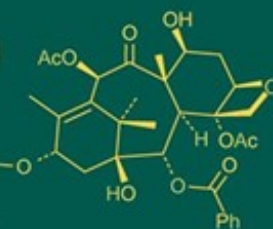
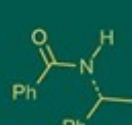
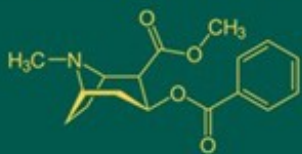


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Strawberry cultivation in soilless growing media: A review of substrate selection, nutrient management, challenges and opportunities

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ABSTRACT

Strawberry (*Fragaria × ananassa* Duch.) is a nutritionally valuable, high-value crop whose fruit quality and yield are strongly influenced by root-zone conditions, making soilless cultivation an increasingly important production strategy. This review synthesizes current knowledge on substrate selection, nutrient management and the broader challenges and opportunities associated with soilless strawberry production. The physical and chemical properties of growing media porosity, water-holding capacity, bulk density, pH, cation exchange capacity and electrical conductivity directly govern root aeration, water availability and nutrient uptake, with strawberries performing best at pH 5.5–6.5 and low EC (1.1–2.1 dS m⁻¹). Organic and inorganic substrates commonly evaluated include cocopeat, perlite, vermiculite, bark, sphagnum moss, bagasse, farmyard manure, rock wool and rice hulls each offering distinct advantages in aeration, drainage, moisture retention and nutrient supply, often requiring blending to achieve balanced media performance. Effective fertigation management, including progressive adjustment of nutrient concentration, pH and EC across crop stages is essential to prevent salt accumulation and optimize growth with both phosphorus deficiency and excess shown to restrict performance. Compared with traditional open field soil-based farming, soilless systems reduce weed pressure and soil-borne disease incidence, minimize pesticide dependence, improve environmental and irrigation control and support higher yields of superior-quality fruit, particularly in regions with poor soil or limited water resources. However, wider adoption is constrained by high capital investment, urban land scarcity, technological and knowledge gaps among farmers and weak infrastructure, especially in developing regions. Opportunities lie in low-cost modular system designs, passive ventilation and waste-heat recovery, use of recycled materials and financial mechanisms such as subsidies and microloans linked to community-based farming models. This review underscores that a clear, context-specific understanding of substrate properties, nutrient dynamics and system economics is essential for realizing the full potential of soilless cultivation in sustainable strawberry production.

Keywords: Strawberry, Soilless culture, Media selection, Nutrient management

Introduction

The strawberry (*Fragaria × ananassa* Duch.), a member of the family Rosaceae, is a stoloniferous perennial herb propagated commercially through runners (Islam *et al.*, 2013) [15]. It exhibits broad climatic adaptability, thriving in both humid and arid regions from the lowlands up to 3000 m altitude, with optimal growth favoured by day temperatures of 22–25 °C and night temperatures of 7–13 °C. Strawberries serve as an important natural reservoir of bioactive compounds, composed of roughly 95% water and only about 5% solid content (Ariza *et al.*, 2016) [3]. Nutritionally, they offer a strong profile of vitamins and minerals each 150 g portion supplies approximately 94 mg of vitamin C, 45 IU of vitamin A and 1.0 g of protein, along with beneficial fatty acids derived from their seed oil. The fruit is also a good source of trace minerals including manganese, potassium, iodine, magnesium, copper, iron and phosphorus. Beyond these nutrients, strawberries contain non-nutritive bioactive substances such as polyphenolic phytochemicals, which contribute additional health-related properties (Giampieri *et al.*, 2012) [13]. In soilless systems, desired root-zone properties are achieved by mixing selected organic and inorganic substrate materials. Container shape and size also matter, since they affect how substrate properties function, making it important to optimize the substrate system container and medium together as a whole (McKean *et al.*, 2019) [24]. Root-zone chemistry is equally critical: a pH of 5.5–6.5 is generally ideal for soilless crop production, keeping nutrients available to plants (Savvas *et al.*, 2013) [33]. Strawberries specifically favor low electrical conductivity (EC), with 1.1–2.1 dS m⁻¹ shown to maximize growth and yield across seven cultivars (Sun *et al.*, 2015) [35]. A key physical requirement for strawberry substrate systems is sufficient air porosity, which supports proper gas exchange and

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allows excess water to drain effectively. At the same time, this porosity needs to be balanced against the substrate's water-holding capacity, ensuring plants have consistent access to water and nutrients (Wallach, 2008) [37]. Growing strawberries in soilless substrates offers a range of agronomic benefits: it substantially curbs weed infestation, markedly lowers the incidence of soil-borne diseases and supports higher yields of superior-quality fruit. This approach is particularly valuable in areas where soil quality is poor, as it creates a more favorable rooting environment and improves the efficiency with which plants use water. For these reasons, soilless cultivation systems have become a critical component of modern strawberry production (Rathod *et al.*, 2021) [30]. Soilless cultivation has emerged as a promising strategy for year-round crop production with reduced land and labor needs, especially valuable in water- or soil-scarce regions. Wider adoption depends on cost-effective, automated systems, while challenges like disease spread in closed systems and reliance on fossil-based energy and materials remain unresolved. Sustainability claims are further limited by a lack of comparative environmental data, particularly on energy use and viable fossil-fuel alternatives. Since system efficiency, plant suitability, substrate impact and economic viability vary widely, a clear understanding of individual systems, substrates and organisms is essential to determine when soilless techniques are truly worthwhile (Fussy *et al.*, 2022) [12]. This review aims to synthesize current knowledge on substrate selection, nutrient and fertigation management and the key challenges and opportunities in soilless strawberry (*Fragaria* × *ananassa*) cultivation, in comparison with traditional soil-based farming, to guide sustainable and resource-efficient production practices.

Historical development of soilless growing media

The development of soilless growing media has drawn on innovations from multiple regions. Japan pioneered the use of carbonized rice hulls as a lightweight, sustainable substrate that was later adopted internationally. In the 1960s, mineral wool rockwool was recognized as a viable horticultural substrate, marking a major technological advance for soilless systems. Around the same time, durable plastics transformed containerization for growing media. Later, during the 1980s and 1990s, Sri Lanka and India advanced coconut coir processing techniques, turning this agricultural by-product into one of the most widely used greenhouse substrates today (Malik *et al.*, 2025) [22].

Media selection

(Alsmairat *et al.*, 2018) [2] The substrate is the physical interface between the strawberry root system and the applied nutrient solution and its physical structure (porosity, air-filled porosity, water-holding capacity, bulk density) and chemical properties (pH, cation exchange capacity, electrical conductivity, nutrient content) directly influence root aeration, water availability and nutrient uptake (Palencia *et al.*, 2016) [29]. A wide range of organic and inorganic materials has been evaluated for strawberry, individually and in mixtures (Jafarnia *et al.*, 2010) [16].

Different growing media

- **Cocopeat:** Cocopeat, a byproduct of coconut husk processing, is widely used as a growing substrate for its cost efficiency, aeration, drainage and durability (Abad *et al.*, 2002) [1]. It is available as loose peat or compressed bricks, the latter reducing shipping costs. Bricks weigh 4-5 kilograms and expand to four to five times their volume upon hydration. Disinfection, typically through steam sterilization, is recommended before use (Mehta *et al.*, 2023) [25].

- **Perlite:** Perlite is produced by subjecting crushed volcanic rock to high-temperature expansion, yielding a lightweight, white-colored material. It is sterile, chemically neutral in pH and functions to improve aeration and drainage within growing media. Perlite is also notably resistant to structural breakdown and is capable of retaining water at approximately three to four times its own weight. Its incorporation into growing substrates contributes to a reduction in overall medium weight relative to soil-based alternatives (Mehta *et al.*, 2023) [25].
- **Vermiculite:** It is a hydrated phyllosilicate mineral formed through the natural weathering breakdown of biotite mica. In terms of chemical composition, it consists of a hydrous magnesium-aluminium-iron silicate that additionally incorporates both potassium and magnesium within its structure (Lakshmikanth, 2019) [20]. It is available in various grades, with finer grades suited to small pots and coarser grades to larger containers. Vermiculite retains substantial moisture, supplies calcium and magnesium and maintains a near-neutral pH. It is valued in soilless substrates for its water and nutrient retention, aeration and low bulk density (Mehta *et al.*, 2023) [25].
- **Bark:** Bark is the byproducts from lumber processing are used as a growing medium, valued for their low cost and good aeration. Since raw bark is low in nutrients and highly acidic (pH 3.5–6.5), dolomitic limestone is typically added to raise the pH to at least 6.0. (Mehta *et al.*, 2023) [25].
- **Sphagnum moss:** Sphagnum moss is considered one of the best forms of organic matter for improving soil quality. It's both readily available and affordable, making it a popular choice for enhancing drainage and aeration in denser, heavier soils. What sets sphagnum moss apart is its remarkable water-holding capacity, its specialized cells can absorb 10 to 20 times its own weight in water (Rathod *et al.*, 2021) [30].
- **Bagasse:** Bagasse is the fibrous residue left over once sucrose, water and other impurities (filter mud) have been extracted from milled sugarcane. On a dry-weight basis, it is composed of roughly 40–50% cellulose, 30–35% hemicellulose and 20–30% lignin, with a small remainder of other materials (Charles *et al.*, 2017) [7].
- **FYM:** Farmers have relied on animal manure, including cow dung, as a natural fertilizer for centuries. Its incorporation into soil enhances physical structure while boosting overall nutrient status, thereby increasing soil fertility over time. Additionally, manure application supports plant nutrition and enriches the soil capacity to supply the trace minerals by stimulating microbial activity within the soil. Rich in nitrogen and various other essential nutrient elements, it plays a supportive role in fostering healthy plant development (Lakshmikanth, 2019) [20].
- **Rock wool:** Rock wool is manufactured by melting a combination of coke, basalt, limestone and iron-production slag at high temperature, after which it is processed into a fine powdered or granular form (Bougoul *et al.*, 2005) [4]. Once mixed into a growing medium, it provides beneficial aeration alongside good moisture retention. Being mildly alkaline in reaction, it neither contributes nor holds onto nutrients to any meaningful extent, which is why it is typically blended with other components such as sphagnum peat moss to form a more balanced substrate (Mehta *et al.*, 2023) [25].
- **Rice hulls:** Ground parboiled fresh rice hulls with a fine particle size of 0.5–1.0 mm (RH₃) showed total pore space, air-filled pore space and water-holding capacity comparable to sphagnum peat, though with higher available water, bulk density and particle density (Buck *et al.*, 2010) [5].

Nutrient solution management is critical in soilless strawberry production, as solution concentration directly affects root-zone EC, nutrient availability and plant growth. Sambo *et al.* (2019) [32] stressed that controlling nutrient concentration, pH and EC is essential to maintaining a suitable rhizosphere environment, while Depardieu *et al.* (2016) [9] showed that EC should be adjusted according to substrate characteristics and crop stage progressively modified during establishment and stabilized during flowering and fruiting with regular monitoring of solution and drainage EC/pH to prevent salt accumulation. Nutrient concentration also strongly influences crop performance: Choi *et al.* (2013) [8] found that both low and excessive phosphorus levels restricted growth in 'Seolhyang' strawberry, underscoring the need to keep nutrients within an optimal range.

Nutrient solution management and fertigation

Soilless culture has become an important strategy in strawberry production for several reasons. Cecatto *et al.* (2013) [6] noted that conventional soil-based cultivation resulted in many environmental and phytosanitary problems and that soilless culture is now advocated for environmental reasons because it greatly reduces the use of chemical pesticide and fungicide inputs. Doust *et al.* (2023) [10] further emphasized that soilless cultivation offers improved quality control over the growth environment and mitigates uncertainties related to soil, water and nutrient availability, making it a promising approach for the future of horticulture. Nichols (2021) [28] explained that soilless culture (hydroponics) allows strawberries to be grown above the ground in table-top systems, providing an improved root environment, nutrition and irrigation, along with easier fruit harvesting (Lakhia *et al.*, 2025) [18].

Table 1. Comparative yield of strawberry in soil and different media

Strawberry	Sr. No.	Substrate yield g/plant	Soil yield g/plant	Refferences	
	1.	Coir	317.83	209.96	Martinez <i>et al.</i> (2017) ^[23]
	2.	Cocopeat + vermicompost (50:50) + jeevamrit	200.74	185.50	Kazimi <i>et al.</i> (2024) ^[17]
	3.	Perlite (75%) + cocopeat 25%) + jeevamrit	210.09	181.33	Maher <i>et al.</i> (2020) ^[21]

Traditional farming refers to open-field, soil-based cultivation without artificial climate control, making it highly dependent on local weather conditions, rainfall patterns and the natural fertility of the soil Rayes *et al.* (2020) [31]. Irrigation in such systems is often carried out through surface or furrow methods, leading to considerable water losses from evaporation, runoff and inefficient distribution (Xue *et al.*, 2024) [40]. Broad application of fertilizers and pest control measures can further contribute to environmental problems such as soil degradation, nutrient leaching and increased greenhouse gas (GHG) emissions (Wang *et al.*, 2025) [39]. Although greenhouse farming and polytunnel structures have been introduced in some regions to protect

crops from extreme weather, they typically offer only partial climate control rather than complete environmental optimization (Wang *et al.*, 2024) [38]. Soilless Farming (SLF), in contrast, is a context-specific cultivation strategy in which plants are grown without natural soil, offering an alternative in environments where conventional soil-based farming is limited by resource or environmental constraints. SLF systems are generally implemented within Controlled Environment Agriculture (CEA), such as advanced greenhouses and vertical farms, where temperature, humidity, light and nutrient supply are precisely managed to optimize plant development (Lakhia *et al.*, 2020) [19].

Table 2. Comparison between soilless farming and traditional farming.

Aspect	Soilless Farming	Traditional Farming
Rooting medium	Plants grow in a nutrient solution or in a substrate	Plants grow in natural field soil
Land requirement	Needs only a small footprint	Needs a larger area of land
Nutrient management	Nutrients are supplied in exact amounts to match plant needs	Mostly determined by how fertile the soil is
Yield and efficiency	Greater output per square meter	Output varies with climate and soil conditions
Pests and diseases	Lower risk of soil-borne pests and pathogens	More exposure to pests, diseases and weeds
Labor and skills	Calls for specialized technical knowledge	Involves more manual work for planting, irrigation and harvesting
Cost	Higher	lower

Challenges in soilless farming

Lakhia *et al.* (2020) [19] Soilless farming adoption in developing regions is constrained by high capital investment, since vertical and hydroponic systems require costly irrigation, lighting, nutrient circulation and climate-control infrastructure, particularly where energy costs are high or grid access is limited Mishra *et al.* (2024) [27]. Urban land scarcity and high property costs further complicate adoption, as valuable urban real estate often competes with agricultural use, though adaptive reuse of rooftops and underutilized buildings offers partial relief depending on land-use policy (Teoh *et al.*, 2024) [36]. A persistent technological and knowledge gap among farmers stemming from limited training Hardman *et al.* (2022) [14], extension services

and capacity-building programs continues to favor traditional practices over soilless farming adoption Savvas and Gruda (2018) [34]. Weak infrastructure, including unreliable electricity, poor internet connectivity and inadequate input supply chains, further impedes implementation (Min *et al.*, 2024) [26].

Opportunities in soilless farming

Low-cost, modular SLF designs adapted to local conditions can reduce setup costs and improve feasibility for small farmers Fei *et al.* (2025) [11]. Simple approaches such as passive ventilation, waste heat recovery and use of recycled or locally available materials further cut costs. Financial tools like subsidies, tax incentives and microloans especially when linked with community-based farming models can im

prove access to SLF technology. Since SLF works best when matched to local conditions, a strategic approach focused on affordability, training, infrastructure and community involvement is key to its success, allowing SLF to strengthen food production resilience in urban and peri-urban areas Lakhiar *et al.* (2025) [18].

Conclusion

Soilless cultivation has emerged as a reliable and increasingly important method for growing strawberries, offering better control over substrate quality, nutrient supply and root environment compared to traditional soil-based farming. By carefully selecting suitable growing media and managing nutrient solutions at appropriate pH and EC levels, this approach helps reduce disease incidence, improve water-use efficiency and support higher yields of good-quality fruit. Although challenges such as high setup costs, limited farmer awareness and unclear environmental sustainability still remain, continued research and low-cost system innovations can help soilless cultivation become a practical and sustainable solution for future strawberry production.

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