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Advances in soilless culture techniques for sustainable vegetable production: Systems, disease management and disinfection strategies

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Abstract

Soilless culture has emerged as an advanced and sustainable technology for vegetable production under conditions of declining arable land, soil degradation, salinity, water scarcity, and climate change. This review focuses on recent advances in soilless culture techniques, including hydroponics, aeroponics, and substrate-based systems, highlighting their role in improving productivity, resource-use efficiency, and produce quality. Historical developments, system classifications, and various hydroponic techniques such as Nutrient Film Technique (NFT), Deep Flow Technique (DFT), and non-circulating methods are discussed in detail. Special emphasis is given to solid media culture and aeroponic systems, particularly their application in high-value vegetable production and seed potato multiplication. The review also addresses disease incidence in soilless systems, identifying major pathogens affecting crops like tomato, cucumber, lettuce, and pepper, with particular attention to waterborne pathogens such as *Pythium* and *Phytophthora*. Various substrate and nutrient solution disinfection methods, including chemical approaches (ozone, hydrogen peroxide, sodium hypochlorite, chlorine dioxide, and copper-silver ionization) and physical methods (heat treatment, ultraviolet radiation, membrane filtration, and slow sand filtration), are critically evaluated. Among these, heat treatment and UV radiation are found to be highly effective in controlling pathogen spread in recirculating systems. Despite its numerous advantages, the adoption of soilless culture is limited by high initial investment, lack of standardized protocols, and insufficient technical awareness. Therefore, further research, technological refinement, and dissemination of scientifically validated practices are essential to enhance its adoption. Overall, soilless culture offers immense potential for sustainable, high-quality vegetable production and future food security.

Keywords: Soilless culture, Hydroponics, Aeroponics, Substrate culture, Nutrient solution, Disinfection methods, Waterborne pathogens, *Pythium*, *Phytophthora*, Vegetable production Protected cultivation, Sustainable agriculture

Introduction

Soilless culture represents one of the most significant technological advancements in modern horticulture, offering innovative solutions for sustainable vegetable production under conditions of declining arable land, soil degradation, salinity, water scarcity, and rapid climate change. Soilless culture refers to the cultivation of plants without the use of natural soil, where plant roots are supplied with essential nutrients through nutrient solutions, either directly in water or through inert substrates such as cocopeat, perlite, vermiculite, rockwool, sand, or other artificial media (Resh, 2013) [36]. This system provides mechanical support, water, oxygen, and mineral nutrition in a controlled environment, thereby ensuring optimal plant growth, enhanced productivity, and superior produce quality.

The concept of growing plants without soil is not entirely modern, as evidence suggests that ancient civilizations practiced primitive forms of soilless agriculture. The Hanging Gardens of Babylon, constructed around 600 BC, are often cited as one of the earliest examples of soilless or semi-hydroponic cultivation systems, while Egyptian records also indicate the use of water-based crop cultivation methods (Jones, 2016) [19]. Scientific investigation into soilless plant growth began during the 17th century when Sir Francis Bacon discussed water culture techniques in his

work *Sylva Sylvarum* (1627). Subsequently, John Woodward in 1699 successfully grew spearmint in water containing dissolved soil particles, demonstrating the importance of mineral nutrients in plant development (Treftz and Omaye, 2015)^[45].

Further advancements were made in the 19th century through the pioneering nutrient solution formulations developed by German scientists Julius von Sachs and Wilhelm Knop during the 1860s, which laid the scientific foundation for modern hydroponics (Sachs, 1860; Knop, 1861)^[20]. The term “hydroponics” itself was coined by Dr. William Frederick Gericke of the University of California in 1929, who popularized large-scale commercial production of crops in nutrient solutions without soil (Gericke, 1937)^[12]. Since then, soilless cultivation technologies have undergone remarkable progress, including the development of the Nutrient Film Technique (NFT) by Allen Cooper in 1965, aeroponics systems in the 1980s, and aquaponics integration combining hydroponics with aquaculture (Cooper, 1979; Jensen, 1997)^[9, 18]. In India, hydroponic cultivation was first introduced in Kalimpong, Darjeeling, during 1947, marking the beginning of controlled environment agriculture in the country (Savvas and Gruda, 2018)^[40].

Soilless culture encompasses diverse systems such as hydroponics, aeroponics, aquaponics, substrate culture, deep water culture, wick systems, drip systems, ebb and flow systems, and vertical farming technologies. Among these, hydroponics remains the most widely adopted method, wherein plants are cultivated in nutrient-enriched water with or without substrate support. Aeroponics involves misting nutrient solutions directly onto roots suspended in air, promoting efficient oxygenation and rapid growth. Aquaponics integrates fish farming with hydroponics, creating a sustainable circular system (Gruda, 2019)^[13].

The growing popularity of soilless culture is largely attributed to its numerous agronomic, environmental, and economic advantages. It eliminates soil-borne diseases, nematodes, and many pests, thereby reducing pesticide dependency and improving crop health. Soilless systems enable year-round production, continuous cropping, and significantly higher yields per unit area and time due to precise nutrient and water management (Sharma *et al.*, 2018)^[43]. Water use efficiency is substantially improved, often reducing water consumption by 70-90% compared to conventional soil-based agriculture, which is especially critical in arid and semi-arid regions (Raviv *et al.*, 2019)^[35]. Additionally, these systems facilitate vegetable cultivation in non-arable lands, urban spaces, saline soils, and desert environments, thereby expanding production potential in resource-constrained areas.

Vegetable crops such as tomato, cucumber, capsicum, lettuce, spinach, strawberry, and herbs have shown exceptional performance under soilless systems due to better nutrient availability, controlled root-zone conditions, and reduced environmental stress. Furthermore, the superior quality of produce including improved size, color, nutritional composition, shelf life, and reduced contamination makes soilless cultivation particularly attractive for commercial horticulture and export markets (Massa *et al.*, 2020)^[26].

With increasing global food demand, urbanization, and unpredictable climatic conditions, soilless culture is emerging as a cornerstone of future protected agriculture. It offers a promising strategy to address challenges related to food security, environmental sustainability, and climate resilience while supporting intensive vegetable production systems. Therefore, understanding the various techniques of soilless culture and their

practical applications in vegetable production is essential for advancing sustainable horticultural practices worldwide.

Types of production systems

1. Soil culture or geponics

Soil culture, also known as geponics, is the traditional and most widely practiced system of crop production in which plants are cultivated directly in natural soil. Soil serves as a natural medium that provides mechanical support, water retention, aeration, and essential mineral nutrients required for plant growth and development. It functions as a dynamic ecosystem containing organic matter, beneficial microorganisms, and physicochemical properties that regulate nutrient cycling and root-zone interactions (Brady & Weil, 2017)^[5]. Under ideal conditions, fertile soils offer an effective environment for vegetable cultivation due to their buffering capacity, nutrient-holding potential, and biological diversity.

Despite its historical importance, soil-based cultivation presents several limitations that increasingly challenge sustainable vegetable production. Soil-borne diseases caused by pathogens such as *Fusarium*, *Pythium*, *Rhizoctonia*, and nematodes can significantly reduce crop yield and quality, particularly in intensive horticultural systems (Savvas *et al.*, 2013)^[41]. Furthermore, unsuitable soil pH, salinity, alkalinity, and nutrient imbalances may restrict plant growth and productivity. Continuous cultivation often leads to soil degradation through erosion, nutrient depletion, salinization, and loss of organic matter, thereby diminishing long-term agricultural sustainability (Lal, 2015)^[23].

Physical constraints such as soil compaction, poor drainage, and inadequate aeration can adversely affect root growth and nutrient uptake, especially under conditions of excessive irrigation or heavy rainfall. Traditional soil cultivation also demands substantial water inputs and labor for land preparation, weeding, irrigation, and disease management. Rapid urbanization and industrial expansion have further reduced the availability of fertile arable land, particularly around metropolitan regions, limiting opportunities for conventional vegetable farming (FAO, 2021)^[11]. In addition, climate change-induced stresses such as drought, flooding, temperature fluctuations, and soil health deterioration have intensified production risks in open-field agriculture (IPCC, 2022)^[17].

These constraints have prompted the search for alternative cultivation systems capable of ensuring stable productivity while conserving natural resources. In this context, soilless culture systems have gained increasing importance as efficient and sustainable production technologies. A wide range of vegetable crops, including fruiting vegetables, leafy greens, root crops, and herbs, have shown excellent adaptability to soilless systems such as hydroponics, Nutrient Film Technique (NFT), Deep Flow Technique (DFT), substrate culture, and aeroponics. The suitability of different crops and their respective advantages under soilless culture systems are summarized in Table 1. These systems offer improved yield, better quality produce, efficient resource utilization, and the ability to cultivate crops under controlled environmental conditions, thereby addressing many of the limitations associated with conventional geponics.

2. Soilless culture

Soilless culture is an advanced plant production system in which crops are grown without natural soil, using nutrient-enriched water or inert substrates to supply plants with water, nutrients, and physical support. This technology was developed to overcome many of the limitations associated with soil

cultivation, particularly soil-borne diseases, declining land resources, salinity, and climate-related production challenges. In soilless systems, plants receive precisely formulated nutrient solutions, allowing optimal control over root-zone conditions, resulting in improved growth, productivity, and produce quality (Resh, 2013)^[36].

Soilless culture is generally classified into three major categories: solution culture, solid media culture and aeroponics.

Solution culture

involves direct plant growth in nutrient solutions and may be further divided into circulating systems, such as Nutrient Film Technique (NFT) and Deep Flow Technique (DFT), and non-circulating systems, including root dipping, floating, and capillary action methods. These systems maximize water and nutrient efficiency while minimizing wastage (Jones, 2016)^[19].

Solid media culture

utilizes inert substrates such as cocopeat, perlite, vermiculite, rockwool, sand, or gravel to provide root support while nutrients are supplied through irrigation. Common techniques include hanging bag culture, grow bag systems, trough culture, and pot culture. These systems are especially suitable for greenhouse vegetable production and protected cultivation (Gruda, 2019)^[13].

Aeroponics

Aeroponics is a highly advanced system in which plant roots are suspended in air and periodically misted with nutrient solutions. This method ensures maximum oxygen availability, faster growth rates, and superior nutrient absorption, making it suitable for high-value vegetable crops and seed production (Barak *et al.*, 1996)^[2].

The advantages of soilless culture include efficient water use, precise nutrient management, year-round production, reduced pesticide application, elimination of soil-related constraints, and the possibility of cultivating crops in urban, arid, saline, or non-arable regions (Sharma *et al.*, 2018)^[43]. Moreover, soilless systems contribute significantly to climate-resilient agriculture by enabling controlled environment production with minimal resource losses. As global agriculture faces increasing pressure from population growth, land scarcity, and environmental degradation, soilless culture has emerged as a sustainable and technologically advanced alternative for modern vegetable production.

Hydroponics

Hydroponics is a highly specialized and scientifically advanced branch of soilless culture in which plants are cultivated without natural soil, with roots supplied directly by nutrient-enriched water solutions under carefully regulated environmental conditions. This system allows precise management of mineral nutrition, water supply, oxygenation, pH, and electrical conductivity, thereby optimizing plant growth and productivity (Gericke, 1937; Resh, 2013)^[12, 36]. The concept of hydroponics evolved from early nutrient solution experiments by Sachs and Knop in the nineteenth century and gained commercial significance when Gericke demonstrated large-scale crop cultivation in water culture. Today, hydroponics is recognized globally as a sustainable production technology capable of overcoming many limitations of conventional soil agriculture, including land scarcity, soil degradation, salinity, water shortages, and climate instability (Savvas & Gruda, 2018)^[40]. A typical hydroponic system used for leafy vegetable cultivation under protected conditions is illustrated in Figure 1.

Hydroponic systems are increasingly important in modern vegetable production because they require substantially less water than field cultivation, often reducing water use by 80-90% through recirculation and efficient nutrient delivery (Barbosa *et al.*, 2015)^[3]. Nutrient solutions can be tailored to crop-specific requirements, resulting in accelerated growth rates, increased yields, improved produce quality, and reduced fertilizer wastage (Sambo *et al.*, 2019)^[38]. Moreover, the elimination of soil minimizes weed competition and greatly reduces the incidence of soil-borne pathogens such as *Fusarium*, *Pythium*, and nematodes (Sharma *et al.*, 2018)^[43]. These advantages make hydroponics particularly suitable for urban agriculture, protected cultivation, vertical farming, and production in environmentally stressed regions.

Hydroponics has been successfully applied to a wide range of vegetable crops including lettuce, spinach, tomato, cucumber, pepper, herbs, and strawberry, with substantial improvements in resource-use efficiency and crop consistency (Jones, 2016)^[19]. Technological advancements have also enabled specialized systems such as automated hydroponic micropropagation for potato seed production, as demonstrated by the Automated Hydroponic System patented by ICAR-Central Potato Research Institute, Shimla, in 2008. Such developments illustrate the growing integration of hydroponics into both commercial horticulture and advanced plant biotechnology.

Classification of hydroponic systems

Hydroponic systems are broadly classified into circulating (closed) systems and non-circulating (open or semi-closed) systems, depending on whether nutrient solutions are recirculated.

Hydroponics is one of the most advanced and widely adopted forms of soilless culture, involving the cultivation of plants in nutrient-enriched water solutions without the direct use of natural soil. In hydroponic systems, plant roots are either suspended in aerated nutrient solutions or supported by inert substrates while receiving precisely balanced macro- and micronutrients through water. The term “hydroponics,” derived from the Greek words *hydro* (water) and *ponos* (labor), was popularized by William Frederick Gericke in 1929, who demonstrated the commercial feasibility of large-scale crop production without soil (Gericke, 1937)^[12]. Hydroponics has since evolved into a highly efficient production technology for vegetables, flowers, medicinal plants, and seed propagation.

Hydroponic cultivation offers substantial advantages over conventional soil-based agriculture, particularly under conditions of land scarcity, water limitations, salinity, and climate stress. Compared with traditional field cultivation, hydroponic systems generally consume only 10-20% of the water required in soil systems because nutrient solutions are recirculated, thereby minimizing evaporation, runoff, and deep percolation losses (Barbosa *et al.*, 2015)^[3]. This remarkable water-use efficiency makes hydroponics highly suitable for arid, semi-arid, and urban environments where freshwater resources are increasingly constrained. In addition, hydroponics eliminates many soil-borne pathogens, weeds, and nematodes, significantly reducing pesticide use and improving crop quality (Sharma *et al.*, 2018)^[43].

Hydroponics is particularly effective for high-value vegetable crops such as lettuce, spinach, tomato, cucumber, capsicum, strawberry, and herbs. Controlled nutrient delivery, oxygenation, and environmental regulation allow plants to achieve faster growth, higher yields, improved nutritional quality, and year-round production under greenhouse or indoor systems (Sambo

al., 2019) [38]. Modern innovations have further expanded hydroponic applications, such as the Automated Hydroponic System (AHS) patented by ICAR-Central Potato Research Institute, Shimla, in 2008 for *in vitro* potato microtuber production, demonstrating its utility in plant propagation and seed systems.

Types of hydroponic systems

Hydroponic systems are broadly classified into circulating methods and non-circulating methods, depending on whether the nutrient solution is continuously recycled.

1. Circulating methods

Nutrient Film Technique (NFT)

The Nutrient Film Technique (NFT) is one of the most commercially successful hydroponic systems. In NFT, a thin film of nutrient solution continuously flows through narrow, slightly sloped channels, allowing plant roots to absorb water, nutrients, and oxygen simultaneously. Excess nutrient solution is collected at the lower end and recirculated back into the reservoir, making the system highly water- and nutrient-efficient (Cooper, 1979) [9] (Figure 2). NFT is especially suitable for leafy vegetables such as lettuce, spinach, basil, and other short-duration crops due to its high oxygen availability and rapid nutrient uptake. Ikeda *et al.* (1995) [16] reported successful year-round spinach production in greenhouse NFT systems when cultivar selection and nutrient solution temperature were optimized. The primary advantages of NFT include minimal water consumption, precise nutrient control, rapid crop turnover, and reduced disease incidence. However, system failures such as pump breakdowns can quickly lead to root desiccation because roots are exposed in shallow nutrient films.

Deep Flow Technique (DFT)

Deep Flow Technique (DFT), also known as deep water culture, involves maintaining a deeper layer (2-3 cm or more) of continuously flowing nutrient solution in channels or PVC pipes, where plant roots remain partially submerged. Seedlings are placed in perforated pots, and the roots directly contact the nutrient solution while oxygen is supplied through aeration systems (Raviv *et al.*, 2019) [35] (Figure 3).

DFT provides a larger nutrient buffer than NFT, reducing plant stress during temporary interruptions in circulation. This system is suitable for lettuce, spinach, Asian greens, and herbs and is often arranged in linear or zigzag layouts to optimize greenhouse space. Due to greater solution volume, DFT offers more stable nutrient and temperature conditions than NFT.

2. Non-circulating methods

Root dipping technique

In the root dipping method, plants are grown in small pots containing inert media, while the lower portion of the root system is submerged in nutrient solution. The upper roots remain exposed to air, ensuring adequate oxygen supply. This system is simple, low-cost, and suitable for small-scale vegetable production or educational purposes (Sardare & Admane, 2013) [39] Figure 4.

Floating technique

The floating hydroponic system consists of shallow nutrient tanks, usually around 10 cm deep, where plants are supported on Styrofoam sheets or floating rafts. Plant roots remain continuously immersed in nutrient solution, while artificial aeration ensures sufficient oxygenation (Nicola *et al.*, 2005) [29].

[30] Figure 5. Floating systems are widely used for commercial lettuce and leafy vegetable production because of their simplicity, low maintenance, and suitability for large-scale operations.

Capillary action (wick) technique

Capillary action systems, also known as wick systems, use absorbent materials to transport nutrient solution from a reservoir into the growing medium via capillary movement. These systems are passive and do not require pumps or electricity, making them ideal for ornamental plants, nursery crops, and small indoor applications (Resh, 2013) [36] Figure 6. However, they are generally less suitable for large vegetable crops with high nutrient demands.

Solid media culture or aggregate systems

Solid media culture, also known as aggregate culture, is an important branch of soilless cultivation in which plants are grown in inert or organic substrates rather than directly in nutrient solution. In this system, the growing media provide physical support to plant roots while water and nutrients are supplied through fertigation or irrigation systems. Common substrates include cocopeat, peat, bark, sawdust, perlite, vermiculite, sand, rockwool, and synthetic materials. Solid media culture is widely used in greenhouse vegetable production because it combines the advantages of controlled nutrient management with improved root support, better aeration, and flexibility for a wide range of crops (Raviv *et al.*, 2019) [35]. Compared with liquid hydroponics, aggregate systems are often easier to manage, particularly for fruiting vegetables such as tomato, cucumber, sweet pepper, and strawberry, due to improved moisture buffering and reduced vulnerability to system failures (Savvas & Gruda, 2018) [40].

Hanging bag technique

The hanging bag technique is a vertical cultivation system in which cylindrical polyethylene bags, usually about one meter long, are filled with sterilized growing media such as cocopeat, sawdust, or peat mixtures. These bags are typically white on the outer surface to reflect excess heat and black on the inner layer to prevent light penetration and algal growth. The bags are sealed at the bottom, suspended vertically from support structures, and equipped with nutrient delivery tubes at the top. Planting holes are made along the sides of the bags, and seedlings are inserted into these openings. Nutrient solution is supplied through drip irrigation, allowing efficient moisture and nutrient distribution throughout the substrate (Gruda, 2019) [13]. This technique is particularly suitable for leafy vegetables, strawberry, herbs, and ornamentals, as it maximizes vertical space utilization, making it ideal for urban agriculture, greenhouse production, and protected cultivation systems. The vertical orientation also improves drainage, minimizes disease incidence, and enhances production per unit area.

Trench or trough technique

The trench or trough technique is a substrate-based system where plants are cultivated in narrow ground-level or raised troughs constructed from bricks, concrete blocks, or other durable materials. These troughs are lined with waterproof materials to prevent nutrient leakage and are filled with selected growing media such as sand, cocopeat, perlite, or gravel. The trough depth is generally maintained at a minimum of 30 cm to ensure adequate root development. Nutrient solution is supplied through drip irrigation or manual fertigation, while drainage

pipes placed at the bottom facilitate excess solution removal and prevent waterlogging (Jones, 2016) ^[19]. This method is particularly effective for long-duration and large vegetable crops such as tomato, cucumber, capsicum, and brinjal. Trough systems offer excellent root-zone stability, efficient nutrient delivery, and ease of management in greenhouse settings. Their durability and adaptability make them a preferred choice in commercial protected horticulture.

Grow bag technique

The grow bag technique is one of the most commercially successful forms of solid media culture, especially in greenhouse vegetable production. In this system, plastic grow bags are filled with suitable growing substrates such as cocopeat, peat, perlite, bark, or substrate blends. Plants are established in these bags, and nutrient solutions are delivered precisely through drip irrigation systems (Barrett *et al.*, 2016) ^[4]. Grow bags are commonly used for tomato, cucumber, sweet pepper, melon, and strawberry production due to their simplicity, cost-effectiveness, and efficient resource utilization. The system offers several advantages, including easy installation, portability, reduced soil-borne disease risk, and precise control over nutrient and water supply. Additionally, grow bags can be arranged in greenhouses to optimize space and improve crop management. However, environmental concerns regarding plastic disposal and the need for periodic substrate replacement remain challenges.

Classification of soilless culture media

Soilless culture media are broadly classified into organic media, inorganic natural media, and synthetic media, based on their origin and physical properties.

Organic media include naturally derived substrates such as sawdust, cocopeat, peat, woodchips, fleece, marc, and bark. These materials generally possess excellent water-holding capacity, moderate aeration, and biodegradability. Among them, cocopeat is particularly popular due to its sustainability, high porosity, and favorable moisture retention characteristics (Gruda, 2019) ^[13].

Inorganic natural media consist of mineral-based substrates such as vermiculite, gravel, rockwool, perlite, sand, glasswool, pumice, zeolite, and sepiolite. These materials are valued for their structural stability, sterility, excellent drainage, and long-term durability. Perlite and vermiculite are especially favored for balancing aeration and water retention, while rockwool remains a dominant medium in commercial hydroponic vegetable production (Savvas *et al.*, 2013) ^[40].

Synthetic media include artificially manufactured materials such as hydrogel, foam mats (polyurethane), and oasis (plastic foam). These substrates are lightweight, sterile, and designed to optimize moisture retention and root-zone conditions. They are often used in propagation systems, nursery production, and specialized ornamental cultivation (Resh, 2013) ^[36].

The choice of growing medium depends on crop species, irrigation method, local availability, economic feasibility, and sustainability considerations. With growing emphasis on environmentally friendly horticulture, renewable and biodegradable substrates such as cocopeat and bark are gaining increasing importance in modern soilless vegetable production systems.

Aeroponics

Aeroponics is an advanced soilless cultivation technology in which plants are grown with their roots suspended freely in air and intermittently supplied with nutrient solution in the form of

a fine mist. Plants are typically anchored in holes on Styrofoam sheets, plastic panels, or specialized support structures, while their root systems remain enclosed within a dark chamber below. This method ensures direct access of roots to oxygen, moisture, and essential nutrients, thereby maximizing nutrient uptake efficiency and root respiration (Chiipanthenga *et al.*, 2012) ^[8]. Compared with conventional soil cultivation and even hydroponics, aeroponics offers superior oxygenation of the root zone, resulting in faster plant growth, increased biomass accumulation, reduced water consumption, and efficient nutrient utilization.

Aeroponic systems are particularly recognized for their exceptional resource-use efficiency. Water consumption can be reduced by up to 90-95% compared with traditional field cultivation because nutrient solution is precisely delivered and recaptured within closed systems (Barak *et al.*, 1996) ^[2]. Additionally, because roots are not embedded in soil or bulky substrate, the system eliminates many soil-borne diseases and facilitates easier root inspection and disease management. These advantages make aeroponics highly suitable for urban agriculture, vertical farming, controlled environment agriculture, and high-value crop production in areas with poor soil quality, salinity, or limited water resources (Buckseth *et al.*, 2016) ^[6].

Principles and working mechanism of aeroponics

In aeroponic systems, nutrient solution is atomized into microscopic droplets and sprayed directly onto plant roots at regular intervals through nozzles or misting devices. This fine mist provides an ideal balance of water, nutrients, and oxygen, promoting vigorous root development and high nutrient absorption efficiency. Since roots are suspended in air, they receive continuous access to oxygen, which is essential for cellular respiration and root metabolism (Otazu, 2010) ^[31]. Automated timers regulate nutrient misting cycles, ensuring optimal root hydration while preventing desiccation.

The major components of aeroponic systems include:

- Root chamber or enclosed misting chamber
- Nutrient reservoir
- High-pressure pump or mist generator
- Misting nozzles
- Support panels for plant anchorage
- Environmental monitoring systems

This precision-based system supports rapid vegetative growth, shortened crop cycles, and improved crop uniformity.

Aeroponics for potato seed production

Aeroponics has emerged as one of the most effective technologies for high-quality seed potato production due to its ability to generate disease-free mini-tubers with exceptionally high multiplication rates. Traditional potato seed systems are often constrained by low multiplication ratios, disease accumulation, and large land requirements. Aeroponics overcomes these limitations by enabling rapid production of pathogen-free mini-tubers from tissue-cultured plantlets under protected environments (Buckseth *et al.*, 2016) ^[6].

At the Central Potato Research Station (CPRS), Shillong, studies were conducted to evaluate cultivars such as Kufri Megha, Kufri Himalini, and Kufri Himsona under aeroponic systems in the North Eastern Hill region of India. Although all three cultivars produced mini-tubers, Kufri Megha exhibited comparatively superior performance, while Kufri Himalini and Kufri Himsona showed lower productivity under local conditions. These studies confirmed the feasibility of aeroponics for disease-free seed

potato production in northeastern India.

Similarly, the Central Potato Research Institute (CPRI), Shimla, assessed six potato cultivars including Kufri Himalini, Kufri Lauvkar, Kufri Sindhuri, Kufri Girdhari, Kufri Jyoti, and Kufri Khyati. First mini-tuber harvests occurred within 55-59 days for most cultivars, except Kufri Jyoti, which required nearly 90 days. Mini-tuber weight ranged from 2.3 g in Kufri Himalini to 3.8 g in Kufri Khyati, demonstrating substantial varietal differences in aeroponic productivity (Otazu, 2010) ^[31]. Such results underscore the potential of aeroponics for high-tech, rapid, and large-scale seed potato multiplication.

Advantages of aeroponics

Aeroponic systems offer numerous agronomic, environmental, and commercial advantages: Aeroponic systems provide exceptionally efficient use of water and nutrients due to precise mist-based nutrient delivery, significantly reducing wastage while maximizing plant uptake efficiency. Enhanced root aeration promotes vigorous root development, faster growth, and improved biomass accumulation compared with many conventional cultivation systems. The elimination of soil and solid substrates substantially lowers the incidence of soil-borne pathogens, while reduced pesticide and fertilizer requirements contribute to environmentally sustainable production. Aeroponics also enables year-round crop cultivation under protected environments, making it highly suitable for vertical farming, urban agriculture, and intensive commercial production. For seed crops such as potato, aeroponics offers remarkably high multiplication rates, reduced land requirements, and superior crop quality, making it a transformative technology for modern horticulture and climate-resilient food systems.

Disease incidence in soilless culture systems

Although aeroponics and other soilless systems substantially reduce exposure to soil-borne diseases, they are not inherently disease-free. Waterborne pathogens, airborne fungal spores, bacterial contamination, viruses, and insect vectors may still compromise crop health if sanitation is inadequate (Stanghellini & Rasmussen, 1994) ^[44]. In recirculating nutrient systems, pathogens such as *Pythium* spp., *Phytophthora* spp., and *Fusarium* spp. can spread rapidly through shared nutrient reservoirs, leading to severe crop losses. The major pathogens affecting important vegetable crops grown under soilless culture systems are presented in Table 2, which highlights the diversity of viral, bacterial, fungal, and nematode pathogens associated with crops such as tomato, cucumber, lettuce, and pepper.

Regulation of growth factors

Maintaining optimal environmental conditions such as temperature, humidity, pH, nutrient concentration, and oxygen availability is essential in aeroponic and hydroponic systems to minimize plant stress and reduce susceptibility to diseases. Proper regulation of these factors ensures balanced physiological processes, enhances plant immunity, and suppresses pathogen development. Stable root-zone conditions also limit the proliferation of opportunistic pathogens commonly listed in Table 2.

Control of pest and disease spread

Strict sanitation protocols are critical to prevent pathogen contamination and spread in soilless systems. This includes regular sterilization of nutrient reservoirs, pipelines, misting nozzles, tools, support structures, and root chambers. The use of

certified pathogen-free planting materials, restricted greenhouse access, and implementation of Integrated Pest Management (IPM) strategies further reduce the risk of infection. Since pathogens listed in Table 2 can spread rapidly through water and contact surfaces, maintaining hygiene is essential for disease prevention.

Removal of infected materials

Early detection and prompt removal of infected plants, diseased roots, and contaminated system components are essential to prevent rapid pathogen transmission in recirculating systems. Infected materials should be carefully disposed of to avoid secondary spread. This practice is particularly important for controlling aggressive pathogens such as *Pythium* and *Phytophthora*, which can quickly infect healthy plants through shared nutrient solutions, as indicated in Table 2.

Water sanitation technologies

Modern soilless culture systems increasingly depend on advanced water sanitation methods to maintain nutrient solution quality and suppress waterborne pathogens. These include ultraviolet (UV) irradiation, ozone treatment, membrane filtration, slow sand filtration, and heat treatment. The various chemical and physical disinfection methods used in soilless systems are summarized in Table 3. Chemical disinfectants such as ozone, hydrogen peroxide, sodium hypochlorite, chlorine dioxide, and copper-silver ionization provide rapid and broad-spectrum microbial control, while physical methods like UV radiation and thermal treatment are effective and environmentally safe alternatives. These technologies play a crucial role in commercial hydroponic and aeroponic systems where continuous recirculation of nutrient solutions can facilitate rapid disease spread (Postma *et al.*, 2008) ^[32].

Salient Findings

Studies on the disinfection of nutrient solutions in soilless culture systems have demonstrated that heat treatment is highly effective in controlling waterborne pathogens. Investigations conducted on tomato and cucumber revealed that the use of heat exchangers at 95 °C for 30 seconds efficiently eliminates major pathogens such as *Phytophthora cryptogea* and *Pythium aphanidermatum*, which are commonly responsible for root diseases in hydroponic systems. This method has been widely recognized as a reliable and environmentally safe approach for pathogen control in recirculating nutrient solutions (Runia *et al.*, 1988) ^[37].

In another study involving pepper and cucumber, the application of non-ionic surfactants proved to be highly effective in managing disease spread, particularly when mobile zoospores serve as the primary source of infection. The addition of surfactants at a concentration of 20 µg ml⁻¹ in the nutrient solution significantly reduced the spread of *Pythium* in cucumber and *Phytophthora* in pepper without causing any phytotoxic effects. This approach is especially useful in hydroponic systems where pathogen dispersal through water is rapid and difficult to control (Stanghellini *et al.*, 1996) ^[44]. Furthermore, Ultraviolet (UV) radiation has been reported as an efficient physical disinfection method, particularly in lettuce cultivation. UV treatment effectively controls *Pythium*-induced root rot by inactivating pathogenic microorganisms present in the nutrient solution. This method offers a chemical-free alternative and is suitable for integration into recirculating hydroponic systems.



Fig 1: Hydroponic cultivation of leafy vegetables in a protected growing structure using a nutrient film technique (NFT) system

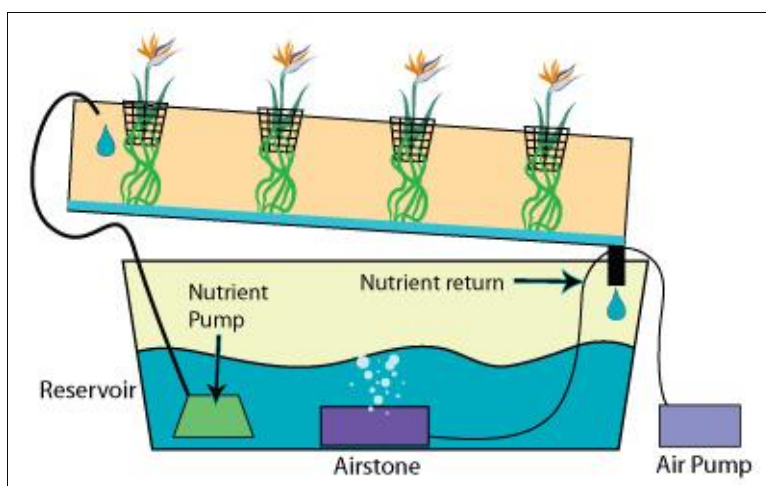


Fig 2: Schematic of a Nutrient Film Technique (NFT) hydroponic system

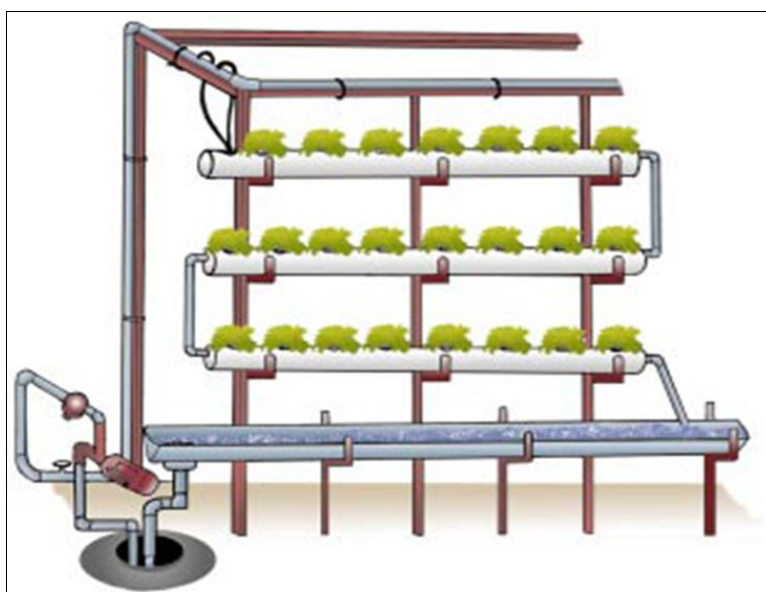


Fig 3: Vertical layout and circulation of a Deep Flow Technique (DFT) setup

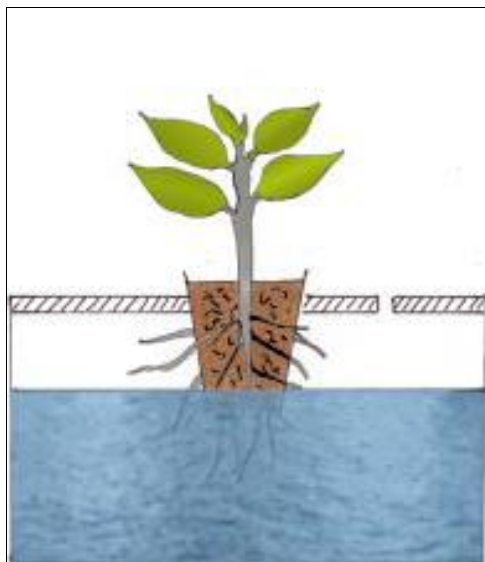


Fig 4: Schematic representation of the root dipping technique in a non-circulating hydroponic system

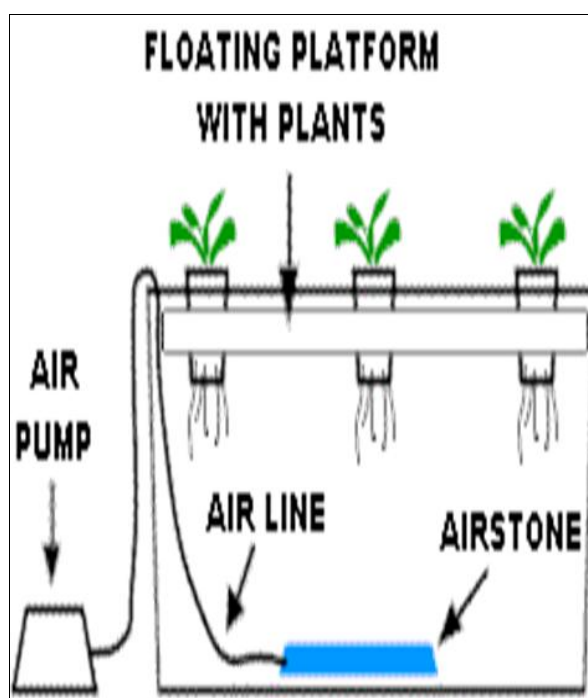


Fig 5: Schematic of a floating raft hydroponic system for leafy vegetable production

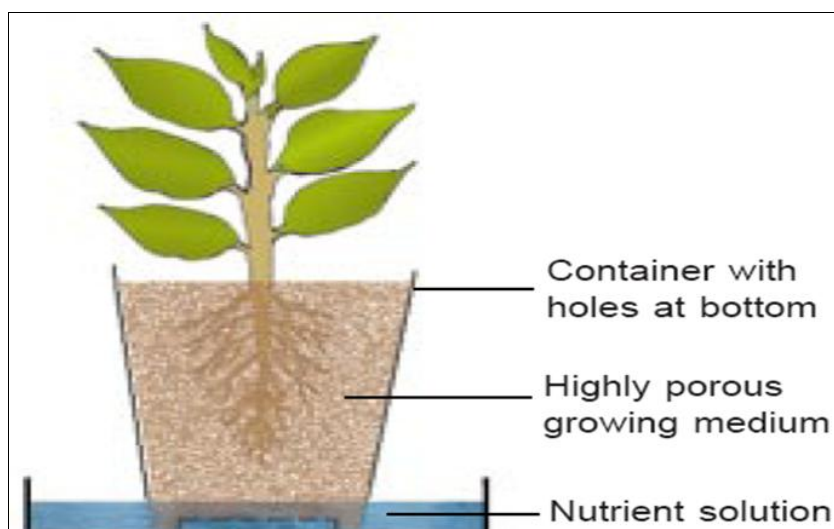


Fig 6: Schematic of a passive capillary action (wick) hydroponic system

Table 1: Crops suitable for soilless culture systems

Crop category	Common crops	Scientific names	Suitable soilless systems	Key advantages	References
Fruiting vegetables	Tomato	<i>Solanum lycopersicum</i>	Hydroponics, NFT, drip system, substrate culture	High yield, premium fruit quality, long production cycle	Resh (2013); Savvas & Gruda (2018) [36, 40]
	Chilli/Hot pepper	<i>Capsicum annum</i>	Hydroponics, substrate culture	Better nutrient control, improved fruit set	Jones (2016) [19]
	Sweet pepper/Bell pepper	<i>Capsicum annum var. grossum</i>	NFT, grow bags, drip hydroponics	Enhanced quality and market value	Savvas & Gruda (2018) [40]
	Brinjal/Eggplant	<i>Solanum melongena</i>	Substrate culture, drip systems	Controlled root-zone management	Kumar <i>et al.</i> (2021) [22]
	Cucumber	<i>Cucumis sativus</i>	NFT, DFT, substrate culture	Rapid growth, high water-use efficiency	Gruda (2019) [13]
Leguminous crops	Melons	<i>Cucumis melo</i>	Substrate culture, hydroponics	Improved fruit uniformity	Resh (2013) [36]
	Green bean	<i>Phaseolus vulgaris</i>	Hydroponics, substrate culture	Efficient nutrient uptake	Sharma <i>et al.</i> (2018) [43]
	Winged bean	<i>Psophocarpus tetragonolobus</i>	Media-based soilless systems	Adaptability to controlled environments	Raviv <i>et al.</i> (2019) [35]
Root and bulb crops	Beetroot	<i>Beta vulgaris</i>	Media beds, substrate culture	Better root quality	Jones (2016) [19]
	Radish	<i>Raphanus sativus</i>	Media-based hydroponics	Rapid crop cycle	Kumar <i>et al.</i> (2021) [22]
	Onion	<i>Allium cepa</i>	Substrate culture	Controlled bulb development	Sharma <i>et al.</i> (2018) [43]
Cole crops	Cabbage	<i>Brassica oleracea var. capitata</i>	Media beds, hydroponics	Nursery and protected cultivation	Savvas & Gruda (2018) [40]
	Cauliflower	<i>Brassica oleracea var. botrytis</i>	Substrate systems	Improved head quality	Raviv <i>et al.</i> (2019) [35]
Leafy vegetables	Lettuce	<i>Lactuca sativa</i>	NFT, floating raft, vertical farming	Fast growth, high profitability	Nicola <i>et al.</i> (2005) [29, 30]
	Spinach	<i>Spinacia oleracea</i>	NFT, DFT	Year-round production	Ikeda <i>et al.</i> (1995) [16]
	Parsley	<i>Petroselinum crispum</i>	NFT, wick systems	High-value herb production	Resh (2013) [36]
	Basil	<i>Ocimum basilicum</i>	Hydroponics, aeroponics	Superior aroma and biomass	Kozai <i>et al.</i> (2016) [21]
	Coriander	<i>Coriandrum sativum</i>	NFT, floating systems	Rapid turnover	Jones (2016) [19]
	Mint	<i>Mentha spp.</i>	Hydroponics, aeroponics	Continuous harvest	Sharma <i>et al.</i> (2018) [43]

Table 2: Important pathogens of soilless culture

Crop	Virus	Bacteria	Fungi	Nematodes	References
Tomato	Tomato mosaic virus, Tobacco necrosis virus	<i>Pseudomonas corrugata</i> , <i>P. viridiflava</i> , <i>Erwinia chrysanthemi</i>	<i>Alternaria solani</i> , <i>Fusarium oxysporum</i> , <i>Phytophthora infestans</i> , <i>Pythium ultimum</i>	<i>Globodera</i> spp., <i>Meloidogyne</i> spp.	Stanghellini & Rasmussen (1994); Schnitzler (2004); Van Os (2010) [42, 44, 47]
Cucumber	Cucumber mosaic virus, Cucumber necrosis virus	<i>Pseudomonas syringae</i> pv. <i>lachrymans</i>	<i>Fusarium solani</i> , <i>Pythium</i> spp., <i>Olpidium brassicae</i>	<i>Meloidogyne incognita</i> , <i>Pratylenchus</i> spp., <i>Longidorus</i> spp.	Moulin <i>et al.</i> (1994); Vallance <i>et al.</i> (2011) [27, 46]
Lettuce	Lettuce mosaic virus	<i>Pseudomonas</i> spp.	<i>Pythium tracheiphilum</i> , <i>Pythium ultimum</i> , <i>Rhizoctonia solani</i> , <i>Sclerotinia sclerotiorum</i>	<i>Meloidogyne hapla</i> , <i>M. incognita</i>	Schnitzler (2004); Van Os (2010) [42, 47]
Pepper	Tobacco mosaic virus, Tomato mosaic virus, Tobacco necrosis virus	—	<i>Phytophthora capsici</i> , <i>Fusarium solani</i> , <i>Pythium</i> spp., <i>Didymella bryoniae</i>	—	Vallance <i>et al.</i> (2011); Van Os (2010) [46, 47]

Table 3: Substrate and nutrient solution disinfection methods in soilless culture

Method Type	Disinfection Method	Principle	References
Chemical methods	Ozone (O ₃)	Strong oxidizing agent; destroys bacteria, fungi, and viruses in nutrient solution	Van Os (2010); Zheng <i>et al.</i> (2019) [47, 48]
	Hydrogen peroxide (H ₂ O ₂)	Produces reactive oxygen species that kill pathogens	Runia (1995); Raudales <i>et al.</i> (2014) [34, 37]
	Sodium hypochlorite (NaOCl)	Releases chlorine; oxidizes microbial cells	López-Gálvez <i>et al.</i> (2010) [24]
	Chlorine dioxide (ClO ₂)	Effective disinfectant against biofilms and waterborne pathogens	Ma <i>et al.</i> (2017) [25]
	Copper-silver ionization	Releases Cu ²⁺ and Ag ⁺ ions that inhibit microbial growth	Huang <i>et al.</i> (2008) [15]
Physical methods	Heat treatment	Thermal inactivation of pathogens (90-95 °C)	Runia (1995); Van Os (2010) [37, 47]
	UV radiation	Damages DNA of microorganisms in recirculating solution	Hijnen <i>et al.</i> (2006) [14]
	Membrane filtration	Removes pathogens based on pore size (micro/ultra-filtration)	Van Os (2010) [47]
	Slow sand filtration	Biological filtration using microbial biofilm layer	Calvo-Bado <i>et al.</i> (2006); Raudales <i>et al.</i> (2014) [7, 34]

Conclusion

Soilless culture represents a transformative advancement in modern horticulture, offering an efficient and sustainable alternative to conventional soil-based vegetable production. By enabling precise control over water, nutrients, and environmental conditions, these systems significantly enhance crop productivity, quality, and resource-use efficiency. Techniques such as hydroponics, aeroponics, and substrate culture have demonstrated their potential in overcoming major constraints associated with soil cultivation, including land scarcity, salinity, and soil-borne diseases. However, the success of soilless culture systems depends largely on effective disease management, particularly the control of waterborne pathogens that can spread rapidly through recirculating nutrient solutions. The integration of suitable disinfection methods, including both chemical and physical approaches, is essential to maintain system hygiene and crop health. Although substantial progress has been made, challenges such as high initial costs, lack of standardization, and limited awareness among growers continue to restrict large-scale adoption. Therefore, the development of cost-effective technologies, improved system designs, and location-specific recommendations is crucial. Strengthening extension services, training programs, and awareness initiatives will further promote the adoption of soilless culture. With continued research and technological advancement, soilless culture is poised to play a vital role in ensuring sustainable vegetable production and global food security in the future.

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Consent for publication

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Competing interests

The authors declare no competing interests.

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