

Soilless Cultivation Techniques for Future Agriculture Prospective

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Abstract

Soilless cultivation techniques have emerged as an innovative and sustainable approach to modern agriculture, addressing the challenges of limited arable land, water scarcity, soil degradation, and the growing demand for food production. These techniques involve growing plants without the use of natural soil by supplying nutrients directly to the root zone through alternative growing media or nutrient solutions. Major soilless cultivation systems include hydroponics, aeroponics, aquaponics, and substrate-based cultivation. These systems provide precise control over plant nutrition, water availability, temperature, and environmental conditions, resulting in improved crop productivity and quality. The adoption of soilless cultivation offers several advantages over conventional soil-based farming. It significantly reduces water consumption through efficient recycling and reuse of nutrient solutions. The absence of soil minimizes the incidence of soil-borne diseases, pests, and weeds, thereby reducing the need for chemical pesticides and herbicides. Furthermore, soilless systems enable year-round cultivation in controlled environments such as greenhouses and vertical farms, making them particularly suitable for urban and urban agriculture. Higher crop yields, faster growth rates, and improved resource-use efficiency contribute to the economic viability of these systems. Despite their numerous benefits, soilless cultivation techniques also face certain challenges, including high initial investment costs, technical expertise requirements, energy dependence, and the need for continuous monitoring of nutrient and environmental parameters. However, advances in automation, sensor technologies, and renewable energy integration are helping to overcome these limitations and enhance system efficiency.

As a modern cropping system, soilless cultivation represents a promising solution for achieving sustainable agricultural development and food security in the face of climate change and population growth. Its ability to optimize resource utilization while maintaining high productivity makes it an essential component of future agricultural practices. Continued research, technological innovation, and policy support are crucial for expanding the adoption of soilless cultivation and ensuring its long-term contribution to global food production and environmental sustainability.

Keywords: Soilless Cultivation, Hydroponics, Aeroponics, Aquaponics, Sustainable Agriculture, Modern Cropping System, Food Security, Resource Efficiency.

Introduction

Soilless farming, also known as hydroponics, aeroponics, or aquaponics depending on the technique used, has emerged as one of the most innovative and rapidly expanding trends in modern agriculture. As

traditional farming faces challenges such as declining soil fertility, shrinking agricultural land, unpredictable climate patterns, water scarcity, and the rising demand for high-quality food, soilless cultivation offers a sustainable and efficient alternative for future food production. By eliminating soil—the conventional medium of plant growth—this method relies on nutrient-rich water solutions, mist environments, or integrated fish–plant systems to supply all essential minerals directly to plant roots. One of the major reasons behind the growing popularity of soilless farming is its ability to produce more food in less space. Vertical farming structures, rooftop gardens, and controlled environment agriculture (CEA) systems enable cultivation in urban areas where soil-based farming is impossible. This not only supports local food production but also reduces transportation costs and carbon emissions. Additionally, soilless farming uses significantly less water than traditional irrigation systems because nutrient solutions are recycled, making it a highly water-efficient technique suitable for drought-prone regions. Another advantage of this approach is improved plant health and productivity. Since plants are grown in a controlled environment free from soil-borne diseases, pests, and weeds, the dependency on chemical fertilizers and pesticides is reduced. As a result, crops tend to grow faster, yield more, and maintain consistent quality throughout the production cycle. Moreover, farmers can precisely control nutrient levels, pH, temperature, humidity, and lighting, which contributes to optimal plant growth. The flexibility of soilless farming allows year-round cultivation, even in harsh climatic conditions, promoting food security and resilience. It is especially useful for countries with limited arable land or extreme weather patterns. Furthermore, this method supports the cultivation of a wide range of crops, including leafy greens, herbs, vegetables, and even some fruits.

Review of literature

Below are concise findings from recent and relevant studies/reviews on soilless farming (hydroponics, aeroponics, aquaponics and related technologies). **Rajaseger (2023)** Comprehensive review highlighting recent advances in hydroponics, smart sensors and automation; concludes hydroponics is becoming a scalable, precision-controlled method for high-value vegetable production in controlled environments. **Fussy et al. (2022)** Compared soil and soilless techniques and reported that soilless systems consistently give higher, more reliable yields and cleaner produce due to elimination of soil-borne pathogens. **Garzón et al. (2023)** studied Systematic review of aeroponics technology showing that mist/atomization delivery plus IoT monitoring increases root oxygenation and water-use efficiency, but requires precise droplet control and robust fault detection. **Lakhiar et al. (2018)** Surveyed energy and control systems for CEA (controlled environment agriculture) and argued that intelligent monitoring (fault detection, automation) is essential to reduce labour and optimize resource use in soilless farms. **Gillani (2022)** reviewed energy-efficient lighting and HVAC for vertical and soilless farms; emphasized trade-offs between LED lighting spectra for yield vs. electricity cost and recommended integration with renewable energy to improve sustainability. **Khatri (2024)** observed that hydroponic advantages and constraints water savings (often large), space efficiency and reduced pesticides, but adoption limited by high capital costs and technical skill requirements. **Rajendran (2024)** evaluated popular hydroponic methods and concluded that recirculating systems (NFT, DWC, ebb-flow) show best resource-use efficiency for leafy crops at commercial small-scale to mid-scale operations. **Wang et al. (2024)** found integrated fish–plant systems can greatly reduce synthetic fertilizer inputs and increase nutrient recycling but need careful balance of fish and plant stocking densities. **Mishra et al. (2020)** examined aquaponics for livelihood improvement and noted social benefits (household food security, protein provision) in smallholder and urban contexts,

while flagging knowledge gaps in long-term economic viability studies. **He et al. (2025)** studied that vertical aeroponic device design showing measurable improvements in uniform nutrient delivery and potential for modular vertical deployment in urban spaces. **Wirza & Nazir (2020)** studied on urban aquaponics that highlights regulatory, institutional and knowledge barriers for city adoption despite clear environmental and spatial advantages. **Rajalakshmi et al. (2022)** Cross-system review (hydroponics, aquaponics, recirculating aquaculture) that synthesizes evidence for resource efficiency (water, nutrients) and recommends integrated policy and training programs to accelerate farmer adoption.

Soilless Farming Techniques

Soilless farming refers to crop production systems where plants are grown without natural soil, using nutrient solutions and inert growing media. The major techniques are described below:

1. Hydroponics

Hydroponics is an advanced method of growing plants without soil, using a nutrient-rich water solution to supply essential minerals directly to plant roots. The term originates from the Greek words *hydro* (water) and *ponos* (labor). This technique is gaining global attention due to its efficiency, sustainability, and suitability for areas with limited arable land. In hydroponic systems, plants are supported by inert media such as coco peat, perlite, vermiculite, or rock wool, while their roots remain in contact with a balanced nutrient solution. Common hydroponic systems include Nutrient Film Technique (NFT), Deep Water Culture (DWC), aeroponics, drip systems, and wick systems. Each system varies in complexity, cost, and suitability for different crops.

One of the major advantages of hydroponics is efficient water use. It consumes up to 80–90% less water than traditional soil-based agriculture because water is recycled within the system. Additionally, plants grow faster and often yield more because nutrients are supplied in optimal concentrations. Hydroponics also minimizes soil-borne diseases, weeds, and the need for chemical pesticides, making it an environmentally friendly option. Hydroponics allows year-round cultivation under controlled conditions, making it ideal for urban farming, greenhouses, vertical farms, and regions with harsh climates. Crops commonly grown using hydroponics include leafy vegetables like lettuce, spinach, and herbs, as well as tomatoes, cucumbers, strawberries, and peppers.

Despite its benefits, hydroponics has certain limitations. Initial setup costs can be high, and successful operation requires technical knowledge of nutrient management, pH control, and system maintenance. Power failures or nutrient imbalances can quickly affect plant health. Hydroponics represents a promising alternative to conventional agriculture. With increasing population pressure, climate change, and land scarcity, hydroponic farming offers a sustainable, resource-efficient solution for future food production.



A



B



C



D



E



F

Figure A to F- Different Models of Hydroponics Farming

2. Aeroponics

Aeroponics is an advanced soilless cultivation technique in which plants are grown with their roots suspended in air and periodically misted with a nutrient-rich solution. It is considered one of the most

efficient and innovative methods of modern agriculture due to its high productivity and minimal resource use. In an aeroponic system, plant roots are enclosed in a dark chamber to prevent light exposure, while fine sprays of water mixed with essential nutrients are delivered at regular intervals. This misting provides roots with optimal moisture, nutrients, and oxygen simultaneously, leading to rapid and healthy plant growth. Common aeroponic setups include low-pressure and high-pressure misting systems, depending on the level of precision required.

One of the key advantages of aeroponics is its exceptional water efficiency, using up to 95% less water than conventional soil farming. Because roots receive ample oxygen, plants exhibit faster growth rates, higher yields, and improved nutrient absorption. Aeroponics also reduces the risk of soil-borne diseases, eliminates the need for weeding, and minimizes pesticide use, making it an environmentally sustainable practice. Aeroponic farming is especially suitable for urban agriculture, vertical farming, research laboratories, and space missions. Crops such as lettuce, herbs, spinach, potatoes, strawberries, and tomatoes perform particularly well in aeroponic systems.

NASA has also explored aeroponics for food production in space due to its lightweight and efficient design. However, aeroponics requires high initial investment, technical expertise, and reliable electricity. System failures, especially in misting schedules, can quickly stress plants. Despite these challenges, aeroponics holds immense potential for future agriculture. Aeroponics offers a highly efficient, clean, and sustainable approach to crop production, addressing global challenges of food security, water scarcity, and land limitation in a rapidly changing world.



G



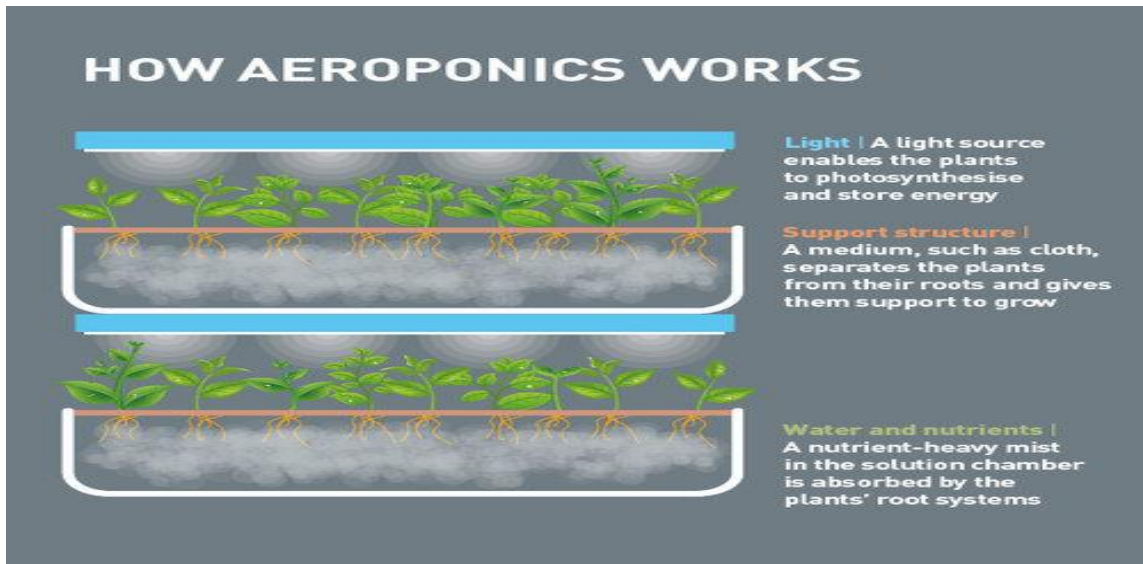
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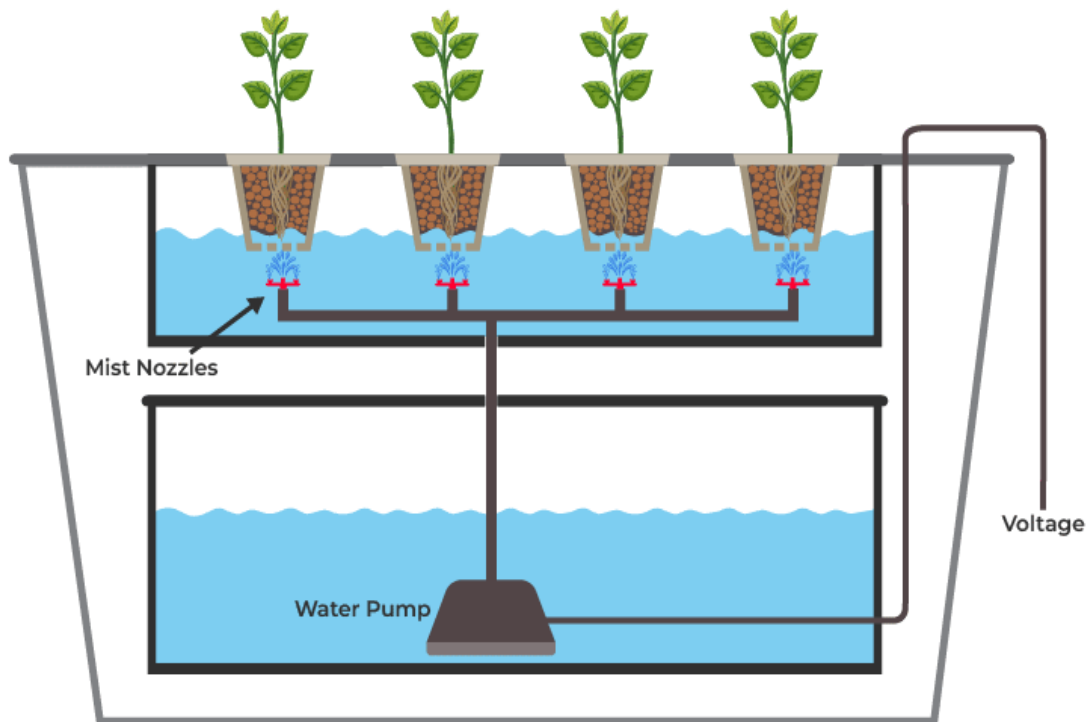
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J



K



L -1



L -2

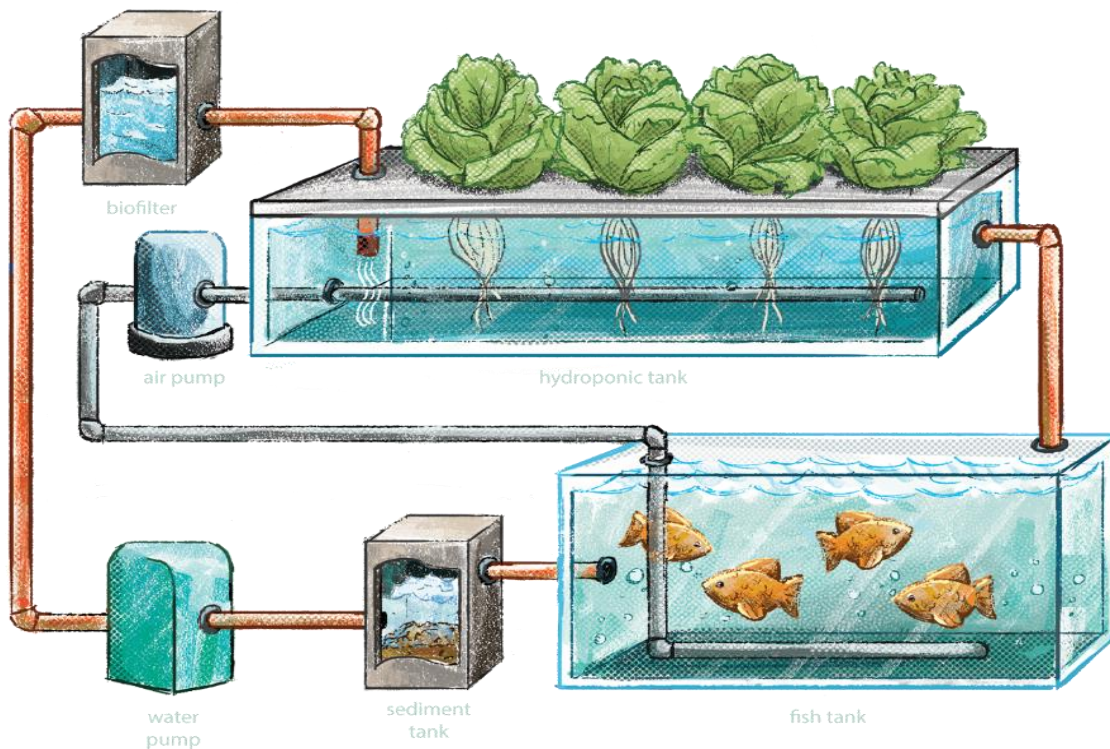
Figure (G to L) showing **vertical aeroponic towers, roots hanging in mist chambers, and illustrations of how mist-based nutrient delivery works** — all characteristic of aeroponic farming systems.

3. Aquaponics

Aquaponics is an integrated and sustainable food production system that combines aquaculture (fish farming) with hydroponics (soilless plant cultivation). In this system, fish and plants grow together in a mutually beneficial environment, where fish waste provides nutrients for plants, and plants help purify water for fish. In an aquaponic system, fish are raised in tanks and produce waste rich in ammonia. Beneficial bacteria convert this ammonia first into nitrites and then into nitrates through a natural process called nitrification. These nitrates act as an excellent nutrient source for plants grown in hydroponic beds. As plants absorb the nutrients, the water becomes cleaner and is recirculated back to the fish tanks, creating a closed-loop system.

Aquaponics offers several advantages over conventional farming methods. It uses up to 90% less water than soil-based agriculture because water is continuously recycled. The system produces two crops simultaneously fish and vegetables making it highly efficient and economically attractive. Additionally, aquaponics avoids chemical fertilizers and pesticides, resulting in fresh, organic, and environmentally friendly food products. Common fish species used in aquaponics include tilapia, catfish, carp, and trout, while plants such as lettuce, spinach, basil, tomatoes, and cucumbers grow well in the system. Aquaponics is suitable for urban farming, greenhouses, educational institutions, and regions with limited land and water resources.

Despite its benefits, aquaponics requires careful management of water quality, pH, temperature, and oxygen levels to maintain balance between fish, plants, and bacteria. Initial setup costs and technical knowledge may also pose challenges. In conclusion, aquaponics represents a sustainable and innovative approach to agriculture, promoting efficient resource use, food security, and environmental conservation in the modern world.



M



N



O

Figure (M to O) showing integrated systems with fish tanks and plant beds working together (plants floating on water above fish).

4. Substrate Culture (Media-Based Systems)

Substrate Culture (Media-Based Systems) is a soilless cultivation method in which plants are grown in solid, inert or organic growing media instead of natural soil. This technique is widely used in protected cultivation such as greenhouses, polyhouses, and net houses to achieve higher productivity and better crop control. In substrate culture, plant roots are supported by media such as coco peat, perlite, vermiculite, sand, gravel, peat moss, rock wool, sawdust, or a mixture of these materials. These substrates provide

physical support, adequate aeration, and moisture retention but do not supply nutrients. Essential nutrients are delivered to plants through a carefully formulated nutrient solution using drip irrigation or fertigation systems. One of the main advantages of substrate culture is improved root-zone management. Growers can precisely control water supply, nutrient concentration, pH, and electrical conductivity, resulting in uniform plant growth and higher yields. The system also reduces soil-borne diseases, salinity problems, and weed infestation, thereby minimizing the need for chemical pesticides and herbicides.

Substrate culture is particularly suitable for high-value crops such as tomatoes, cucumbers, capsicum, strawberries, flowers, and nursery plants. It allows cultivation in areas with poor or contaminated soils and supports efficient water use, making it environmentally sustainable. However, substrate culture has certain limitations. The cost of substrates and infrastructure can be high, and proper disposal or reuse of media requires careful management. Technical knowledge is essential for successful operation. In conclusion, substrate culture is a reliable and efficient soilless farming technique that enhances crop productivity, resource efficiency, and sustainability in modern agriculture.



Figure P. Strawberries cultivation on substrate under plastic stock

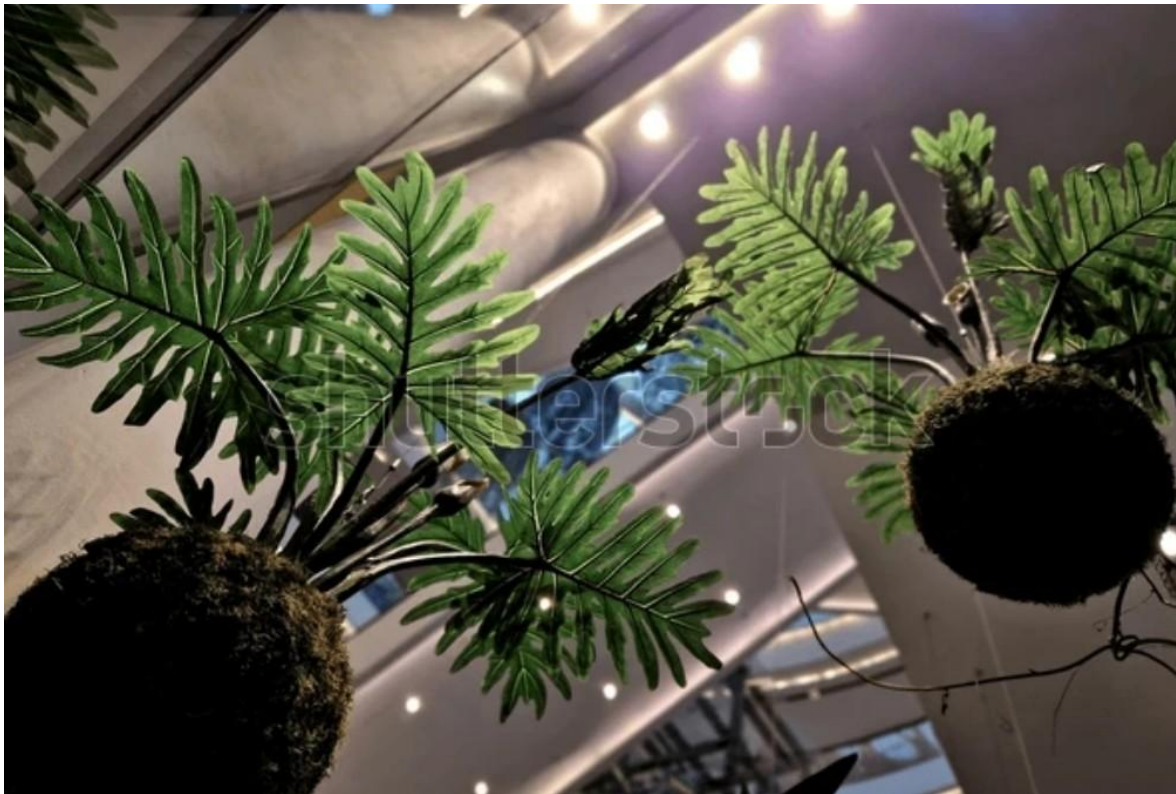


Figure Q Farming on Moss struck substrate

5. Vertical Farming

Vertical Farming is an innovative agricultural practice in which crops are grown in vertically stacked layers or structures, often inside controlled environments such as buildings, warehouses, or greenhouses. This method maximizes space utilization and enables food production in urban areas where land availability is limited. Vertical farming commonly uses soilless cultivation techniques such as hydroponics, aeroponics, or aquaponics. Plants receive precise amounts of water, nutrients, and light, usually through LED systems, allowing optimal growth throughout the year. Environmental factors like temperature, humidity, carbon dioxide, and light intensity are carefully regulated to ensure consistent crop quality and yield. Crops commonly grown in vertical farming like Lettuce, herbs, microgreens.

One of the major advantages of vertical farming is its efficient use of resources. It requires significantly less land and up to 90% less water compared to traditional agriculture. Since crops are grown indoors under controlled conditions, the risk of pests, diseases, and weather-related losses is greatly reduced, minimizing the need for chemical pesticides. Additionally, vertical farming shortens supply chains by enabling local food production, which reduces transportation costs and carbon emissions. Vertical farming is especially suitable for leafy vegetables, herbs, microgreens, and some fruiting crops such as strawberries and tomatoes. It also provides fresh, pesticide-free produce to urban populations.

Despite its benefits, vertical farming involves high initial investment and energy costs, particularly for lighting and climate control. Skilled management and technological expertise are required for successful operation. In conclusion, vertical farming offers a sustainable and efficient solution to future food challenges by improving productivity, conserving resources, and supporting urban food security.



Figure R-Indore Vertical Farming



Figure S-Moden Indore vertical farming



Figure T-Organic vertical Farming

6. Floating Raft System

Floating Raft System, also known as **Deep Water Culture (DWC)**, is a popular hydroponic technique in which plants are grown on floating platforms placed over a nutrient-rich water solution. Plants are held in net pots fitted into rafts made of foam or thermocol, allowing roots to hang freely into the oxygenated nutrient solution below. In this system, plant roots continuously absorb water and essential nutrients directly from the solution, while air pumps and air stones supply dissolved oxygen to prevent root suffocation. The crops like Lettuce, spinach can be cultivated by this method. The simplicity of design and continuous nutrient availability promote rapid plant growth and uniform development.

One of the major advantages of the floating raft system is its high water-use efficiency, as the nutrient solution is recycled within the system. It is easy to operate, requires minimal growing media, and is well suited for commercial production. The system also reduces weed growth and soil-borne diseases, resulting in healthier crops with minimal pesticide use. Floating raft systems are widely used for growing leafy vegetables such as lettuce, spinach, kale, basil, and other herbs. They are particularly effective in greenhouses and controlled environments.

However, careful management of water temperature, nutrient concentration, and oxygen levels is essential. Power failures affecting aeration can quickly stress plants. In conclusion, the floating raft system is a cost-effective, efficient, and reliable hydroponic method for sustainable vegetable production.

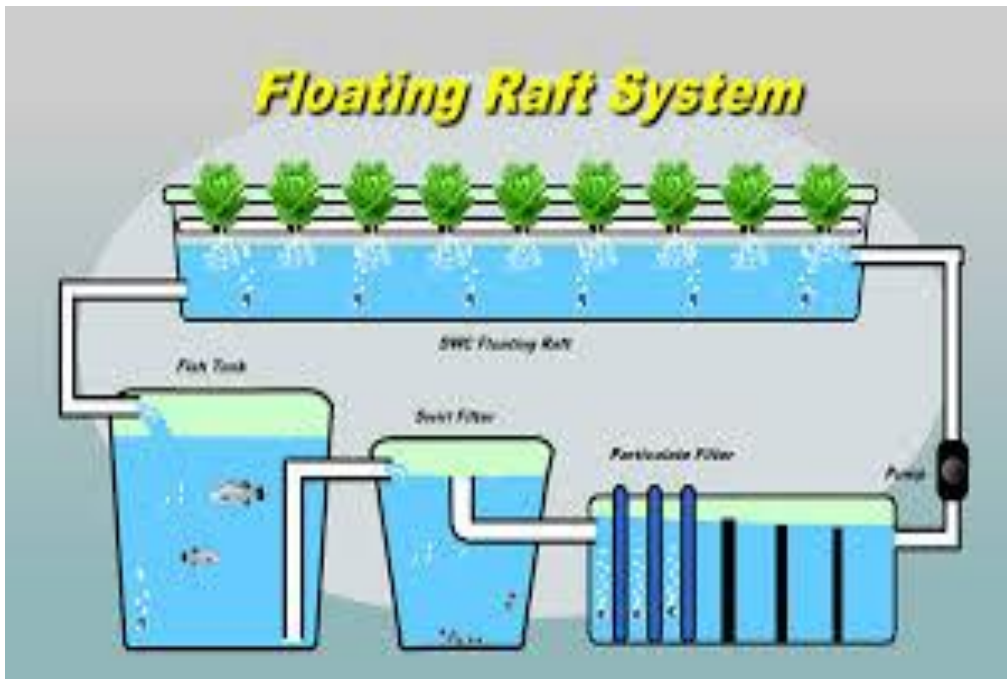


Figure U. A model showing continuous nutrient availability



Fig V. Water spinach farming on floating raft hydroponics system

7. Nutrient Film Technique (NFT)

Nutrient Film Technique (NFT) is a widely used hydroponic system in which a thin, continuous film of nutrient-rich water flows over plant roots, providing essential nutrients, water, and oxygen simultaneously. The system was developed in the 1960s and is especially popular for growing fast-growing leafy vegetables and herbs. In an NFT system, plants are placed in small holes along slightly sloped channels or gullies made of PVC or similar materials. A nutrient solution is pumped from a reservoir and allowed to flow as a shallow stream along the base of each channel, bathing the roots before draining back into the reservoir for reuse. The shallow depth ensures that part of the root system remains exposed to air, promoting efficient oxygen uptake. NFT offers several advantages, including efficient use of water and

nutrients, rapid plant growth, and minimal growing media requirements. Since the nutrient solution is continuously recycled, wastage is reduced, making the system environmentally sustainable. The absence of soil also minimizes weed growth and soil-borne diseases, leading to cleaner and healthier produce. Leafy vegetables and herbs can be cultivated by this technique.

NFT systems are particularly suitable for crops with small, non-woody root systems such as lettuce, spinach, basil, coriander, and strawberries. They are commonly used in greenhouses, vertical farming units, and urban agriculture setups. Despite its benefits, NFT requires careful monitoring of nutrient concentration, pH, and flow rate. Pump failure or channel blockage can quickly affect plants due to limited water storage around roots. Initial setup costs and technical expertise may also be challenges. In conclusion, the Nutrient Film Technique is an efficient, space-saving, and high-yield hydroponic method, well suited for modern, sustainable crop production.

Nutrient Film Technique

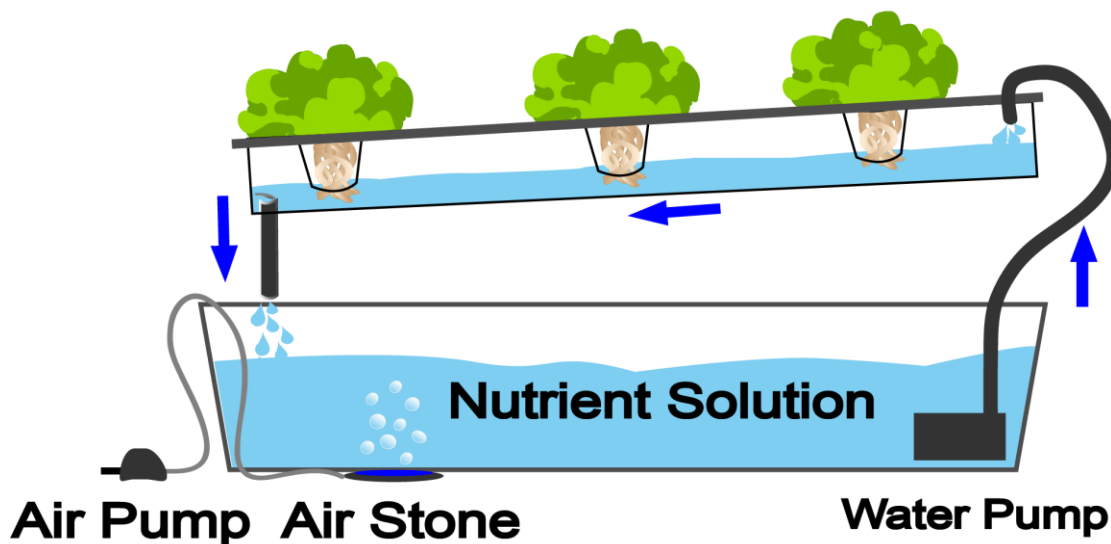


Figure W-Nutrient Film Farming Technique (NFT)

Advantages of Soilless Farming

Soilless farming offers several advantages that make it an efficient and sustainable alternative to conventional farming.

- 1. Higher productivity:** Soilless farming ensures higher crop yield and faster plant growth by supplying nutrients directly to plant roots in precise and readily available forms. Unlike soil-based systems, plants do not expend energy searching for water and nutrients, allowing them to focus on growth and development. Optimal control of pH, oxygen, moisture, and nutrient concentration creates ideal growing conditions throughout the crop cycle. This results in rapid root development, uniform plant growth, and shorter cropping periods. Consequently, multiple crop cycles can be achieved in a year, leading to increased productivity, consistent yields, and improved overall crop performance., independent of seasonal or climatic limitations, making it suitable for urban and peri-urban areas.
- 2. Efficient water use:** Soilless farming ensures efficient use of water by supplying it directly to plant roots in controlled and measured amounts. Unlike conventional soil-based agriculture, water in soilless

systems such as hydroponics and aeroponics is recirculated and reused, minimizing wastage through runoff, evaporation, and deep percolation. Plants absorb only the required quantity of water, improving uptake efficiency. This method can save up to 80–90% water compared to traditional farming practices. Efficient water management not only supports cultivation in water-scarce regions but also enhances plant growth, reduces irrigation costs, and promotes sustainable agricultural production.

3. **Precise and balanced nutrient management:** It is a key advantage of soilless farming. In this system, plants are supplied with nutrients in accurately measured concentrations through nutrient solutions, ensuring optimal availability at each growth stage. Essential macro- and micronutrients are delivered directly to the root zone, improving absorption efficiency and preventing deficiencies or toxicities. Growers can easily adjust nutrient composition, pH, and electrical conductivity according to crop requirements. This precision reduces nutrient wastage and environmental pollution while promoting uniform growth, higher yields, and improved crop quality. As a result, soilless farming enables efficient, sustainable, and scientifically managed plant nutrition.
4. **Minimizes soil-borne diseases, pests, and weeds:** Soilless farming significantly reduces soil-borne diseases, pests, and weeds because crops are grown without natural soil, which is a primary source of pathogens and weed seeds. The controlled growing environment limits pest infestation and disease spread, resulting in healthier plants. This reduction lowers the need for chemical pesticides and herbicides, leading to safer produce, improved crop quality, and more sustainable and eco-friendly agricultural practices.
5. **The system supports space-efficient cultivation:** The system supports space-efficient cultivation enabling vertical farming and high-density planting, which is ideal for areas with limited land availability. Additionally, soilless farming allows greater control over growing conditions, including pH, temperature, and nutrient concentration, leading to uniform crop quality. It is also suitable for degraded, saline, or contaminated soils, making it a promising solution for sustainable food production and future agricultural challenges.
6. **Enables year-round and off-season production:** Soilless farming enables year-round and off-season production by allowing complete control over the growing environment. Factors such as temperature, light, humidity, and nutrient supply can be regulated to suit crop requirements, regardless of external climatic conditions. This independence from seasons and weather extremes ensures continuous crop production, stable yields, and consistent market supply. It also helps farmers meet consumer demand throughout the year and achieve better economic returns.
7. **Challenges of Soilless Farming:** Soilless farming, though an emerging alternative cropping trend, faces several challenges. High initial investment for infrastructure, technology, and skilled labour limits adoption, especially among small and marginal farmers. Continuous power supply and precise monitoring of nutrients, pH, and temperature are essential, increasing operational costs. Technical knowledge and training are required to manage systems effectively. Dependence on external inputs and vulnerability to system failures can cause rapid crop losses. Limited crop diversity and market awareness also restrict expansion. Despite sustainability benefits, these challenges hinder the large-scale adoption of soilless farming.

Conclusion:

Soilless farming represents a promising and sustainable alternative to conventional agriculture, addressing challenges such as land degradation, water scarcity, and climate variability. By enabling efficient resource

use, precise nutrient management, and year-round production, it enhances crop productivity and quality. Although initial costs and technical requirements remain constraints, continued technological advancement, training, and policy support can promote wider adoption, making soilless farming a viable solution for future food security.

Apologies:

I sincerely apologize for using some figures from external sources without proper acknowledgment. It was not my intention to overlook academic integrity.

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