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Overview of Soilless Agriculture Systems: Advantages and Disadvantages

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ABSTRACT

Soilless agriculture presents a promising alternative to traditional farming systems in regions facing soil degradation, fast urbanization, water scarcity, and environmental stress, particularly in arid regions. Consequently, the increasing demand for sustainable agricultural practices has led to significant interest in soilless farming systems to substitute soil-based cultivation systems. This study highlights types of soilless farming sustems and their pros and cons. Soilless cultivation - encompassing both hydroponic (Nutrient Film Technique (NFT), Deep Flow Technique (DFT), Root Dipping Technique (RDT), aquaponics and aeroponic and substrate-based systems - offers numerous advantages over conventional agriculture, including enhanced resource use efficiency, improved crop quality, higher yields per unit area, and reduced environmental impact. However, significant challenges remain, particularly regarding energy consumption, initial capital costs, and technical complexity. Nutrient solution composition and management represent critical factors determining soilless system success. The controlled environment provided by these systems allows for precise management of plant nutrition, water supply, and root zone conditions, leading to optimized plant growth and development.

Keywords: soilless systems, hydroponics, Nutrient Solution.

INTRODUCTION

The world's population is expected to increase to 9.5 billion people within the next 40 years. This massive population requires water and food, so food production must be increased to meet their nutritional needs. Soil is generally used for plant growth, providing nutrients and water for plants (Khan, 2018; United Nations, 2019). Soilless farming, also known as soilless cultivation or controlled environment agriculture (CEA), represents a paradigm shift in modern agricultural practices. As the global population is projected to reach 9.7 billion by 2050, there is an urgent need for sustainable and efficient food production systems that can operate independently of traditional soil-based agriculture (Lakhiar et al., 2025).

Agriculture is a cornerstone of global food security, with traditional farming methods contributing significantly to economic development and sustenance. However, challenges such as soil degradation, water scarcity, and pest infestations have posed significant limitations to traditional soil-based farming systems, particularly in regions with arid climates like Egypt. Researchers have emphasized the urgent need to explore innovative techniques to overcome these challenges and ensure sustainable agricultural practices (Mohamedin et al., 2010; El-Rawy et al.,2024). The comparison between soil-based and soilless cultivation systems has gained significant attention due to their respective impacts on crop productivity and quality. Soil-based farming, the conventional approach, relies on the natural soil's properties to provide nutrients, water, and a growth medium for plants. However, this method is often constrained by environmental factors, such as soil fertility and water availability, which can vary significantly across regions. On the other hand, soilless systems, such as hydroponics, use nutrient-rich solutions or inert media to support plant growth, allowing precise control over the growing environment and efficient resource utilization (Karimi et al., 2013; Barbosa et al., 2015).

One of the most pressing issues is soil degradation, which arises from climate change and unsustainable practices such as the excessive use of chemical fertilizers and pesticides. These practices have led to a decline in soil fertility, structure, and organic matter content. Additional problems like salinity, particularly prevalent in reclaimed desert areas and the eastern Delta, have further diminished soil productivity. Soilless systems have been suggested as a stand by to traditional agriculture (Mohamedin et al., 2010; Praveen et al., 2022; Sharaf-Eldin et al., 2023). Soil erosion due to urban expansion and over-irrigation has also resulted in the loss of topsoil, reducing land suitability for crop cultivation (Abowaly et al., 2021). Soilless systems offer compelling solutions by eliminating dependency on arable land while providing precise control over plant nutrition, water management, and environmental conditions (Fussy and Papenbrock, 2022).

Soilless farming dates back to ancient civilizations such as the civilization of Egyptian. There are numerous published studies on growing plants in soil, but few studies focus on growing plants in soilless farms, as the latter offer a solution to the problem of water and fertilizer shortages necessary for plant growth (Gruda et al., 2004). The origins of hydroponic farming can be traced back to ancient civilizations, such as the Hanging Gardens of Babylon and the floating gardens of the Aztecs, which were early forms of soilless agriculture (Jones, 2016). However, Resh (2022) showed that modern hydroponics began in the 20th century when researchers like Dr. William F. Gericke developed a systematic approach to growing crops in water solutions. The concept of soilless cultivation has evolved significantly since the early hydroponic experiments of the 1930s. Modern soilless systems encompass a diverse range of technologies,

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from simple nutrient film techniques to sophisticated aeroponic towers and integrated aquaponic systems. Recent advances in automation, sensor technologies, artificial intelligence, and LED lighting have transformed soilless farming from experimental laboratory setups to commercially viable production systems (Heuvelink et al., 2025).

Soilless agriculture refers to the cultivation of plants without the use of natural soil, where growth is sustained through alternative systems such as nutrient-rich water solutions (hydroponics), inert substrates (e.g., perlite, rockwool, or coco coir), or aeroponic misting. This method provides precise control over nutrient delivery, water use, and environmental conditions, optimizing plant growth while minimizing soil-borne diseases and resource waste (Gruda, 2019; Resh, 2022). In this article, we aim to provide a comprehensive review of the importance of soilless culture, its types, and its importance in plant nutrition.

2. Importance and Advantages of Soilless Cultivation

Hydroponics offers a means for food production in urban and peri-urban areas, which helps lower carbon emissions associated with long-distance food transportation(Gruda, 2009). Soilless cultivation to be crucial for achieving agricultural sustainability, as it provides a practical solution to the challenges associated with traditional agriculture. It enables crop cultivation in urban areas and regions with water scarcity or unsuitable soil, thereby contributing to local food security (Despommier, 2010). The many benefits of soilless cultivation systems. They offer a sustainable solution for areas with poor soil quality and limited arable land, allowing for high-quality crop production without requiring large amounts of water or soil. Moreover, these systems reduce the risk of soil-borne diseases and pests, enhancing crop yield and quality. The flexibility in managing plant nutrition and root zone conditions further supports growth, especially in controlled environments like greenhouses (Holmes, 2017). Hydroponics is often promoted as an environmentally sustainable agricultural practice. Compared to traditional soil agriculture, hydroponics uses 90% less water, reduces land use by up to 75%, and decreases the need for pesticides and herbicides (Despommier, 2010; Spadaro and Gullino, 2019).

Hydroponics allows for precise nutrient delivery to plants, reducing waste and increasing nutrient use efficiency. One of hydroponics' main advantages is its high water efficiency, as hydroponic systems can save up to 80% more water than traditional agriculture. Hydroponics relies on nutrient-enriched water instead of soil, making it ideal for regions facing water scarcity or unsuitable soils. This system significantly reduces water consumption as water can be reused repeatedly within the system. And also noted that in hydroponics, water is recirculated through closed-loop systems, significantly reducing waste. This makes it particularly suitable for arid areas where water scarcity is a major concern. The recycling feature also minimizes water loss, making it ideal for regions with limited water resources. Hydroponics also reduces the need for chemical fertilizers and pesticides, improving the final product's quality. (Sonneveld and Voogt, 2009; Barbosa et al., 2015; El-Essawy et al., 2019). Soilless systems provide significant environmental advantages including reduced pesticide usage, elimination of nutrient runoff, decreased greenhouse gas emissions from reduced transport distances, and conservation of arable land (Fussy and Papenbrock, 2022). Soilless systems demonstrate remarkable water conservation, achieving 50-95% reductions in water usage compared to conventional field agriculture. Also, it consistently demonstrate superior productivity per unit area. Research documents yield improvements of 5.4-11 times compared to field cultivation, depending on the crop and system type (Lakhiar et al., 2025).

3. Soilless farming systems

System Classification

Soilless farming systems can be broadly categorized into two primary types: (i) substrate-based culture (solid media), and (ii) water-based culture (liquid media) (Fussy and Papenbrock, 2022; Lakhiar et al., 2025). This classification is based on the physical support provided to plant roots and the method of nutrient delivery. Substrate-based systems utilize solid growing media to provide physical support and nutrient retention. These systems include organic substrates such as coconut coir, peat moss, pine bark, and rice hulls, as well as inorganic substrates like perlite, vermiculite, rockwool, and expanded clay pellets. Water-based systems, however, suspend plant roots directly in nutrient solutions or provide intermittent nutrient delivery through various mechanisms. These systems include traditional hydroponics, aeroponics, and aquaponics.

Hydroponic Systems

Hydroponic systems represent the most widely adopted form of soilless cultivation, with numerous subsystem variations developed for specific crops and growing conditions.

Nutrient Film Technique (NFT)

Hydroponics is a method of growing plants without soil. Hydroponics relies on using a nutrient solution containing the nutrients necessary for plant growth instead of soil (Mariyappillai et al., 2020). As shown Fig. 1 the system utilizes channels typically measuring 0.10 m height × 0.05 m width × 1.2 m length, with plant spacing of 15.24 cm apart, and maintains nutrient solutions at pH 5.8 and electrical conductivity of 1.5-2.0 mS/cm. The Nutrient Film Technique involves circulating a thin, continuous film of nutrient solution through sloped channels, allowing plant roots to access both nutrients and oxygen (Singh and Yang, 2021). NFT systems demonstrated remarkable efficiency in recent studies, with lettuce cultivation achieving 62% water savings compared to traditional irrigation methods (Lakhiar et al., 2025).

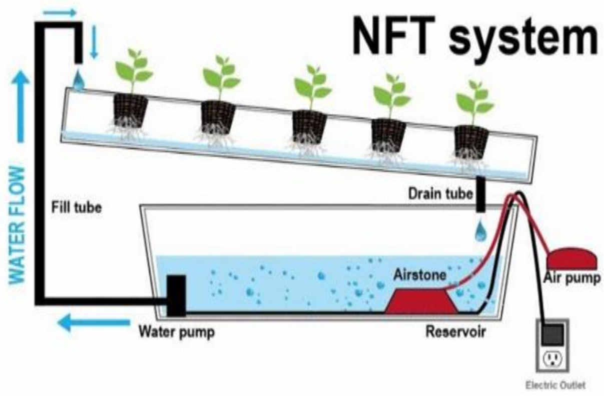

Figure 1. Nutrient Film Technique (NFT) (Sharma et al., 2018)

Deep Flow Technique (DFT)

Deep Flow Technique (DFT) as shown Fig 2 is a closed hydroponic system and one of the prominent methods in hydroponics that has gained significant attention due to its ability to enhance plant growth and achieve high resource efficiency. Similar to other hydroponic systems, DFT does not rely on soil; instead, it uses a nutrient solution to feed the plant roots. However, unlike NFT, DFT involves deeper nutrient solution flow, providing a more stable and robust environment for the plant roots. This technique is ideal for growing plants with large roots and extensive root systems, and it has increasingly been adopted in both small- and large-scale commercial operations. In DFT system, plants are placed in a growth medium (such as mesh pots) above a deep, flowing nutrient solution. The roots of the plants are submerged in the nutrient solution, which continuously flows at a depth typically ranging from 15 to 20 cm. Unlike NFT system, where the water layer is shallow, DFT system ensures that the roots are directly exposed to the nutrient solution while being adequately exposed to air, ensuring proper aeration. Water is pumped from the reservoir to the growing channels, flowing over the plant roots. After passing through the roots, the water returns to the reservoir for recirculation. This process ensures a continuous flow of water and nutrients to the plants, helping to improve their growing conditions. The depth of the nutrient solution in DFT systems helps to reduce fluctuations in nutrient concentration, temperature, and pH, creating a morestable environment for growth (Resh, 2022; Lakhiar et al., 2025).

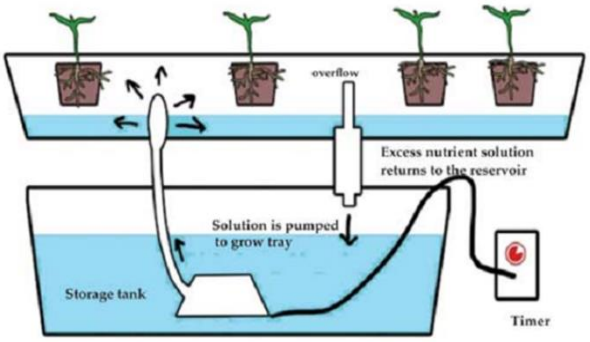

Figure 2. Deep Flow Technique (DFT) (Sharma et al., 2018)

Root Dipping Technique (RDT)

According to Mariyappillai et al. (2020) and Resh, (2022), the root dipping technique (RDT) as shown Fig 3 is one of the modern approaches in hydroponics, where plant roots are directly immersed in a nutrient-rich solution. This technique aims to improve nutrient absorption by providing the roots with constant access to a high concentration of nutrients, leading to enhanced plant growth and productivity. It differs from traditional hydroponic systems such as the Nutrient Film Technique (NFT) and Deep Flow Technique (DFT), as it focuses on the depth of immersion and the direct interaction of roots with the nutrient solution. The principle of the RDT is simple: plants are placed in a growing medium (such as net pots or foam blocks), and the roots are submerged in a reservoir containing the nutrient solution.

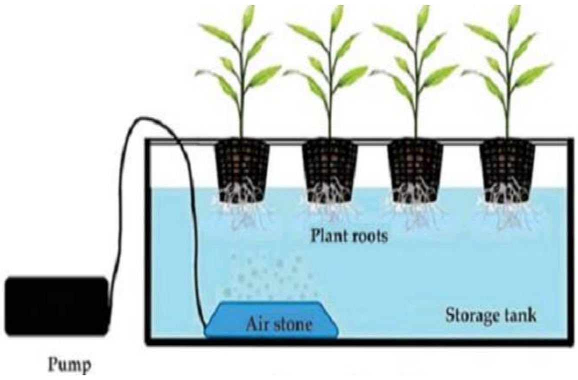

Figure 3. Root Dipping Technique (RDT) (Sharma et al., 2018)

Aquaponic Systems

Aquaponics integrates recirculating aquaculture with hydroponic plant cultivation, creating symbiotic systems where fish waste provides nutrients for plants while plants filter water for fish. Recent life cycle assessments demonstrate that aquaponics produces 45% lower environmental impacts than standalone hydroponic systems. These systems achieve 90-99% water savings compared to conventional aquaculture and utilize 50% of fish-feed nutrients for plant production, as shown Fig 4 (Fussy and Papenbrock, 2022; Lakhiar et al., 2025).

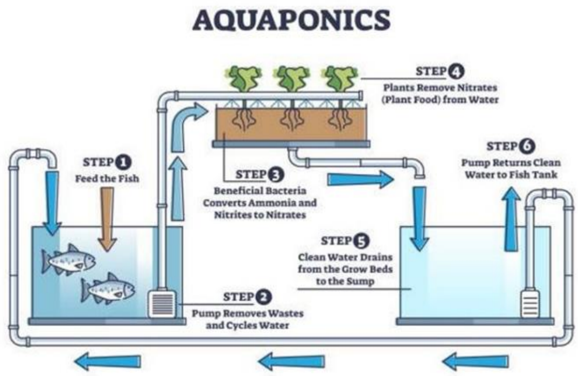

Figure 4. Aquaponics system (Balaur and Calin, 2023).

Aeroponic Systems

Aeroponics represents the most advanced form of soilless cultivation, where plant roots are suspended in air and periodically misted with nutrient solutions. NASA research has demonstrated that aeroponic systems can reduce water usage by up to 99%, nutrient requirements by 50%, and crop cycles by 45% compared to conventional agriculture, as shown in Fig. 5 (Lakhiar et al., 2018).

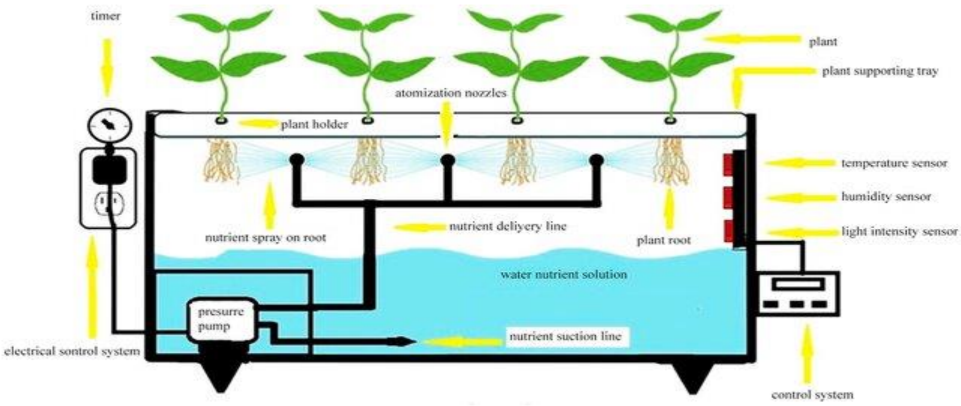

Figure 5. Aeroponic system (Lakhiar et al., 2018).

Aeroponics is one of the most water-efficient farming methods. Resh, (2022) noted that aeroponics is highly suited for vertical farming systems, making it ideal for urban agriculture. Plants can be arranged in multiple layers, maximizing the use of limited space. This design also enables high-density crop cultivation, thereby increasing productivity per unit area

4. Growing Media and Substrate (Solid Media Culture)

The selection of appropriate growing media is crucial for soilless system performance, affecting water retention, aeration, nutrient availability, and root development. Recent research has provided comprehensive comparisons of various substrates based on physical properties, environmental impact, and economic considerations. Solid Media Culture represent a type of soil-less farming, where plants are grown in an inert growing medium that provides structural support to the roots, while nutrients are supplied through an irrigation system. Organic media such as peat moss, wood shavings, rice husks, coconut fibers, and inorganic growth media such (e.g. gravel, perlite, vermiculite, and rock wool) are also utilized in these systems (Khalaf and Chali, 2021).

Figure 6. Some examples of the substrate materials (Lakhiar et al., 2025).

Characteristics of solid media culture

Table 1 show a detailed analysis of different growing media reveals significant variations in pH characteristics, and performance metrics.

5. Nutrient Solution Formulations and Management

Several nutrient solutions are commonly used in soilless agriculture as shown in Table 2. Modern hydroponic nutrient solutions contain all 17 essential elements required for plant growth: macronutrients (nitrogen, phosphorus, potassium), secondary nutrients (calcium, magnesium, sulfur), and micronutrients (iron, manganese, zinc, copper, boron, molybdenum). Nutrient solution composition and management represent critical factors determining soilless system success. Recent research has advanced understanding of optimal nutrient formulations, pH management, and electrical conductivity control for various crops and growing conditions (Meselmani, 2022). For the majority of crops, the ideal EC range for hydroponics is 1.5 to 2.5 dS m^{-1}. While, the ideal pH range for a fertilizer solution is between 5.5 and 6.5 for plant growth (Sharma et al., 2018).

Table 1. Characteristics of some types of solid media culture (Fussy and Papenbrock, 2022).

Growing Medium	pH	Water Retention	Aeration	Advantages	Disadvantages
Rockwool	Basic (7.0-8.0)	High	18-25% air	Excellent water/air balance, sterilizable	High pH, non-biodegradable, dust irritation
Coconut Coir	Neutral	Excellent	Good	Biodegradable, contains growth promoters	High salinity potential, requires Ca/Mg supplementation
Perlite	Neutral	3-4x weight	Excellent	Low cost, sterile, excellent oxygen retention	Lightweight, dust issues, algae prone
Vermiculite	Basic	Very high	Moderate	High CEC, excellent water retention	Can waterlog, disintegrates during sterilization
Sand	Neutral	Very low	Good	Inexpensive, durable, chemically inert	Heavy, low nutrient holding, salt buildup
Peat Moss	Acidic (3.8-4.5)	Up to 10x weight	Good	High moisture holding, easy disposal	Disease prone, acidic, unsustainable extraction

Table 2 Concentrations of macro- and micronutrients in some nutrient solution in mgL^{-1} (Meselmani, 2022).

Element	Hoagland and Arnon	Hewitt	Cooper	Steiner
	mg L^{-1}			
Nitrogen	210	168	200–236	168
Phosphorus	31	41	60	31
Potassium	234	156	300	273
Calcium	160	160	170–185	180
Magnesium	34	36	50	48
sulfur	64	48	68	336
Iron	2.5	2.8	12	2–4
Copper	0.02	0.064	0.1	0.02
Zinc	0.05	0.065	0.1	0.11
Manganese	0.5	0.54	2	0.62
Boron	0.5	0.54	0.3	0.14
Molybdenum	0.01	0.04	0.2	Not considered

6. Disadvantages

Despite significant advantages, soilless farming faces several challenges that limit widespread adoption. Soilless systems require sophisticated technical knowledge for successful operation, including understanding of plant physiology, nutrient chemistry, environmental control, and system maintenance. Failure risks are high, as equipment malfunctions or management errors can result in total crop loss (Fussy and Papenbrock, 2022). High initial capital investments represent the primary barrier to soilless farming adoption. Infrastructure costs for controlled environment facilities, lighting systems, climate control, and automation equipment can be 10-100 times higher than conventional farming setups. Operational costs, particularly energy consumption for lighting and climate control, can significantly impact profitability. Also, Energy demands, particularly for artificial lighting in vertical farming systems, create substantial operational costs and environmental concerns. LED lighting advances have improved efficiency, but energy costs remain a significant challenge. In addition, Current soilless systems are economically viable primarily for high-value, short-cycle horticultural crops such as leafy greens, herbs, and certain fruiting vegetables. Staple crops like grains and root vegetables remain economically challenging due to space requirements and energy costs (Lakhiar et al., 2025).

CONCLUSION

Soilless farming systems have evolved from experimental technologies to commercially viable agricultural production methods. These systems offer compelling solutions to global challenges including water scarcity, land limitations, and food security concerns. Research demonstrates remarkable achievements in resource efficiency, with water savings of 50-95% and yield increases of 5-11 times compared to conventional agriculture.

However, significant challenges remain, particularly regarding energy consumption, initial capital costs, and technical complexity. Continued research into crop diversification, biological system optimization, and economic models will determine the extent to which these systems can contribute to global food security. As climate change intensifies and urban populations grow, soilless farming systems represent essential technologies for developing resilient, sustainable food production systems. The research reviewed here demonstrates that while challenges remain, the potential benefits justify continued investment in soilless agriculture development and deployment.

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نظرة عامة على أنظمة الزراعة بدون تربة: المزايا والعيوب

مدحت عصام محمد الصعيدى[1] ، ايمان محمود فرحات[1] ، مجدي محمد الشازلي[2] ، أحمد عبد القادر طه[1]

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الملخص

تُمثل الزراعة بدون تربة بديلاً واعداً للزراعة التقليدية في المناطق التي تعاني من تدهور التربة وندرة المياه والضغوط البيئية، وهي تحديات شائعة بشكل خاص في مصر. وقد أدى الطلب المتزايد على الممارسات الزراعية المستدامة إلى اهتمام كبير بأنظمة الزراعة بدون تربة كبدائل للزراعة التقليدية القائمة على التربة. تُسلط هذه الدراسة الضوء على أنواع الزراعة بدون تربة وأهم مزاياها وعيوبها. تُقدم الزراعة بدون تربة - التي تشمل كلاً من الزراعة المائية (تقنية الغشاء المغذي، تقنية التدفق العميق ، الزراعة السمكية النباتية، الزراعة الهوائية) والأنظمة القائمة على البيئات الصلبة - العديد من المزايا مقارنةً بالزراعة التقليدية، بما في ذلك تحسين كفاءة استخدام الموارد، وتحسين جودة المحاصيل، وزيادة الغلة لكل وحدة مساحة، وتقليل الأثر البيئي. ومع ذلك، لا تزال هناك تحديات كبيرة، لا سيما فيما يتعلق باستهلاك الطاقة، وتكاليف رأس المال الأولية، والتعقيد التقني. يشكل تركيب المحلول المغذي وإدارته عوامل حاسمة في تحديد نجاح النظام الخالي من التربة. تتيح البيئة المُتحكم بها التي توفرها هذه الأنظمة إدارة دقيقة لتغذية النبات، وإمدادات المياه، وظروف منطقة الجذور، مما يؤدي إلى نمو وتطور مثاليين للنبات.