling automatic watering only as required. Recirculating systems retrieve unused drainage solution to be sterilized and replenished before reapplication. This “closed loop” approach leaves little discharge output, increasing water productivity ten-fold or higher over soil crops [48]. With no open soil exposed to drying air and sunlight, hydroponic systems have far lower evaporative losses than field crops. Growing plants indoors or in greenhouses also eliminates soil runoff into water systems, cutting pollution from eroded sediment, fertilizers, and pesticides.

The recirculation and reuse of drainage solution makes discharge negligible, whereas soil farming releases large contaminated effluents [50]. Nutrient uptake efficiency is also higher in hydroponic systems when favourable conditions prevent nutrient excess. This saves water by reducing the eutrophication of nearby ecosystems that trigger algal blooms and dead zones. By scaling vertically, facilities can co-locate food production near urban centres, minimizing transportation miles and spoilage losses. LEDs tailored to drive photosynthesis cut electricity use, while renewable energy integration further shrinks the ecological footprint [49].

2.4 Higher Yield Rates in Hydroponics

Hydroponic systems significantly outperform conventional agricultural practices for most produce categories regarding growth speed, harvest size, and yearly output consistency. Controlled settings enable optimization of various yield-influencing factors while circumventing risks from variable outdoor conditions.

2.5 Faster Growth Cycles and Year-Round Production

Plants cultivated via hydroponics commonly reach maturity 30-50% quicker than soil-grown equivalents [46]. Accelerated development results from the stabilized delivery of tailored nutrient solutions directly to root zones rather than needing to diffuse from the ground. Suspended root structures also enjoy ample air exposure and space for increased growth.

Freed from seasonal changes, protected hydroponic operations can churn out rapid-cycling crops year-round rather than just spring/summer [47]. Greenhouses allow adjustment of environmental variables to mimic optimal outdoor growing periods. In colder months, supplemental lighting substitutes for sunlight while heating maintains ideal temperatures for continued plant processes.

2.6 Optimal and Stable Growing Environments

While open-field farms experience fluctuating conditions with associated yield variability, hydroponics enables precise control over critical environmental factors [48]:

- **Solution chemistry:** Careful monitoring and adjusting of nutrient and oxygen levels, pH, etc ensures availability for uptake.
- **Water:** Programmed irrigation cycles provide ideal moisture with zero wasted excess.
- **Light**: Artificial lighting supplements and extends daily exposure periods compared to sunlight only.
- **Air temp/humidity:** Desired setpoints are maintained to balance growth and disease prevention.

Automated systems rapidly respond to data from sensors to keep parameters within target ranges for each crop phase. Enclosed structures exclude external climate and weather events from impacting crops like excess rain, wind, hail, frost, etc.

2.7 Enhanced Light, Temperature and Humidity Control

Photosynthesis drives biomass accumulation and fruiting in plants via conversion of light energy, water and CO2 into carbohydrates and oxygen. Hydroponic operations bolster light exposure through closer-spaced planting, reflectors, artificial lighting, and transparent coverings [50]. Customizable spectral outputs from LEDs or plasma lamps provide lighting optimized for every crop growth phase.

Monitoring systems maintain optimal day/night temperature curves matched to each plant species in hydroponic units. Humidity is similarly controlled through venting and misters to balance growth versus disease proliferation. Tight regulation of all three parameters synergistically fosters sizable performance gains compared to variable outdoor climates.

The combination of stabilized environmental conditions, precision delivery of tailored nutrient solutions directly to roots, and extended annual production enables hydroponic systems to reliably achieve substantially higher yields than soil-based methods for most produce types. With ample growing room capacity and sufficient lighting systems, hydroponic operations can greatly bolster local crop output levels within urban centers or remote areas to enhance food security.

2.8 Improved Quality and Food Safety

Hydroponic production within fully enclosed and monitored structures enables superior fruit, vegetable and herb quality compared to field cultivation. Preventing air and pest entry combined with precision control over growing conditions reduces risks of microbial contamination, toxins, and damage to crops.

2.9 Clean and Controlled Conditions

Open farming faces uncontrollable exposure to air pollutants as well as erratic weather that facilitates the spread of mold, fungi and bacterial plant pathogens [51]. Rain splash is responsible for dispersing over 50% of infections from initial infection sites [52]. Meanwhile, hydroponic greenhouse or warehouse settings prevent pathogen entry and dispersion factors, creating near-sterile growing environments.

Table 5. Average increase in harvest size achievable via hydroponics vs soil farming

Crops	Yield Increase
Lettuce	70-80% more
Cucumbers	25-30% more
Peppers	30-50% more
Tomatoes	25-30% more
Potatoes	25-30% more

Source: [49]

Table 6. Key quality and safety advantages in hydroponics vs soil-based farming

Factor	Effect
Controlled settings	Block air/water pollutants, pests, and weather variables
Isolated crop growth	Greatly reduces microbial and pest contamination routes
Pure nutrient solutions	Eliminate soil-borne pathogens and weeds
Advanced IPM options	Layered physical, biological and tactical controls

Table 7. Hydroponic Crop Yields from a 3’x3’ Grow Space

Crops	Annual Yield
Lettuce	90-100 heads
Herbs	20-30 lbs
Strawberries	30-40 lbs
Tomatoes	35-50 lbs
Peppers	25-40 lbs
Cucumbers	25-40 lbs

Fig. 3. Improved light exposure for indoor hydroponic vs open-field plants
Source: [50]

Purified or sterilized nutrient solutions flowing directly to roots also essentially eliminate soil-borne diseases and weed seed issues. Rooftop gardens avoid risks associated with tainted runoff or groundwater from industrial processes. Isolation from outside conditions prevents produce defects like superficial scarring, irregular ripening and internal tissue deterioration.

2.10 Reduced Microbial Contaminations

Incidence rates of dangerous bacterial contaminations like Salmonella and E. coli are up to 100 x lower on hydroponically versus conventionally grown produce as microbes chiefly originate from fecal matter contacting plants in fields [53]. Wildlife intrusions, livestock grazing nearby, inadequately composted manures, and runoff from concentrated animal feeding operations all elevate risks. Hydroponics thus bolsters safety for raw consumption of items like leafy greens.

Without variable weather, pest entries or soil dynamics enabling viral and bacterial spread, hydroponics facilitates safer growing conditions. Lower and more targeted application rates of pesticides/fungicides also minimize chemical residues in harvests compared to soil releases [54]. Receiving constant optimal moisture and nutrients further elevates crop quality.

2.11 Ability to Implement Superior IPM Practices

The enclosed nature of hydroponics enables growers to establish multi-tiered integrated pest management (IPM) regimens superior to outdoor options [55]. Physical isolation methods like greenhouse screening and air filters block pests. Entry points can be protected with strip curtains, vacuum chambers, positive air pressure and rigorous sanitation protocols.

Biological control agents like predator/parasite species can safely be introduced without environmental exposure/escape risks. Beneficial insect auxiliaries eliminate pests while avoiding pesticide usage or resistance. Targeted fumigants or traps supplement natural methods with minimal chemical inputs overall [56]. Crops also can complete entire life cycles free of pest damage rather than facing sequential exposure risks. Preventive tactics spare the need for therapeutic pesticide interventions that leave residual contamination. Implementing this spectrum IPM techniques fosters exceptionally high harvest quality and safety unmatched in field production.

2.12 Indoor Vertical Farming Systems

Indoor vertical farming refers to the cultivation of produce in vertically stacked layers within structures like warehouses, shipping containers or repurposed buildings. Instead of expanding horizontally across acres of land, crops grow upwards in a compact facility outfitted with advanced technologies for optimization. This agricultural approach integrates controlled environment agriculture (CEA) with renewable energy systems and precision feeding. By co-locating food production near cities, it minimizes food miles while recycling resources to shrink environmental footprints [57-58].

2.13 Stacking Methods and Controlled Environments [59]

Vertical farming facilities utilize vertical space through stacking methods that make efficient use of the site’s footprint. Common configurations include [60]:

- Racking systems with horizontal growing beds arranged vertically.
- Tower systems with plants arranged on vertical panels or suspended fabric.
- Vertical conveyor belts cycling plants through an enclosure.
- Stackable shipping containers serving as modular growing units.

Controlled environment agriculture (CEA) technologies enable precise regulation over growing conditions year-round [61]:

Lighting: LED fixtures are tailored to photometric and duration needs.
Climate: HVAC systems maintain optimal air temperature, humidity and ventilation.
Nutrition: Hydroponic, aeroponic or aquaponic systems deliver water and nutrients automatically.
Automation: Smart sensors monitor crops and growing parameters to enable rapid responses.

By moving food production into indoor environments safeguarded from contaminants, pathogens and climate fluctuations, reliable yields can be sustained with speed and precision [62].

2.14 Integration of Renewable Energies [63]

Indoor vertical farms aim for net-zero or positive energy systems, generating as much or more clean power than they consume. Renewable systems are integrated into facilities, including [64]:

- **Solar PV:** roof panels or nearby ground arrays
- **Wind turbines:** mounted onsite or offsite to divert excess grid power
- **Biofuels:** from food waste fed into anaerobic digesters
- **Geothermal:** subsurface heat pumps that provide HVAC needs

Excess heat and carbon dioxide from renewable systems may also be captured for plant growth stimulation. Insulated building materials, daylighting designs, and energy-efficient LEDs further shrink the power draw [65].

2.15 Waste Reduction and Resource Recycling [66]

Indoor vertical farms employ circular economies to recapture and reuse resources. Key recycling initiatives include:

2.15.1 Water

- Closed-loop irrigation with collected rainwater or municipal wastewater.
- Condensate capture and nutrient solution recycling.

2.15.2 Nutrients

- Aquaponic systems extract nutrients from fish farm effluent.
- Precision dosing prevents excess discharge.

2.15.3 Waste streams

- Inedible biomass gets composted or digested for energy.
- Anaerobic digestion recycles food waste into fuels and fertilizers.

Overall, the combination of renewable energy and circular resource flows minimizes the ecological footprints of vertical farming systems [67].

2.16 Potential Sites in Urban Areas and Non-Arable Lands [68]

The compact footprint of vertical farms suits them for locations in or close to cities, situating production right where demand is concentrated. Urban sites include [69]:

- Abandoned factories, warehouses and commercial spaces.
- Underutilized lots between buildings.
- Rooftops of supermarkets, hospitals and transport hubs.

Moving farming away from remote rural regions toward population centers slashes food miles for fresher produce with less transport energy. Indoor conditions also enable previously non-arable land unusable for conventional agriculture to begin contributing food yields [70]. Marginal sites like deserts and cold northern regions can support vertical farms. Even floating barges offer mobile farming solutions where land is extremely limited [71].

2.17 Rooftop and Small-Scale Hydroponics

Hydroponics is the method of growing plants without soil, using mineral nutrient solutions in a water solvent. Terrestrial plants may be grown with only their roots exposed to the mineral solution, or the roots may be supported by an inert medium such as perlite, gravel, or other substrates [72]. The nutrients used in hydroponic systems can come from an array of different sources including, but not limited to, byproducts from fish waste, duck manure, or purchased minerals.

Compared to conventional agriculture, hydroponics allows growers to have greater control over nutrient delivery, light, air composition, water, and other environmental conditions. This can lead to higher yields, faster growth, the ability to grow in non-arable land, less water usage, no need for pesticides from soil borne insects/pathogens, and less labor for weeding and soil maintenance [73]. Hydroponics is also well suited for urban agriculture and growing food much closer to consumers, reducing transportation costs and fossil fuel usage.

2.18 Accessible Hydroponic Kits and Compact Systems

There has been increasing popularity and availability of small hydroponic units designed for rooftops, patios, balconies, and other modest spaces [74]. Many companies sell full hydroponic kits with basic ‘plug and play’ functionality that are affordable and easy to operate for home growers and hobbyists. These systems come with simple instructions and often have small footprints facilitating production in unused outdoor or indoor spaces.

Some examples of compact hydroponic systems include:

Tabletop Systems: These small units sit directly on a patio/balcony table and can grow a handful of lettuce heads or herbs. Prices typically range from $50 to $150.

Vertical Towers: Vertical hydroponic towers utilize vertical space by stacking grow sites on top of one another. This increases yield and saves floorspace. Standing between 3 to 5 feet tall, they are an excellent choice for patios and balconies.

Wall Mounted Racks: By mounting racks of hydroponic grow sites on walls, the floorspace usage is minimized. Grow lights can also be mounted above wall systems.

Raised Beds and Benches: For larger spaces there are raised bed systems and hydroponic benches which accommodate bigger and/or greater quantities of plants.

Indoor Grow Cabinets: For unused indoor spaces, there are indoor hydroponic grow cabinets and rooms of varying sizes. These have climate control and grow lights integrated for completely self-contained, indoor food production.

By utilizing vertical space and having compact footprints, even a small apartment patio or balcony can produce substantial yields to supplement a family’s vegetable needs. For urban residents with no outdoor space, indoor hydroponic systems provide a convenient solution as well.

Table 7 shows some of the crop yields possible with a modest home hydroponic system.

The variety of compact systems on the market makes hydroponics accessible and scalable for both hobby and commercial growers alike. Whether starting with a small tabletop unit or graduating to a fully climate controlled grow room, the flexibility of these systems enables step-wise adoption for almost any budget. Their small footprints also unlock unused spaces in homes, offices, restaurants, and community spaces for localized food production.

2.19 Localized Food Production and Self-Sufficiency

In addition to individual households benefiting from compact hydroponic units, community-oriented agriculture initiatives can also utilize these systems to convert unused urban spaces into food production areas. Transforming vacant lots, abandoned buildings, sidewalks, rooftops, and other underutilized infrastructure creates opportunities for education, job skills training, food security for underserved groups, and community building [75].

Some examples of localized food production using small-scale hydroponics include:

Congregational Gardens: Places of worship such as churches, temples, and mosques can install compact hydroponic systems to supplement their food banks and pantries for the surrounding neighborhood [76]. These provide fresh, nutritious options beyond non-perishable items.

Neighborhood Grow Hubs: Retrofitting shipping containers, tiny houses, sheds, multi-story warehouses and other structures to function as hydroponic vertical farms. These can be dispersed throughout neighborhoods and operated by local residents, providing food and jobs.

Balcony Cooperatives: Participating building tenants dedicate a portion of their personal balcony/patio space for a jointly managed hydroponic garden, with shared maintenance duties and crop yields. This also encourages community bonding.

Restaurants & Grocerants: The enhanced productivity of hydroponics makes it feasible for urban restaurants and specialty grocers to grow their own ingredients on premises. Customers connect more deeply to the dining experience knowing their food was grown steps away.

Office Perks: Hydroponic systems can provide companies with a way to produce ultra-local food for their cafeterias. For technology companies, having office farms also serves as an innovation showcase.

Localized food systems reduce distribution distances between the farm and consumer's plate. Minimizing transportation lowers food costs due to less handling, storage, and fuel usage. Growers can also opt for higher pricing based on the premium quality of freshly harvested, vine/stem-ripened crops. Furthermore, lower distribution miles shrinks the overall environmental footprint of each item produced.

Community oriented agriculture strengthens social cohesion and self-reliance. It provides opportunities for meaningful work, education, and addressing local nutritional deficiencies. Compact hydroponic kits and systems make all of this possible, even in space limited urban locations.

2.20 Applications in Urban Agriculture and Home Gardens

Innovations in LED grow lights, renewable energy, IoT sensors, and monitoring software provide advanced capabilities for controlled environment agriculture. Much of this technology is now economical and user friendly enough for adoption by hobby growers rather than just commercial operators. These latest tools and automation allow urban farmers of all scales to maximize productivity in confined spaces [77].

Some specific applications of emerging technologies for small urban farms include:

Optimized Light Recipes: New LED fixtures provide precise control over the light spectrum, intensity and duration given to plants. Matching these light recipes to the growth stage and morphology of each variety maximizes yields.

Renewable Energy: Solar panels, small wind turbines, and energy storage systems allow self-contained renewable power for supplemental grow lights and system operation. This increases resiliency while reducing environmental impact.

Climate Integration: Smart controllers unify the management of lighting, humidity, CO2 injection, nutrient dosing, pH balancing, and other environmental optimizations through data algorithms tailored to each crop.

Vertical Integration: Multi-level and multi-variety crop production is made simpler through integrated automation across vertically stacked grow sites. Sophisticated food production occurs efficiently even with limited horizontal space.

Crop Monitoring & Harvesting: Internet connected sensors periodically measure key parameters like moisture levels, EC, pH, plant coloration, leaf temperature, fruit size, etc. This data feeds into machine learning algorithms which determine ripeness and send crop advisories to garden managers. Remote crop monitoring enables timely harvesting.

The latest tools provide both commercial-scale efficiency as well as user friendliness for ordinary citizens. Hydroponic kits designed for patios, rooftops, windowsills and countertops now contain many of the same technologies used in large indoor vertical farms. Automation handles much of the horticultural complexity, while Apps provide guidance and notifications to the everyday grower. This empowers urban farmers of all skill levels to produce abundant, nutritional food.

Home and community gardens can also take advantage of these solutions to make gardening more productive and enjoyable. Enriching neighborhood green spaces with beautiful and functional hydroponic gardens creates positive environmental and social change from the ground up. When existing infrastructure and unused spaces are repurposed for agriculture, cities can overcome many bureaucratic and zoning hurdles typical of large scale urban farming initiatives [78]. Rooftop and small container gardens are more feasible starting points to demonstrate benefits before expanding to larger buildings and acreage.

Table 8 highlights some of the crop-specific advantages enabled through precision agriculture technologies, applicable for both commercial and hobby systems.

Whether on an urban rooftop or backyard patio, integrating smart hydroponics enables home growers to sustainably harvest higher yields, better nutrition, and superior flavor. Sharing extra produce across community and congregational networks further spreads the social benefits locally. Over time, multiplying these small-scale gardens across cities accrues into major progress around issues of food security, resiliency, justice, nutrition, and ecological regeneration.

Table 8. Advantages of Precision Agriculture Technologies

Crops	Key Benefits
Lettuce & Leafy Greens	Optimized light spectra, automated harvesting based on leaf maturity
Herbs & Microgreens	Dialed-in climates maximize flavor & nutrition compounds
Strawberries	Machine vision identifies prime ripeness for sweetness
Tomatoes & Peppers	Monitor fruit size and color for ideal vine ripeness
Cucumbers & Squash	Targeted humidity and foliar sprays prevent diseases
Peas & Beans	Precise climates extend flowering and increase pod sets
Radishes & Carrots	Dial in flavor profiles based on real time root scans
Fresh Fish & Shrimp	Real time water quality optimization reduces mortality

Table 9. Learning Outcomes with Community Hydroponics

Domain	Key Learning Outcomes
Plant Biology	Germination stages, tropisms, photosynthesis process
Technical Skills	Measurement, construction, programming, troubleshooting
Food Origins	Requirements to yield fruits/vegetables, timescales
Nutrition	Identifying plant parts, bioactive ingredients
Environmental Cycles	Capturing solar energy, producing oxygen

Table 10. Desert Community Challenges Addressed by Hydroponics

Challenge	Hydroponic Solution
Non-arable soils	Soilless systems
Low precipitation	Water recirculation
Extreme heat	Indoor climate control

Table 11. Commercial Hydroponic Farm Models

Model	Scale Context	Crops
Urban Vertical Farms	Repurposed warehouses	Leafy greens, herbs
Rooftop Greenhouses	Atop stores and buildings	Tomatoes, cucumbers, peppers
Container Farms	Stackable mobile units	High value berries, microgreens
Facility Aggregation	Co-located growers around infrastructure	Ornamental flowers, hemp

The innovations lowering costs and complexity of controlled environment agriculture are creating on-ramps for newcomers to participate. As more people experiment with compact hydroponics to grow their own food, they become empowered contributors to regional food system transformation. Enabling ordinary citizens to meaningfully impact complex systemic issues like sustainability and self-reliance is the deeper promise of precision agriculture. The local food movement is strengthened when families, friends and neighbors each play a small role in growing the larger food ecology surrounding them. Cities filled with edible gardens on window sills, balconies, patios, rooftops, and greenspaces provide infinitesimal pieces adding up to major change.

2.21 Community Outreach Initiatives

Hydroponic systems provide opportunities to engage communities in agricultural experiences right in their neighborhoods through community gardens at schools, clinics, libraries and recreation centers. These onsite gardens serve as interactive education platforms for experiential learning. By operating small-scale hydroponics, people gain first-hand skills while connecting plant growth to nutrition and environmental concepts [78-79]. Local facilities essentially become empowered community centers for knowledge sharing around food production.

2.22 Hydroponic Gardens at Schools and Community Centers [80]

Installing compact hydroponic units at local institutions like schools and community hubs builds community connections to agriculture. Teachers, students, patients, and visitors can observe plant development cycles directly within buildings as an immersive learning feature [81]. Typical implementation models include:

School gardens: Outdoor raised hydroponic beds or indoor growing walls in hallways and classrooms give students direct access and responsibility over crops.

Therapy gardens: Produce grown hydroponically provides healthy snacks for patients while the gardening engages motor skills.

Library gardens: Public libraries incorporate demonstration hydroponic systems into community programming for skill building.

Community center gardens: On-site gardens supply local pantries and meals programs with fresh vegetables while serving as gathering spaces [82].

2.23 Experiential Learning and Skill Building [83]

Hydroponic installations at community sites become platforms for interactive education through experience-based learning. Key opportunities include:

Plant biology: Observe first-hand how seeds germinate and environmental factors influence growth.

Technology skills: Engage with monitoring sensors, control systems and aquatic chemistry.

Food origins: Gain appreciation for the land, water and care required to bear fruit.

Nutrition connections: Harvest produce for community meals and connect plant compounds to health.

Environmental cycles: Understand photosynthesis as means of renewable energy capture and oxygen generation [84].

These domains foster broad interdisciplinary comprehension spanning science, ecology and community development [85].

2.24 Connecting People to Agriculture and Nutrition [86]

On-site community hydroponic gardens provide the public access to observe agriculture first-hand to gain understanding. Key connections made include:

Farming methods: Experience modern soilless approaches and controlled techniques.

Food sourcing: Grow ingredients for local kitchens to see “farm-to-table”.

Nutritional value: Compare tastes and qualities among cultivars.

Ecological cycles: Witness interdependencies between plants, water, and energy.

Technology integration: See automation and mechanization in action.

These direct links from “seed to feed” re-establish relationships between people and food disconnected by modern supply chains [87]. There is no replacement for personally growing and eating a vegetable yourself from start to finish. The hands-on cultivation empowerment renews community bonds.

2.25 Hydroponics in Challenging Environments

Hydroponic farming methods are uniquely suited for establishing resilient food production in challenging contexts from arid deserts to regions struck by disasters. Soilless systems circumvent many harsh environmental conditions that would suppress conventional crop yields. Their controlled indoor settings and precision delivery of water and nutrients can sustain yields even amidst droughts or limited arable land [89-90]. Just as hydroponics transforms non-arable building interiors into thriving farms, it can cultivate liveable solutions providing nutritional support otherwise lacking.

2.26 Food Security Solutions for Arid, Desert Communities [91]

Many communities reside in hot, arid regions with minimal precipitation unable to support most traditional agriculture. However, hydroponic systems can sidestep common desert restraints to supply nutritional needs [92]:

Lack of arable soil: Hydroponics requires no soil, circumventing infertility issues.

Water scarcity: Water recirculation with low loss enables precise use.

Extreme heat: Indoor climate control maintains optimal temperate conditions.

With solar renewable systems powering the small footprint farms, compact hydroponic units integrated into communities can provide essential access to fresh produce amidst desert climates [93].

2.27 Post-Disaster Food Production and Emergency Preparedness [94]

Following disruptive natural disasters like floods, hurricanes or fires, hydroponic modules can provide stopgap nutritional support until regional agriculture recovers. Benefits as emergency food systems include:

Rapid deployment: Mobile, stackable container units are transported quickly.

Off-grid operation: Self-contained renewable systems allow independence.

All-weather production: Enclosed conditions prevent external exposure.

Stable yields: Steady, optimized growth sustains output.

These productive oases stabilize community health during the volatile recovery and rebuilding in a disaster's aftermath. Past emergencies where hydroponics provided urgent food access include desert refugee camps and communities isolated by earthquakes [95].

2.28 Resilient Agriculture and Climate Adaptation [96]

As climate change intensifies extreme weather events and temperature variability, traditional agriculture struggles with unpredictable impacts. Hydroponics' controlled settings buffer crops from external climate variations for consistent output. Key resilience features adapting to climate flux include [97]:

- **Enclosed stable conditions:** enable precisely optimized growing parameters for each crop.
- **Reduced water usage:** through recirculation sustains yields amidst droughts.
- **Decentralized modularity:** allows incremental expansion to match needs and mitigate localized losses.

With farmlands increasingly vulnerable to uncertain seasonal changes, hydroponics offers adaptive relief valves bolstering community food security. Islands threatened by rising seas can adopt the soilless systems using minimal land [98].

2.29 Economics and Scalability of Hydroponics [100]

As hydroponic farming methods deliver higher, more reliable yields than conventional agriculture while using fewer inputs, their operational costs are lower per unit of produce grown. These economic savings combined with hydroponics' modular scalability enable commercially viable expansion to help meet rising food demands. However, investments into supportive infrastructure, distribution networks, and technological improvements are still needed to drive widespread adoption [101].

2.30 Reduced Production Costs and Stable Yields [102]

By precisely controlling growing conditions and nutrient availability within recirculating water systems, hydroponics can achieve higher yields per hectare using fewer inputs than soil farming. Key economic advantages include:

Higher productivity: Optimal indoor parameters accelerate growth rates and dense spacing [103].

Lower labor costs: Automation replaces certain sowing, weeding and harvesting tasks [104].

Reduced water/fertilizer: Recycled nutrient solutions minimize input needs [105].

Year-round production: Enclosed systems permit continual harvests unaffected by seasons [106].

Minimized crop losses: Protected conditions prevent pests, disease and weather damage [107].

These compounding benefits make hydroponics approximately 30-50% more cost effective for the same produce poundage compared to traditional farming [108].

2.31 Expanding Commercial Scale Operations [109]

While small hydroponic systems have supplied restaurants and niche retailers for decades, full-scale commercial farms are now expanding outputs to wholesale markets. Key expansions underway include:

- **Logistics networks** – Distributing produce from indoor urban farms to mass grocers [110].
- **Enterprise financing** – Venture capital and bonds supporting large facilities [111].
- **Regional specialization** – Clustering infrastructure around dedicated crop niches [112].
- **Public sector partnerships** – Co-developing municipal greenhouse zones [113].

These industrial-scale ventures aim to establish long-term profits leveraging hydroponics' advantages as investments outpace conventional farmlands [114].

2.32 Investments Needed in Supportive Growth [115]

Reaching the full potential of commercial hydroponics requires further development across several domains:

Technological improvements: Innovations in automation, renewable energy systems, LED lighting, and data analytics to improve crop quality, speed, and cost efficiencies [116].

Infrastructure expansion: Building enclosed farms and distribution capacity tailored to regional contexts [117].

Workforce training: Cultivating labor talent across plant science, engineering, software, and business functions [118].

Financial incentives: Government subsidies and private financing to stimulate entrepreneurship [119].

Though promising, hydroponic systems require significant continued investment to make the methods scalable fixtures providing food security for future generations [120].

2.33 Current Status and Adoption Rates of Hydroponics

Hydroponics is the method of growing plants without soil, using mineral nutrient solutions in an aquatic environment. Hydroponics is being increasingly adopted as it offers several advantages over traditional soil-based agriculture such as faster growth, higher yields, less water usage, and control over nutrients provided to plants.

2.34 Geographic Regions with Most Hydroponic Installations

Some of the leading regions utilizing hydroponic systems include:

- **Europe:** The Netherlands, Spain and France have large areas dedicated to hydroponic greenhouse farming, mainly for tomatoes, cucumbers and lettuce. The Netherlands has over 4,000 hydroponic farms.
- **North America:** Canada, Mexico and the United States have seen rapid growth in hydroponics in recent years driven by technological improvements. Canada leads adoption in vertical farming using hydroponics.
- **Asia:** China, India, Indonesia, Japan and Singapore have government support and investments in hydroponic farming. South Korea and Japan also have advanced hydroponic plantation infrastructure.
- **Middle East:** Countries such as UAE and Qatar are investing in hydroponics to enhance food security. UAE has some of the largest commercial hydroponic farms.
- **Australia:** High-tech hydroponic farms have emerged across major cities over the past decade, mainly focused on lettuce and herbs.

2.35 Challenges Limiting Wider Implementation

Some key barriers to broader hydroponic adoption globally include:

- High upfront installation costs for hydroponic infrastructure and technology.
- Lack of expertise and technical skills to operate complex hydroponic systems.
- Inadequate research and access to affordable equipment, especially in developing countries.
- Limited support from governments in the form of licensing, funding and incentive policies.
- Stigma associated with produce grown without soil among some consumer segments.

2.36 Cultural Perceptions and Misconceptions

There are some prevalent misconceptions regarding hydroponically grown food:

- That it lacks the full flavor or is not natural - In reality, scientifically controlled nutrients fed to root systems result in consistent and often superior taste compared to soil-grown crops.
- That it lacks minerals - Plants obtain the same or higher mineral levels, as nutrient solutions are carefully formulated to deliver optimum quantities.
- That there are health risks - There are no proven risks from eating hydroponically grown produce, and in fact nutrition levels can be higher.

2.37 Government Policies and Proposed Legislation

Hydroponics is still an emerging industry globally and policies as well as legislation governing it are still evolving. There is a lack of targeted government interventions and overarching regulatory frameworks in most countries presently (Singh & Kaur, 2022). Key global and India-specific initiatives include:

2.38 Global Perspective

2.38.1 Lobbying efforts and advocacy

- International groups like the Global Forum on Agricultural Research (GFAR) advocate for more investments and reforms supporting non-traditional farming methods including hydroponics (Mondot, Lopez-Lauri, & Sallanon, 2019).
- Associations such as American Society of Agronomy (ASA) lobby governments for funds, pilot projects and regulatory initiatives promoting hydroponic adoption (Foo & Alkolaibe, 2021).
- Private companies like BrightFarms actively campaign for hydroponics R&D funding and grants from organizations like Sundrop Farms (Singh & Kaur, 2022).

2.38.2 Tax incentives and grant programs

- Canada and Australia have government tax incentive schemes for hydroponic business purchases [127].
- The Netherlands provides energy tax relief for hydroponic greenhouse operations and input purchases [128].
- The European Commission's Horizon 2020 program offers research and innovation grants focused on sustainable food production including hydroponic vertical farming systems [129].

2.38.3 Standards and oversight

- Global G.A.P. certification system includes standards for hydroponically grown produce including food safety, environmental and crop protection criteria [130].
- Australia's Produce Safety Framework provides national coordination around fresh food safety risks applicable to hydroponic growers[131].

2.39 India Perspective

2.39.1 Lobbying and advocacy efforts

- The South India Growers Association (SIGA) actively lobbies the government for policies to promote greenhouse protected cultivation using hydroponics and aeroponics [132].
- Associations such as the Federation for Horticulture Sector in India (HOSI) advocates regulatory support for hi-tech farming technologies including hydroponics [133].

2.39.2 Tax incentives and grant programs

- India provides subsidies of 50-90% for promotion of hi-tech farming methods like hydroponics, aeroponics and aquaponics through programmes like Mission for Integrated Development of Horticulture (MIDH) [134].

2.39.3 Standards and oversight

- BIS Group operates technical committees aiming to develop national quality standards for hydroponic produce and growing systems [135].
- Food Safety and Standards Authority of India (FSSAI) set up expert panels in 2022 to formulate regulation policies and guidance for fresh produce including hydroponic crops [136].

3. RESULTS

Precision agriculture technologies have shown significant benefits for enhancing sustainable crop production globally as well as in the India context specifically.

3.1 Global Perspective

1. Use of sensor-based monitoring and automated irrigation systems have been found to reduce water usage by up to 40% while increasing crop yields by 5-15% for major grain crops [138]. Similar water savings paired with yield improvements have been achieved through variable rate irrigation based on remote sensing maps [139].
2. Multi-hybrid planting technologies enabling tailored seed varieties for microclimate conditions within fields can improve yields for maize and soybean by over 5% [140]. This approach also promotes crop diversity and resilience.
3. Weed control through machine vision-enabled robotic weeders reduces herbicide usage by 80-90% while lowering labor requirements [141]. Manual weeding is decreased to only 5% of total needs.
4. Deployment of numerous low-cost wireless soil moisture sensors across fields linked to a cloud-based irrigation automation system cut water usage by 20-25% [142]. This allowed preventing overwatering and conserved pumping energy.

3.2 India Perspective

5. Small and marginal farmers adopting automated plant health monitoring and pest warning systems saw 10-15% higher yields and 50% reduction in pesticide usage for tomato and potato crops [143].
6. Integrating humidity and soil moisture sensors with Indigenous Internet of Things (IIoT) gateways and machine learning models increased grape yield by 8-12% while lowering fungicide usage [144].
7. Automated direct fertilizer injection into irrigation waters (fertigation) optimized for local soil variances boosted vegetable yields by 30% while decreasing fertilizer usage also by 30% [145].
8. Drone-based remote sensing and spectrographic analysis paired with a crop growth model led to the creation of customized nitrogen application maps for wheat. This precision fertilization reduced nitrogen use by 25kg/ha while increasing yields 4-6% [146].

4. DISCUSSION

The results clearly demonstrate the potential of emerging precision agriculture approaches to significantly transform crop production systems globally as well as in India towards more sustainable and climate-smart agricultural models.

Key innovations in sensing, data analytics and automation enable precise monitoring of field, crop and environmental parameters to customize interventions, detect stresses early and model future outcomes [147,148]. Instead of habitual calendar-based schedules, precise insights can trigger informed just-in-time actions [149].

Technologies like AI, drones and robotics further augment and amplify the capabilities from precision equipment and practices [150]. They can take over tedious, unsafe and unskilled tasks while leaving farmers to focus on supervision and higher-level decision making [151].

System-wide optimization rather than isolated improvements is also a pivotal aspect underpinning the sustainability benefits across dimensions of productivity, economics, environment and communities [152,153]. This stems from the integrated milieu created by converging digital and physical agricultural worlds [154].

However several barriers related to costs, technical skills, infrastructure and fragmented land holdings constrain widespread precision agriculture adoption in India [155]. Targeted governmental support programs in terms of training, subsidies and promotion of frugal innovation can assist broader reception [156]. Leasing equipment on pay-per-use terms and community farming models also provide implementation pathways for smallholders [157].

4.1 Future Directions and Technological Innovations

Significant advances and innovations in hydroponic systems are expected in coming years across following aspects:

4.1.1 Novel hydroponic techniques and automation

- Development of movable hydroponic grow modules allowing flexibility in cropping [121].
- Commercialization of floating hydroponics enabling crops to be grown on water bodies [122].

- Integration of AI and robotics for automated monitoring and control of hydroponic farms [123].

4.1.2 Incorporation of renewable energies and biocontrols

- Scaling up of solar renewable energy systems to power hydroponic installations, reducing carbon footprint [124].
- Increased usage of biopesticides and organic nutrient sources for more sustainable hydroponic production [125].
- Testing of integrated aquaponic systems to recycle water and utilize fish waste as crop nutrients [126].

4.1.3 Development of new adapted crop varieties

- Breeding and gene-editing initiatives to develop plant varieties optimized for soilless culture [121].
- Programs targeted at enhancing the nutritional profile and flavor of hydroponically grown produce [122].
- Research to identify and domesticate new species amenable to hydroponic cultivation [123].

5. CONCLUSIONS

Hydroponics has emerged as a viable complementary farming approach to traditional soil-based agriculture and has the potential to enhance global food security. Some major points are:

- Hydroponics allows cultivation in non-arable areas not suitable for conventional farming and increases productivity per unit land and water used (summarize key benefits).
- Leading application areas are lettuce and leafy greens, tomatoes, peppers, cucumbers and herbs based on suitability and profit margins (summarize major crops).
- Europe and North America lead adoption driven by technological advances and commercial investments (geographic adoption patterns).
- Greater regulatory support, R&D funding and customized infrastructure can promote wider implementation (key future needs).

5.1 Hydroponics as a Sustainable Strategy for Future Food Security

With rising global populations and constraints on land and water resources, hydroponics can be a sustainable strategy to complement traditional agriculture. Benefits include no soil erosion, reduced water usage, ability to optimize and recycle nutrients, and higher yield potential. Continued technological innovations and creative integrations with vertical farming, renewable energies and biocontrols can further enhance the environmental sustainability of hydroponic farming.

5.2 Recommendations for Further Research and Investments

More public and private investments into the following domains can help hydroponics realize its full disruptive potential:

- Development of cheaper and decentralized hydroponic kits and equipment.
- Optimizing energy efficiency, renewable integrations and resource recycling mechanisms.
- Breeding next-generation plant varieties tailored for soilless systems.
- Expanding technology transfer and technical skills training, especially for developing countries.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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