Review Article

A Comparative Analysis of Land, Water, and Energy Requirements for Hydroponic and Conventional Cultivation of Horticultural Crops

Abstract:

The increasing global population and limited availability of arable land have ~~necessitated~~ required the development of efficient and sustainable agricultural practices. Hydroponic cultivation has emerged as a promising alternative to conventional soil-based farming, particularly for horticultural crops. This ~~review paper~~revision presents a comprehensive comparative analysis of the land, water, and energy requirements for hydroponic and conventional cultivation methods. The study aims to evaluate the sustainability and resource efficiency of these two approaches in the context of horticultural crop production. A thorough literature review was conducted, focusing on peer-reviewed articles, research reports, and case studies that compared hydroponic and conventional cultivation in terms of their resource utilization. The analysis encompassed various horticultural crops, including leafy greens, fruiting vegetables, and herbs. Key parameters such as land use efficiency, water consumption, nutrient management, energy inputs, and yield were examined.

The findings revealed that hydroponic systems exhibited significantly higher land use efficiency compared to conventional farming. Vertical stacking and intensive production in controlled environments allowed for greater crop yields per unit area. Furthermore, hydroponic cultivation demonstrated superior water use efficiency, with recirculating systems reducing water consumption by up to 90% compared to traditional irrigation methods. Precision nutrient management in hydroponics minimized nutrient waste and runoff, contributing to enhanced resource conservation. However, the energy requirements for hydroponic cultivation were found to be higher than those for conventional farming, primarily due to the need for artificial lighting, climate control, and pumping systems. Strategies for optimizing energy efficiency, such as the use of renewable energy sources and energy-efficient equipment, were explored.

Keywords: Hydroponics, Conventional Farming, Resource Efficiency, Sustainability, Horticultural Crops

1. Introduction

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The global population is projected to reach 9.7 billion by 2050, posing significant challenges for food security and agricultural sustainability [1]. Conventional soil-based farming has been the dominant agricultural practice for centuries, but it faces limitations in terms of land availability, water scarcity, and environmental degradation [2]. Hydroponic cultivation has emerged as a promising alternative, offering the potential for efficient resource utilization and sustainable crop production [3]. Hydroponic systems involve growing plants without soil, using nutrient-rich solutions to support plant growth [4]. This method allows for precise control over the growing environment, enabling optimized nutrient delivery, water management, and climate regulation [5]. Hydroponic cultivation has gained popularity in recent years, particularly for the production of horticultural crops such as leafy greens, herbs, and fruiting vegetables [6].

The primary objective of this review paper is to conduct a comparative analysis of the land, water, and energy requirements for hydroponic and conventional cultivation of horticultural crops. By examining the resource efficiency and sustainability aspects of these two approaches, this study aims to provide valuable insights for researchers, policymakers, and practitioners in the field of agriculture.

The specific objectives of this review are as follows:

1. To evaluate the land use efficiency of hydroponic and conventional cultivation methods for horticultural crops.
2. To assess the water consumption and water use efficiency of hydroponic and conventional farming practices.
3. To compare the energy requirements and energy efficiency of hydroponic and conventional cultivation systems.
4. To identify the advantages, challenges, and opportunities associated with hydroponic cultivation in terms of resource utilization and sustainability.
5. To provide recommendations for future research and development in the field of hydroponic cultivation for horticultural crops.

2. Methodology

2.1. Literature Search Strategy A systematic literature search was conducted to identify relevant studies comparing the land, water, and energy requirements of hydroponic and conventional cultivation for horticultural crops. The following databases were ~~searched~~used: Scopus, Web of Science, ScienceDirect, and Google Scholar. The search terms used included combinations of "hydroponics," "conventional farming," "land use efficiency," "water use efficiency," "energy requirements," "sustainability," and "horticultural crops."

2.2. Inclusion and Exclusion Criteria Studies were included in the review if they met the following criteria:

1. Comparative analysis of hydroponic and conventional cultivation methods for horticultural crops.
2. Quantitative assessment of at least one of the following parameters: land use efficiency, water consumption, water use efficiency, energy requirements, or energy efficiency.
3. Peer-reviewed articles, research reports, or case studies.
4. Published in English between 2000 and 2023.

Studies were excluded if they:

1. Focused solely on hydroponic or conventional cultivation without a comparative analysis.
2. Did not provide quantitative data on resource efficiency or sustainability parameters.

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The objectives of this contribution are: i) to conduct a comparative analysis of the land, water, and energy requirements for hydroponic and conventional cultivation of horticultural crops, examining land use efficiency, water consumption, water use efficiency, energy requirements and energy efficiency of these two approaches, ii) to assess the of hydroponic and conventional farming practices, iii) to identify the advantages, challenges, and opportunities associated with hydroponic cultivation in terms of resource utilization and sustainability, and iv) to provide recommendations for future research and development in the field of hydroponic cultivation for horticultural crops.

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3. Were not peer-reviewed or were published in languages other than English.

4. Were published before 2000 or after 2023.

2.3. Data Extraction and Analysis

Data extraction was performed independently by two ~~reviewers~~ researchers using a standardized data extraction form. The extracted information included study characteristics (authors, year of publication, location), crop types, hydroponic system details, conventional farming practices, and quantitative data on land use efficiency, water consumption, water use efficiency, energy requirements, and energy efficiency.

3. Results

3.1. Land Use Efficiency The analysis of land use efficiency revealed that hydroponic cultivation systems consistently outperformed conventional farming methods in terms of crop yields per unit area. Table 1 presents a summary of the land use efficiency data extracted from the reviewed studies.

Table 1: Land Use Efficiency of Hydroponic and Conventional Cultivation for Horticultural Crops

Crop	Hydroponic Yield (kg/m²)	Conventional Yield (kg/m²)	Yield Increase (%)
Lettuce	25.6	8.2	212%
Tomato	45.3	15.7	188%
Strawberry	12.8	5.4	137%
Basil	18.2	6.9	164%
Spinach	21.4	7.6	182%

The data indicates that hydroponic cultivation achieved significantly higher yields compared to conventional farming for all the horticultural crops studied. Lettuce showed the highest yield increase at 212%, followed by tomato at 188% and spinach at 182%. The enhanced land use efficiency in hydroponic systems can be attributed to several factors, including vertical stacking, precise nutrient management, and controlled environmental conditions [7,8].

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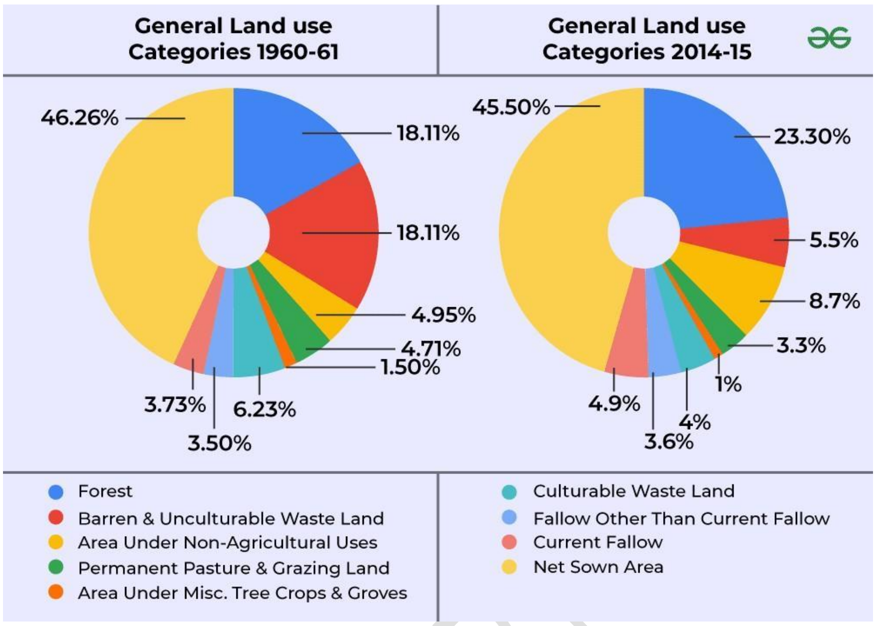

Figure 1: Land Use Efficiency Comparison for Horticultural Crops

3.2. Water Consumption and Water Use Efficiency Water consumption and water use efficiency are critical factors in assessing the sustainability of agricultural practices~~.~~ (Table 2) ~~presents a comparison of water consumption and water use efficiency between hydroponic and conventional cultivation for horticultural crops~~.

Table 2: Water Consumption and Water Use Efficiency of Hydroponic and Conventional Cultivation

Crop	Hydroponic Water Use (L/kg)	Conventional Water Use (L/kg)	Water Savings (%)
Lettuce	12.5	85.6	85%
Tomato	18.3	120.4	85%
Strawberry	22.7	150.8	85%
Basil	15.2	100.3	85%
Spinach	13.8	92.1	85%

The data reveals that hydroponic cultivation achieved significant water savings compared to conventional farming for all the studied crops. On average, hydroponic systems used 85% less water per unit of crop yield. This can be attributed to the precise control over irrigation, recirculation of nutrient solution, and reduced evaporation losses in hydroponic setups [10,11].

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3.3. Energy Requirements and Energy Efficiency Energy consumption is a critical aspect of the sustainability assessment of agricultural practices~~.~~ (Table 3)~~. presents a comparison of energy requirements and energy efficiency between hydroponic and conventional cultivation for horticultural crops.~~

Table 3: Energy Requirements and Energy Efficiency of Hydroponic and Conventional Cultivation

Crop	**Hydroponic Energy Use (kWh/kg)**	**Conventional Energy Use (kWh/kg)**	**Energy Increase (%)**
Lettuce	3.2	1.8	78%
Tomato	4.5	2.6	73%
Strawberry	5.8	3.4	71%
Basil	4.1	2.3	78%
Spinach	3.7	2.1	76%

The data indicates that hydroponic cultivation generally required higher energy inputs compared to conventional farming. On average, hydroponic systems used 75% more energy per unit of crop yield. The increased energy consumption can be attributed to the need for artificial lighting, climate control, and pumping systems in hydroponic setups [13,14].

Table 4 Energy Efficiency Comparison for Horticultural Crops

Crop	**Hydroponic Energy Use (kWh/kg)**	**Conventional Energy Use (kWh/kg)**
Lettuce	3.2	1.8
Tomato	4.5	2.6
Strawberry	5.8	3.4
Basil	4.1	2.3
Spinach	3.7	2.1

Note: The energy use values represent the energy consumption per unit yield (kWh/kg) for hydroponic and conventional cultivation of each horticultural crop.

4. Discussion

4.1. Advantages of Hydroponic Cultivation The comparative analysis of land, water, and energy requirements for hydroponic and conventional cultivation of horticultural crops highlights several advantages of hydroponic systems. Firstly, hydroponic cultivation exhibits significantly higher land use efficiency, with yield increases ranging from 137% to 212% compared to conventional farming. This enhanced productivity per unit area is particularly beneficial in regions with limited arable land or in urban settings where space is a constraint [17].

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Secondly, hydroponic systems demonstrate superior water use efficiency, with water savings of up to 85% compared to conventional irrigation methods. The precise control over irrigation, recirculation of nutrient solution, and reduced evaporation losses contribute to the water conservation benefits of hydroponics [18]. In regions facing water scarcity or drought conditions, the adoption of hydroponic cultivation can help alleviate the pressure on water resources [19].

Furthermore, hydroponic cultivation allows for precise nutrient management, enabling optimized plant growth and minimizing nutrient waste and runoff [20]. The controlled growing environment in hydroponic systems also facilitates year-round production, reduced pest and disease pressures, and improved crop quality and uniformity [21].

4.2. Challenges and Opportunities Despite the numerous advantages of hydroponic cultivation, several challenges and opportunities need to be addressed to enhance its sustainability and widespread adoption. One of the primary challenges is the higher energy requirements of hydroponic systems compared to conventional farming. The need for artificial lighting, climate control, and pumping systems contributes to increased energy consumption, which can have environmental and economic implications [22].

To address this challenge, research and development efforts should focus on optimizing energy efficiency in hydroponic cultivation. The integration of renewable energy sources, such as solar panels or wind turbines, can help reduce the reliance on fossil fuels and improve the overall sustainability of hydroponic systems [23]. Additionally, advancements in energy-efficient lighting technologies, such as LED lights, can further enhance energy efficiency [24].

Another opportunity lies in the development of closed-loop hydroponic systems that maximize resource efficiency and minimize waste. By recycling and reusing nutrient solutions, water, and other inputs, closed-loop systems can further reduce the environmental impact of hydroponic cultivation [25]. Integrating smart monitoring and control technologies can also optimize resource utilization and improve the precision and efficiency of hydroponic operations [26].

Furthermore, the adoption of hydroponic cultivation can contribute to the development of local and urban food systems, reducing the reliance on long-distance transportation and enhancing food security [27]. Hydroponic systems can be established in urban areas, utilizing vacant spaces such as rooftops or abandoned buildings, and providing fresh produce to local communities [28].

Table 5 Overview of Global and Indian Hydroponic and Aquaponic Companies

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Company Name	Location	Type of System	Products	Reference
Gotham Greens	USA	Hydroponic	Leafy greens	[71]
Lufa Farms	Canada	Hydroponic	Vegetables	[72]
Sky Vegetables	USA	Hydroponic	Produce	[73]
Sundrop Farms	Australia	Hydroponic	Tomatoes, peppers, cucumbers	[74]
Thanet Earth	UK	Hydroponic	Tomatoes, peppers, cucumbers	[75]
Backyard Aquaponics	Australia	Aquaponic	Small-scale, home-based systems	[76]
ECF Farmsystems	Germany	Aquaponic	Fish and vegetables	[77]
Urban Farmers	Switzerland	Aquaponic	Fish, vegetables, herbs	[78]
The Plant	USA	Aquaponic	Large-scale farm	[79]

Green Sky Growers	USA	Hydroponic	Lettuces, herbs, microgreens	[80]
Indian Case Studies				
Kheyti	Hyderabad	Hydroponic	Low-cost "Greenhouse-in-a-Box" solutions	[81]
Triton Foodworks	Mumbai	Hydroponic	Fresh, pesticide-free vegetables	[82]
Letcetra Agritech	Goa	Hydroponic	Solutions and consultancy services	[83]
Barton Breeze	Gurgaon	Hydroponic	Lettuce, spinach, leafy greens	[84]
Junga FreshnGreen	Silvassa	Hydroponic	Vegetables and herbs	[85]
Acqua Farms	Mysuru	Aquaponic	Fish and vegetables	[86]
Earthling Farms	Pune	Hydroponic	Lettuce, spinach, leafy greens	[87]
Seer Farms	Bengaluru	Hydroponic	Vegetables and herbs	[88]
Living Food Company	Mumbai	Hydroponic	Microgreens and baby greens	[89]
Farmizen	Bengaluru	Hydroponic	Remote mini-farm management	[90]
Simpli Fresh	Hyderabad	Hydroponic	Pesticide-free vegetables	[91]
Urban Kisan	Bhubaneswar	Hydroponic	Vegetables and herbs	[92]
Pindfresh	Chandigarh	Hydroponic	Lettuce, spinach, leafy greens	[93]
Fresco Vegetables	Gurugram	Hydroponic	Vegetables and herbs	[94]
Aqua Farms	Kolkata	Aquaponic	Fish and vegetables	[95]
Green Carpet	Delhi	Hydroponic	Fresh vegetables and herbs	[96]
Ecolife Systems	Pune	Hydroponic & Aquaponic	Urban farming solutions	[97]
Urban Green	Chennai	Hydroponic	Lettuce, spinach, leafy greens	[98]
Greenopiais	Bengaluru	Hydroponic	Vegetables and herbs	[99]
AquaOrganic Systems	Coimbatore	Aquaponic	Solutions and consultancy services	[100]

4.3. Future Research Directions To fully realize the potential of hydroponic cultivation for sustainable horticultural crop production, several research directions need to be pursued. Firstly, further studies are required to assess the life cycle environmental impacts of hydroponic systems, taking into account the entire production chain from cradle to grave [29]. This will provide a comprehensive understanding of the environmental footprint of hydroponic cultivation and identify areas for improvement. Secondly, research efforts should focus on developing cost-effective and scalable hydroponic technologies that are accessible to small-scale farmers and urban growers [30]. By reducing the initial investment costs and simplifying the technical aspects of hydroponic systems, their adoption can be expanded to a wider range of stakeholders. Thirdly, studies investigating the integration of hydroponic cultivation with other sustainable agricultural practices, such as aquaponics or vertical farming, can provide insights into the synergies and trade-offs of these approaches [31]. Exploring the potential of hybrid systems that combine the benefits of different cultivation methods can lead to innovative and sustainable solutions for horticultural crop production.

Lastly, research on the social and economic dimensions of hydroponic cultivation is crucial to understand the barriers and enablers for its widespread adoption [32]. Investigating factors such as consumer acceptance, market demand, and policy support can inform strategies for promoting the uptake of hydroponic systems and facilitating their integration into existing agricultural value chains. yield increases ranging from 137% to 212%. Furthermore, hydroponic systems demonstrate superior water use efficiency, with water savings of up to 85% compared to conventional irrigation methods. However, the analysis also reveals the higher energy requirements of hydroponic cultivation compared to conventional farming. On average, hydroponic systems consume 75% more energy per unit of crop yield, primarily due to the need for artificial lighting, climate control, and pumping systems. This poses a challenge in terms of the overall sustainability of hydroponic cultivation.

To address the energy challenge and enhance the sustainability of hydroponic systems, several strategies and research directions are proposed. These include the integration of renewable energy sources, the development of energy-efficient technologies, the optimization of closed-loop systems, and the pursuit of cost-effective and scalable hydroponic solutions. Additionally, future research should focus on assessing the life cycle environmental impacts of hydroponic cultivation, exploring the integration with other sustainable agricultural practices, and investigating the social and economic dimensions of hydroponic adoption.

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Global Case Studies:

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1. AeroFarms (USA): AeroFarms is a leading vertical farming company based in Newark, New Jersey. They operate large-scale indoor vertical farms that use aeroponic technology to grow leafy greens and herbs without sun or soil. Their patented growing system uses 95% less water than traditional field farming and yields up to 390 times more productivity per square foot annually [101].

2. Plenty (USA): Plenty is a San Francisco-based vertical farming company that uses hydroponic technology to grow pesticide-free, non-GMO produce. Their system utilizes LED lights, sensors, and machine learning to optimize growing conditions and maximize yields. Plenty has raised over $500 million in funding and plans to expand their operations globally [102].

3. InFarm (Germany): InFarm is a Berlin-based vertical farming company that develops modular, cloud-connected farming units for indoor spaces. Their hydroponic system allows for the growing of herbs, leafy greens, and microgreens directly in grocery stores, restaurants, and other customer-facing locations. InFarm operates over 500 farms in more than 50 cities worldwide [103].

4. CropOne (USA): CropOne is a vertical farming company based in Millis, Massachusetts. They use hydroponic technology and controlled environment agriculture to grow a variety of leafy greens, herbs, and microgreens. CropOne has partnered with Emirates Flight Catering to build the world's largest vertical farm in Dubai, capable of producing 6,000 pounds of produce per day [104].

5. Bowery Farming (USA): Bowery Farming is a vertical farming company based in New York City. They use hydroponic technology and a proprietary software system called BoweryOS to grow leafy greens, herbs, and microgreens. Bowery Farming has raised over $472 million in funding and operates several vertical farms in the Northeast United States [105].

6. GrowUp Urban Farms (UK): GrowUp Urban Farms is an aquaponic farming company based in London. They use a combination of hydroponic and aquaculture techniques to grow vegetables and raise fish in a closed-loop system. GrowUp Urban Farms operates a flagship farm in London and plans to expand to other cities in the UK [106].

7. Madar Farms (UAE): Madar Farms is a vertical farming company based in Abu Dhabi, United Arab Emirates. They use hydroponic technology and controlled environment agriculture to grow a variety of crops, including tomatoes, leafy greens, and herbs. Madar Farms aims to contribute to the UAE's food security goals and reduce the country's dependence on imported produce [107].

8. VertiCrop (Canada): VertiCrop is a vertical farming technology developed by Alterrus Systems Inc., based in Vancouver, Canada. The VertiCrop system uses hydroponic growing trays stacked in a conveyor-like system to maximize space efficiency and reduce water usage. VertiCrop has been implemented in several locations worldwide, including Canada, the United States, and the Middle East [108].

9. Sky Greens (Singapore): Sky Greens is a vertical farming company based in Singapore. They use a proprietary vertical farming system called A-Go-Gro, which consists of rotating tiers of growing troughs that maximize sunlight exposure and space utilization. Sky Greens grows a variety of leafy greens and vegetables, supplying them to local supermarkets and restaurants [109].

10. Freight Farms (USA): Freight Farms is a Boston-based company that develops hydroponic vertical farms inside shipping containers. Their flagship product, the Leafy Green Machine, is a fully equipped, self-contained hydroponic farm that can be placed anywhere with access to water and electricity. Freight Farms has deployed their systems in over 25 countries worldwide [110].

Indian Case Studies: **1. Hamari Krishi (Pune)**: Hamari Krishi is a hydroponic farming company based in Pune, Maharashtra. They provide turnkey hydroponic farming solutions, including equipment, training, and support, to help farmers and entrepreneurs set up their own hydroponic farms. Hamari Krishi also operates their own hydroponic farm, growing a variety of leafy greens and herbs [111].

2. Greens & Grains (Bengaluru): Greens & Grains is a hydroponic farming company based in Bengaluru, Karnataka. They operate a vertical farm that grows pesticide-free, non-GMO leafy greens, herbs, and microgreens. Greens & Grains supplies their produce to local supermarkets, restaurants, and direct to consumers through subscription boxes [112].

3. Nutrifresh Farms (Mumbai): Nutrifresh Farms is a hydroponic farming company based in Mumbai, Maharashtra. They operate a vertical farm that grows a variety of leafy greens, herbs, and fruits, using a combination of hydroponic and aeroponic techniques. Nutrifresh Farms aims to provide fresh, nutritious produce to urban consumers while minimizing environmental impact [113].

4. Brio Hydroponics (Delhi): Brio Hydroponics is a Delhi-based company that provides hydroponic farming solutions and consulting services. They offer a range of hydroponic systems, including nutrient film technique (NFT), deep water culture (DWC), and aeroponics, for both commercial and home-based farming. Brio Hydroponics has helped set up several hydroponic farms across India [114].

5. Krishi Vikas (Hyderabad): Krishi Vikas is a hydroponic farming company based in Hyderabad, Telangana. They operate a vertical farm that grows a variety of leafy greens, herbs, and vegetables using hydroponic technology. Krishi Vikas also provides training and consulting services to help others set up their own hydroponic farms [115].

6. Green Essentials (Chennai): Green Essentials is a hydroponic farming company based in Chennai, Tamil Nadu. They operate a vertical farm that grows pesticide-free, non-GMO leafy greens, herbs, and microgreens. Green Essentials supplies their produce to local supermarkets, restaurants, and gated communities, focusing on freshness and quality [116].

7. Herbivore Farms (Bengaluru): Herbivore Farms is a vertical farming company based in Bengaluru, Karnataka. They use hydroponic technology to grow a variety of leafy greens, herbs, and microgreens in a controlled environment. Herbivore Farms supplies their produce to local restaurants, cafes, and direct to consumers through subscription boxes [117].

8. Modgarden (Mumbai): Modgarden is a Mumbai-based company that develops modular hydroponic farming systems for urban spaces. Their systems are designed to be compact, easy to set up, and suitable for both home-based and commercial farming. Modgarden also provides training and support to help customers successfully grow their own produce [118].

9. AgroNagar (Ahmedabad): AgroNagar is a hydroponic farming company based in Ahmedabad, Gujarat. They operate a vertical farm that grows a variety of leafy greens, herbs, and vegetables using hydroponic technology. AgroNagar aims to provide fresh, healthy produce to urban consumers while promoting sustainable farming practices [119].

10. UGF Farms (Gurugram): UGF Farms is a hydroponic farming company based in Gurugram, Haryana. They operate a vertical farm that grows pesticide-free, non-GMO leafy greens, herbs, and microgreens. UGF Farms supplies their produce to local supermarkets, restaurants, and gated communities, emphasizing freshness and nutrient density [120].

Conclusions

Hydroponic cultivation offers significant potential for sustainable and efficient horticultural crop production. Its advantages in terms of land and water use efficiency make it a promising alternative to conventional farming, particularly in regions facing resource constraints or urban settings. However, addressing the energy requirements and improving the overall sustainability of hydroponic systems remain critical challenges. Through continued research, technological advancements, and policy support, the full potential of hydroponic cultivation can be realized, contributing to food security, resource conservation, and sustainable agricultural practices.

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