



REVIEW ARTICLE

Growing media in vertical farming: Current advances, challenges and future opportunities

Konappan Surya¹, Ramanujam Krishnan^{1*}, Vaddi Saitheja¹, Ratchagar Arockia Infant Paul², Anbazhagan Ammaiappan¹ & Sornam Gowtham³

¹Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

²International Rice Research Institute, New Delhi 110 012, India

³Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, TamilNadu, India

*Email: agrikrish@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY

Received: 20 April 2026

Accepted: 13 August 2026

Available online

Version 1.0 : 01 October 2026

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/TCB/open_access_policy

Publisher's Note: The article processing was done by atom e-Publishing, Thiruvananthapuram, India. Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

CITE THIS ARTICLE

Konappan S, Ramanujam K, Vaddi S, Ratchagar AIP, Anbazhagan A, Sornam G. Growing media in vertical farming: Current advances, challenges and future opportunities. Trends in Current Biology. 2026; 4(4): 16-31. <https://doi.org/10.14719/tcb.9476>

Abstract

Vertical farming has emerged as a promising approach to address food security, urbanization, climate change and declining arable land, but the selection of appropriate growing media remains critical for achieving efficient and sustainable crop production. This review critically evaluates the role, performance and sustainability of growing media used in vertical farming, with emphasis on their effects on water availability, aeration, nutrient retention, root development, crop performance and resource-use efficiency. A systematic literature search was conducted using Scopus and studies were selected based on their relevance to growing media, soilless cultivation and vertical farming systems. The synthesis indicates that organic and inorganic substrates differ substantially in water-holding capacity, aeration, structural stability, nutrient retention, weight, reusability and environmental footprint, while emerging bio-based composites and engineered substrates show potential for improving resource efficiency and reducing substrate-related environmental impacts. Across the reviewed literature, growing-media performance was strongly influenced by substrate physicochemical properties, crop requirements, irrigation management and production intensity. However, limited information is available on long-term substrate reuse, microbial interactions, lifecycle impacts and the performance of lightweight and recyclable materials under intensive stacked production. This review integrates agronomic performance with physicochemical and sustainability criteria to provide a framework for selecting and designing growing media that can simultaneously optimize crop productivity, resource-use efficiency and environmental sustainability in scalable vertical farming systems.

Keywords

biochar; biostrate; growing media; organic carbon; soil health; sustainable agriculture; vermiculite; vertical farming

Introduction

As the global population is projected to reach 9.7 billion by 2050, food production must increase by at least 50 % to meet the rising demand (FAO, 2016). This need is complicated by limited arable land, water scarcity and the effects of climate change (1, 2). These challenges have intensified interest in controlled-environment agriculture (CEA), including vertical farming, as a complementary production approach that can reduce dependence on land availability and climatic conditions. Recent reviews emphasize that vertical farming can improve land-use efficiency and enable year-round production, although its sustainability depends strongly on resource use, energy requirements, crop selection and system design. With only about 24 % of Earth's land being arable, much of it already under cultivation, innovative solutions like vertical farming offer a way to sustain future food supplies in controlled environments (3).

Vertical farming allows high-density crop production in controlled urban spaces, using soilless techniques such as hydroponics and aeroponics, reducing dependence on fertile soil and maximizing crop yield in limited areas (4). Unlike conventional agriculture, these systems allow precise regulation of temperature, humidity, light, carbon dioxide concentration, irrigation and nutrient availability, thereby providing greater control over the crop growing environment. However, the benefits of vertical farming are not universal and vary according to crop type, production technology, environmental conditions and management practices. Consequently, claims regarding yield enhancement and water savings should be interpreted in relation to specific production systems rather than as fixed advantages over conventional agriculture. Soilless techniques such as hydroponics and aeroponics conserve up to 95 % of the water used in conventional farming and enable continuous year-round production (5). Recent assessments have also highlighted that, despite improvements in land and water-use efficiency, energy consumption, material inputs, economic viability and overall lifecycle sustainability remain important challenges for vertical farming (6).

Within these systems, growing media represent a critical but comparatively less integrated component of vertical farming. Selecting appropriate growing media is essential for scalability, as each medium's properties affect water retention and nutrient availability. Innovations in growing media, ranging from organic bio-based materials to synthetic substrates, have shown promising results in enhancing resource efficiency and promoting sustainable growth cycles. In vertical farming, growth media are essential as they support root development, retain moisture and provide nutrients to plants, enabling optimal growth in controlled, soilless environments. A wide range of organic, inorganic and engineered substrates has therefore been investigated, but their suitability depends on the interaction between substrate properties, crop requirements, irrigation management and production intensity. Recent research has further emphasized the need to evaluate growing media not only in terms of crop performance but also in relation to resource efficiency and environmental sustainability.

However, previous reviews of vertical farming have largely focused on broader aspects such as production technologies, resource-use efficiency, environmental sustainability, automation, energy consumption and economic feasibility, while growing media are generally discussed only as one component of the overall production system. Consequently, there remains a need for a dedicated and critical synthesis that connects the physicochemical characteristics of growing media with crop performance, resource-use efficiency, durability and environmental sustainability specifically within vertical farming systems. Significant research gaps remain, particularly regarding the environmental impact and biodegradability of widely used substrates like coco coir and synthetic polymers. Similarly, emerging materials such as bio-based composites, hydrogels and nanomaterial-enhanced substrates require further evaluation for their long-term stability, nutrient-release behaviour, microbial interactions and environmental safety. Limited research also exists on microbial interactions within soilless media, which could aid in nutrient cycling and plant health. Moreover, media durability under intensive use remains a challenge, as frequent replacement can increase costs and waste. In stacked vertical systems, the use of lightweight yet sturdy media is crucial to minimize structural load while still supporting plant growth effectively.

Therefore, this review aims to critically evaluate the major growing media used in vertical farming by integrating their physicochemical properties, effects on root development and crop performance, resource-use efficiency, durability and environmental sustainability. The review covers conventional organic and inorganic substrates as well as emerging bio-based and engineered materials, with particular emphasis on their advantages, limitations and potential for reuse and sustainable application. The manuscript further examines emerging research areas, including microbial interactions, substrate lifecycle assessment, lightweight materials and recyclable alternatives. By bringing these dimensions together, this review provides a substrate-centred framework for selecting and developing growing media that can simultaneously support crop productivity, resource efficiency and environmental sustainability, thereby addressing an important research gap in the development of scalable vertical farming systems. The selection of suitable growing media depends on crop requirements, hydroponic system characteristics, substrate properties and practical production conditions (Fig. 1).

Brief history on vertical farming:

Vertical farming, though often regarded as a modern innovation, has deep historical roots and reflects humanity's ongoing pursuit of sustainable food production in confined spaces. Early forms can be traced to the Hanging Gardens of Babylon around 600 BCE, an architectural marvel that grew plants on tiered terraces through an intricate irrigation system, showcasing the potential for vertical cultivation in urban landscapes. Similarly, ancient East Asian terrace farming systems, especially prominent in China and Southeast Asia, employed strategic land management techniques to cultivate crops on mountainsides, essentially increasing arable land through stacked horizontal planes (7). These terraces laid foundational principles of maximizing land utility and efficient water use, essential to today's vertical farming (8). However, it wasn't until the 20th century that the concept evolved into the modern form we recognize. In 1915, American geologist Gilbert Ellis Bailey introduced the concept of "vertical farming" in his book, suggesting the cultivation of plants at multiple soil levels (9, 10). Then, in 1999, Dr. Dickson Despommier, a professor of public health at Columbia University, pioneered the idea of large-scale indoor vertical farms as a solution to growing urban populations and land scarcity. He envisioned a future where high-rise indoor farms within urban centres can help meet the growing demand for food while preserving natural ecosystems and his research proposed urban farms within skyscrapers that could provide local, sustainable food production using hydroponics and controlled environments (11). He highlights how vertical farming could contribute to food security by offering a controlled environment for year-round production, insulated from climate-related disruptions such as droughts or floods (12).

The transition from conceptual vertical farming to technologically intensive production was driven by major advances in soilless cultivation and controlled-environment technologies. Hydroponics provided the foundation for precise delivery of water and dissolved nutrients to plant roots without soil, while aeroponics further reduced the rooting medium by suspending roots and delivering nutrients through fine nutrient-rich mist. These systems enabled precise control of water, nutrients, root-zone oxygen and plant density, making them particularly suitable for stacked production. The development of efficient light-emitting diode (LED)

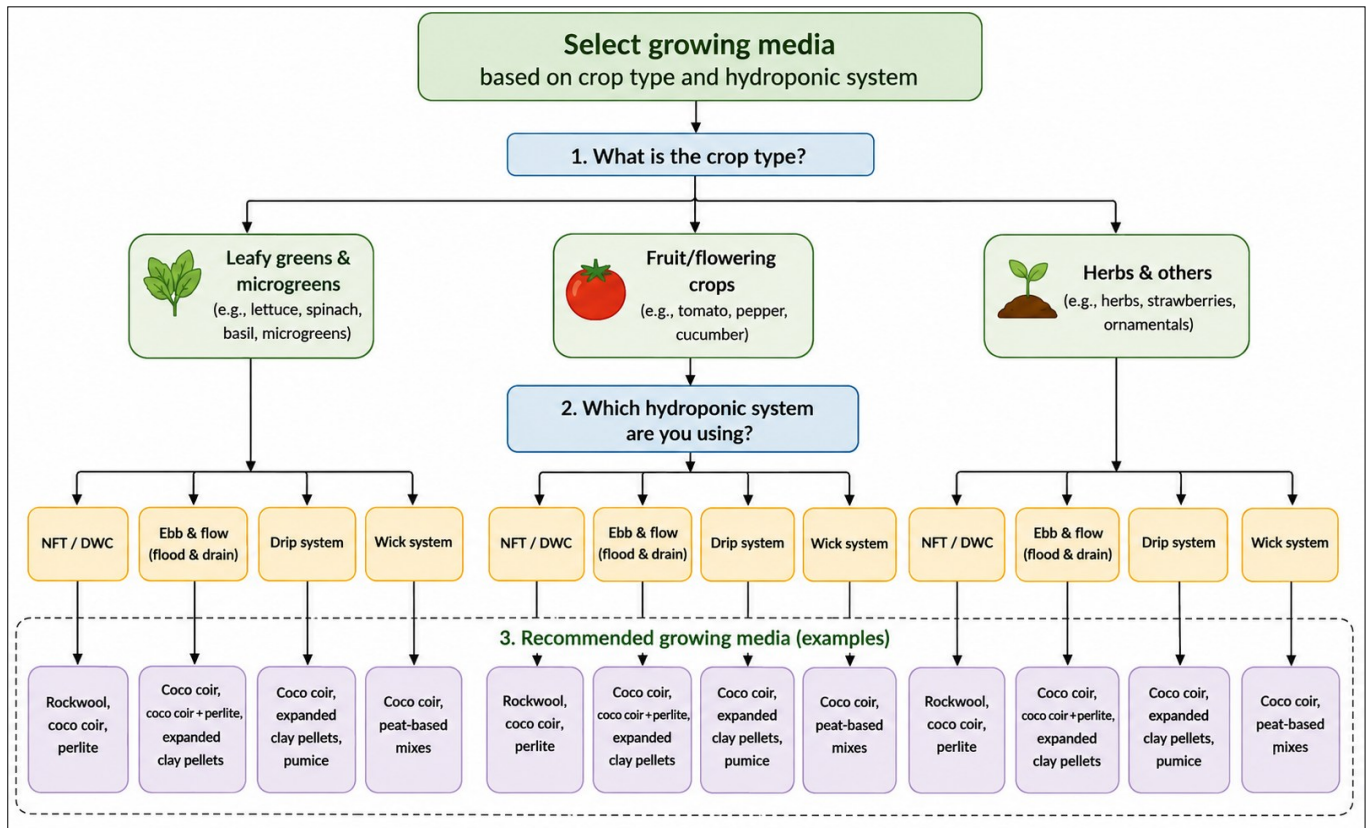


Fig. 1. Decision tree for selecting suitable growing media based on crop type and hydroponic system, considering key substrate requirements and practical production conditions.

technology represented another breakthrough, as LEDs enabled growers to manipulate light intensity, photoperiod and spectral composition while reducing the heat load and energy requirements associated with earlier artificial lighting systems. Concurrent advances in sensors, automated irrigation, environmental control systems and digital monitoring further transformed vertical farms into highly controlled production environments (13).

Since the early 2000s, advances in LED lighting, hydroponics, aeroponics and climate control have supported the development of vertical farming as a viable production system (13, 8). Its expansion has been driven by urban food security, land and water scarcity, climate variability and sustainability concerns. However, high capital investment, energy requirements, infrastructure costs and limited crop suitability remain key constraints, with energy consumption strongly influencing production costs and environmental sustainability. Economic feasibility also depends on crop type, energy prices, production scale and automation level. Thus, vertical farming is best considered a complementary production system whose benefits depend on local environmental, technological and economic conditions.

The expansion of vertical farming has been driven by urban food security, land and water scarcity, climate variability and sustainability concerns. However, high capital investment, energy consumption, infrastructure costs and limited crop suitability remain major barriers to economic and environmental sustainability. Energy-efficient technologies, renewable energy integration, automation and AI-based crop management are therefore increasingly important for improving system viability. Growing media are also critical to this evolution, as substrate properties influence water retention, aeration, nutrient availability, root development, crop performance and resource-use efficiency. Advances in lightweight, reusable and sustainable substrates

therefore offer an important pathway for improving the productivity, sustainability and scalability of modern vertical farming systems (14–17). This evolution reflects a convergence of ancient ingenuity and modern technology, aiming to secure food resilience in a rapidly urbanizing world.

Growth Media and their selection for vertical farming

Any materials, apart from soil, that are used to cultivate plants are referred to as growing media or plant substrates (18). In general, growing media can be divided into inorganic and organic categories. Inorganic substrates can be derived from natural sources, such as sand and gravel or processed minerals like perlite and rockwool. On the other hand, organic growing media can either be synthetic, such as polyurethane, or naturally occurring, including materials like peat, bark, coir and wood fibres. In vertical farming, growing media are a mixture of materials that provides plants with water, nutrients, air and support. It is a key component of vertical farming because it provides the necessary nutrition to plants in the limited volume of containers (19). These materials support plant growth in various contexts, typically in containers and encompass fertilized planting media for trees and shrubs, as well as casing soil for mushrooms. While "substrate" is often used as a synonym, its definition is less precise. The suitability of different growing media varies with crop category, particularly because leafy greens, fruiting vegetables, herbs, microgreens and ornamentals differ in their requirements for moisture retention, aeration, root support and nutrient availability (Table 1).

Growing media consist of constituents like peat, composted bark, wood fibre, coir, perlite and vermiculite, which form the bulk of mixes typically measured by volume. Additionally, media may include additives, such as fertilizers, lime, wetting agents and biological products, usually measured by weight. These additives, although present in smaller quantities, enhance the properties of the

Table 1. Comparison of growing media suitability, key requirements, advantages and limitations across major crop categories in vertical farming

Crop category	Recommended growing media	Key requirements	Suitable media characteristics	Major advantages	Key limitations
Leafy greens	Coco coir; Perlite-coir blends; Rockwool; Vermiculite	Good moisture retention, aeration and nutrient availability	Moderate-high water-holding capacity, good porosity and stable root support	Rapid growth; efficient water and nutrient management	Salt accumulation in coir; rockwool disposal concerns
Fruiting vegetables	Coco coir; Rockwool; Perlite-coir blends; Expanded clay pellets	High root-zone stability, aeration, drainage and nutrient control	High structural stability with balanced air-water ratio	Supports vigorous root growth and prolonged production	Higher irrigation and nutrient management requirements; substrate cost
Herbs	Coco coir; Peat-perlite blends; Rockwool; Vermiculite	Balanced moisture and aeration with adequate nutrient retention	Moderate water-holding capacity and good drainage	Supports uniform growth and quality; suitable for hydroponic systems	Excess moisture can affect root health; coir may require washing/buffering
Microgreens	Biostrate; Coco coir; Peat-based media; Rockwool; Vermiculite	High moisture availability, good seedling support and cleanliness	Fine texture, uniform moisture and adequate aeration	Lightweight; easy handling; rapid germination and harvest	Some media dry rapidly; commercial cost and availability vary
Ornamentals	Coco coir; Peat-perlite; Vermiculite; Perlite; Expanded clay pellets	Long-term structural stability, drainage, aeration and moisture retention	Durable structure with adjustable air-water balance	Supports diverse root systems and repeated cultivation	Media requirements vary considerably among species; some substrates are heavy

mix, supporting optimal plant growth. Growth media are pivotal because they directly influence root development, nutrient absorption and overall plant health. In vertical farming, growth media serve essential functions by providing root stability and support, ensuring plants remain securely anchored in stacked or tiered systems. They regulate moisture effectively, retaining and gradually releasing water to keep roots consistently hydrated while conserving water. Growth media also deliver and retain nutrients, supplying plants with a steady nutrient flow while minimizing waste.

By facilitating oxygen flow around the roots, they prevent waterlogging and promote healthy root growth. Additionally, certain growth media possess natural disease suppression abilities, which help prevent root infections and reduce reliance on chemical treatments. Coco coir has natural antifungal properties, making it resistant to some soil-borne pathogens. Rockwool and compost-based mixes can also support beneficial microorganisms that inhibit harmful pathogens. However, the use of peat and rock wool in these mediums has caused environmental issues, which have encouraged a search for more sustainable alternatives (20). The future of growth media is in using sustainable, affordable and renewable materials that meet environmental standards and ensure quality. This approach minimizes ecological impact, conserves resources and supports the long-term sustainability of vertical farming and other modern cultivation methods (21).

Non-soil growth media are increasingly favoured in vertical farming for their ability to retain moisture and create a stable

environment for plant roots, optimizing water usage and enhancing root development (22). These roles make growth media critical to the success and sustainability of vertical farming. Vertical farming integrates both widely used and advanced growing media, each carefully selected to enhance plant growth and resource efficiency in controlled environments. The following paragraphs explore these diverse media types and their specific roles within vertical farming systems. The suitability of different growing media for major hydroponic systems used in vertical farming is summarized in Table 2.

Peat

Sphagnum peat moss (*Sphagnum spp.*), commonly referred to as peat, is extensively utilized in plant propagation, particularly in Europe and North America (23). Peat is an organic material formed from the accumulation of partially decayed plant matter in waterlogged conditions, primarily in peatlands or bogs. Its dark colour, spongy texture and capacity to retain moisture and nutrients have made peat a popular choice for horticultural and agricultural growing media (24). Currently, peat makes up approximately 77–80 % of the growing media used annually in the horticultural industry in Europe (25) and it is considered the most widely used growing media (26). In Lithuania, 90 % of peat resources are used for crop production, with the remaining 10 % utilized as a raw material for energy production, while globally, 42 % of peat is used in the crop sector, 50 % in energy production, 5 % to enrich the soil and 3 % for other purposes (27).

Table 2. Suitability of different growing media for major hydroponic systems used in vertical farming

Hydroponic system	Suitable growing media	Key media requirements	Advantages	Limitations
NFT (Nutrient Film Technique)	Rockwool; Coco coir; Perlite; Foam-based media	Lightweight; good root support; adequate aeration	Supports continuous nutrient flow; suitable for leafy greens and herbs	Excessive media can obstruct channels; requires careful moisture management
DWC (Deep Water Culture)	Rockwool; Coco coir; Expanded clay pellets; Perlite	Good aeration and root anchorage; moderate water retention	Provides continuous water and nutrient availability; simple system design	Media should not restrict root-zone oxygenation; algae growth may occur
Drip irrigation	Coco coir; Rockwool; Perlite-coir blends; Vermiculite	Good water retention, drainage and nutrient-holding capacity	Highly adaptable; precise fertigation; suitable for fruiting crops	Requires regular monitoring of irrigation and nutrient accumulation
Ebb-and-flow	Expanded clay pellets; Perlite; Gravel; Coco coir	Good drainage, aeration and structural stability	Effective wetting and drainage cycles; media can be reused	Heavy media increase structural load; frequent cycles may require careful water management
Aeroponics	Expanded clay pellets; Rockwool cubes; Foam-based media	Lightweight; strong seedling support; high aeration	Excellent root oxygenation; very efficient water and nutrient use	Requires precise environmental control; unsuitable media can interfere with root exposure and spray distribution

In vertical farming, peat is valued for its excellent water retention, which ensures consistent hydration of plant roots while preventing waterlogging, an essential factor in space-constrained environments (28). Its good aeration and drainage properties foster a stable environment for root development and its neutral to slightly acidic pH supports a diverse range of plants, including vegetables, herbs and ornamentals (18). However, despite these advantages, peat has significant drawbacks such as restricted availability, high cost, environmental damage from extraction and inconsistent quality (26). It typically contains few nutrients (27), necessitating constant fertilization to maintain plant health. This reliance on fertilizers not only increases costs but also limits access to essential minerals and biologically active compounds, compromising overall plant vitality (29).

Peat extraction faces significant criticism due to the ecological importance and fragility of peatland ecosystems. Peatlands function as major long-term carbon stores and provide important ecosystem services, including water regulation, habitat provision and biodiversity conservation (30, 31). Drainage and extraction expose previously waterlogged peat to oxygen, accelerating the decomposition of stored organic matter and releasing carbon dioxide and other greenhouse gases. At the same time, extraction alters peatland hydrology, degrades habitats and can contribute to biodiversity loss, thereby reducing the capacity of peatlands to function as effective carbon sinks. Additionally, the natural production of peat is an extremely slow, non-sustainable process. These concerns have prompted efforts in Europe to protect peatlands, preserve their ecosystems and mitigate carbon emissions, while growing pressure on the horticulture industry has driven demand for alternative, renewable and sustainable growing media (23).

European efforts are increasingly focused on reducing horticultural peat use and promoting peat-free growing media. While the EU has no single-wide ban on horticultural peat, the 2024 EU Nature Restoration Law emphasizes peatland restoration and rewetting for climate and biodiversity benefits. These policy measures and growing sustainability concerns are driving the development of renewable, locally available peat alternatives. Furthermore, growing in peat resembles hydroponics using an inert substrate, which lacks the benefits of natural soil. When dried, peat can quickly become hydrophobic, causing water to repel from its surface and run down the sides of containers (32). This issue often requires the addition of wetting agents to improve water absorption, raising further sustainability concerns (33).

The extraction and use of peat contribute to greenhouse gas emissions (34) and disrupt natural habitats, prompting efforts to cease peat extraction and replace a substantial portion of peat with alternative substrates (35). This transition has gained momentum in Europe over the past decade, driven by increasing consumer awareness of environmental issues, regulatory pressures to limit the extraction of ecologically sensitive peatlands and a heightened sense of personal responsibility (19). In recent years, environmental and ecological concerns have driven efforts to reduce peat usage, as its extraction is damaging endangered wetland ecosystems globally (36). Several organic compounds have been proposed as alternatives to peat for plant growth media. Among these alternatives, composted bark, wood fibre, green waste compost and coir pith have demonstrated reliability as effective growing media (37). Hirschler and Thrän (34) explained that the increased use of

peat substitutes is mainly due to the need to reduce peat usage rather than improvements in the quality or availability of alternative growing media. This highlights the need to develop growing media that combine the desirable physical and biological properties of peat with lower carbon emissions, reduced ecological impacts and greater potential for circular use in sustainable vertical farming systems.

Coconut Coir

Coco coir is a natural Growing media derived from the fibrous husks of coconuts, known for its excellent water retention and aeration properties; furthermore, it is exported mainly from India and Sri Lanka (38, 39). This biodegradable and renewable resource offers a sustainable alternative to traditional soil and peat moss, making it ideal for various applications in gardening and agriculture due to its tough structure, suitable properties, excellent hydrophilicity and high biosafety (37, 40). It contains about 26.72 % cellulose, 17.73 % hemicellulose and 41.19 % lignin, along with a high mineral content that enables strong water retention and storage capabilities (41) makes it ideal for vertical farming. Coco coir offers a sustainable alternative to peat moss, as it is biodegradable and contributes to a circular economy in agriculture (42).

Before use, it undergoes a washing and buffering process to remove excess salts and reduce potentially high concentrations of potassium (K) and sodium (Na), which can interfere with nutrient balance and crop performance (43, 44). However, the concentrations of K, Na and other soluble salts can vary considerably among coir sources and processing methods, resulting in variability in physicochemical quality and batch-to-batch consistency. Therefore, adequate washing, buffering and quality testing are important before commercial use, particularly in controlled vertical farming systems where precise nutrient management is required. Its neutral pH allows for tailored nutrient management, while its natural resistance to pests and diseases minimizes the need for chemical treatments. Coir offers a balanced ratio of air to water similar to that of peat, along with superior re-wetting capability (45). However, coir has a higher pH and a lower cation exchange capacity (CEC) compared to peat (24) and coir degrades or physically deteriorates when used as a Growing media, eventually requiring sustainable disposal or repurposing methods, such as composting, incineration or use as landfill material (46).

Moreover, its lightweight nature enhances its adaptability for different urban settings, whether in rooftop gardens, balconies or community plots, enabling innovative solutions for maximizing space. Coconut fibre is frequently evaluated in various ratios within soilless growing media mixtures alongside other materials, making it challenging to assess coir on its own, particularly due to its lower cation exchange capacity. Cutting or shredding coco coir into smaller pieces for recycling increases its surface area, facilitating decomposition and making it an excellent mulching material that retains moisture, suppresses weeds and regulates soil temperature, while enriching the soil with nutrients as it breaks down (47, 48). Both and associates (49) developed coco coir composites by activating its lignin with bifunctional linkers and crosslinking with biodegradable PVA, offering an eco-friendly alternative to traditional methods. These composites exhibit favourable properties, including an ideal carbon-to-nitrogen ratio, water-holding capacity and stability, making them suitable for hydroponic growth media. Unlike coco coir powder and fibres, the composites' stability prevents clogging in recirculating hydroponic systems.

Perlite

Perlite is a naturally occurring volcanic glass, highly valued in horticulture for its ability to improve soil structure and growing media. Perlite has lower water-holding capacity (WHC) than most organic components, is commonly added to soilless growing media to enhance drainage and increase porosity (50, 51). The water retention capacity of perlite depends on particle size, with larger particles (0.5–1.0 mm) retaining more water compared to smaller particles (0.25–0.50 mm) used in horticulture (52). Perlite undergoes heating at 800–1100 °C to vaporize internal water, causing the particles to expand (53). Although this expansion produces a lightweight and highly porous material, the requirement for high-temperature processing increases energy demand and the associated environmental footprint of perlite production. In addition, perlite mining and processing can disturb geological landscapes and generate particulate dust.

This expansion process creates lightweight, highly porous particles that are stable and resistant to decomposition, making them a durable component in growing media (54). This heating process known as ‘popping’, can increase its volume up to 16 times of its original size, producing small, white, spherically shaped particles that easily blend with other substrates like peat moss, coco coir and soil (55). Fine perlite particles can become airborne during mining, crushing, expansion, mixing and handling; therefore, appropriate ventilation and respiratory protection are important to minimize occupational exposure to dust during commercial production and use.

Perlite's lightweight nature makes it ideal for providing root zone aeration, which promotes healthy root growth and minimizes risks of waterlogging by ensuring efficient drainage (56). It is also non-toxic, virtually pH-neutral and has high durability, allowing it to be reused multiple times without breaking down, which distinguishes it from organic amendments (57). Perlite is commonly used across various agricultural applications, including hydroponics, soilless mixes and seed propagation, as it helps to prevent compaction and enhances air porosity (58). Its ability to retain moisture on its outer surface while allowing excess water to drain off makes it suitable for maintaining optimal water content in root zones, thus reducing fungal and bacterial growth, root rot and issues like molds and mildews (59).

In comparison with similar amendments, perlite offers distinct advantages for certain crops and environments. For instance, unlike vermiculite, which retains more moisture, perlite is better suited for crops needing well-draining conditions. Perlite has poor water retention capacity and it lacks ion-exchange capacity (60). It is also lighter and more cost-effective to transport than pumice. Due to its inert composition, perlite is approved by the USDA for organic farming despite being classified as inorganic. Perlite is highly stable and generally unaffected by acids or microorganisms, allowing it to remain intact in growing media for many years (52). However, excessive use of perlite can lead to increased nutrient leaching from containers, reduced fertilizer efficiency and adverse effects on plant nutrition. Additionally, in media with low pH, there is a risk of toxic aluminium release from perlite (50).

In Highbush Blueberry, adding perlite to growing media resulted in reduced plant growth, with little effect on nutrient composition or plant nutrient uptake [52]. Maaswinkel and associates (61) compared perlite and rice husk and then investigated

the effect of substrates on grow and yield of green pepper and understood that grow plants of rice husk is higher and included more yield in compare with grow plants of perlite. Choi and associates (62) compared culture medium of rock wool and perlite reported that peat and coconut are cause of 19–20 % increase in dry and weight of cucumber and also marketable of cucumber was better than perlite.

Vermiculite

Vermiculite is a hydrated magnesium aluminium silicate clay (smectite mineral group) known for its high cation exchange capacity (CEC) of 50–150 meq/100 g, which enables it to effectively adsorb cations, minimizing nutrient loss through leaching. This property, along with its high water-holding capacity, makes vermiculite valuable as a soil amendment and a potting medium, particularly for seedlings. Research has shown that increasing vermiculite dosage in soil and potting mixes enhances water absorption and fertilizer retention, benefiting crop nutrition and minimizing nutrient waste (63). When subjected to high temperatures, vermiculite expands, transforming into lightweight, layered, sponge-like granules that effectively hold water. This unique property provides plants with consistent hydration, making it an ideal medium for maintaining stable moisture levels.

Additionally, vermiculite is pH-neutral, lightweight and provides good aeration for roots, which promotes robust plant growth. These features make it suitable for a wide range of plant species and applications, from hydroponics and indoor gardening to propagation and seed sowing (64). The interactions among these physical, chemical and biological properties collectively determine root-zone conditions, plant responses, crop performance and resource-use efficiency (Fig. 2). In hydroponic systems, vermiculite is particularly valuable, often used in wicking beds and net cups due to its ability to reliably retain both water and nutrients, supporting efficient nutrient uptake by plants. Indoor plants that thrive in moist environments also benefit from vermiculite; when mixed with soil in varying ratios, such as 70/30 or 50/50 (soil to vermiculite), it enhances water retention and keeps the soil evenly moist. This adjustability allows gardeners to cater to plants with varying moisture needs, providing just the right balance for each species (65).

Vermiculite is also widely used in plant propagation. It supports aerated root development, reducing the risk of rot commonly encountered in water-based propagation. By placing cuttings in moist vermiculite rather than water, gardeners encourage healthier root growth, as the medium allows air circulation around developing roots while maintaining the necessary moisture (66). For seed sowing, vermiculite offers an ideal environment by holding moisture steadily, which aids in the germination process. A thin layer of vermiculite over seeds in a drainage-ready container helps protect young seedlings and promotes consistent growth.

However, vermiculite is less durable than other growing media, such as sand or perlite, which makes it prone to compaction over time. Therefore, vermiculite is generally used in mixtures rather than as a stand-alone growing medium, particularly for long-term cultivation. For long-term use and to enhance its benefits, vermiculite is often combined with other substrates like perlite or coconut fibre, creating a balanced blend (67). These additions improve drainage and provide a firmer structure, which helps prevent waterlogging and enhances the medium's longevity (68). With its versatile properties and adaptability, vermiculite remains a popular choice in horticulture, especially in applications where

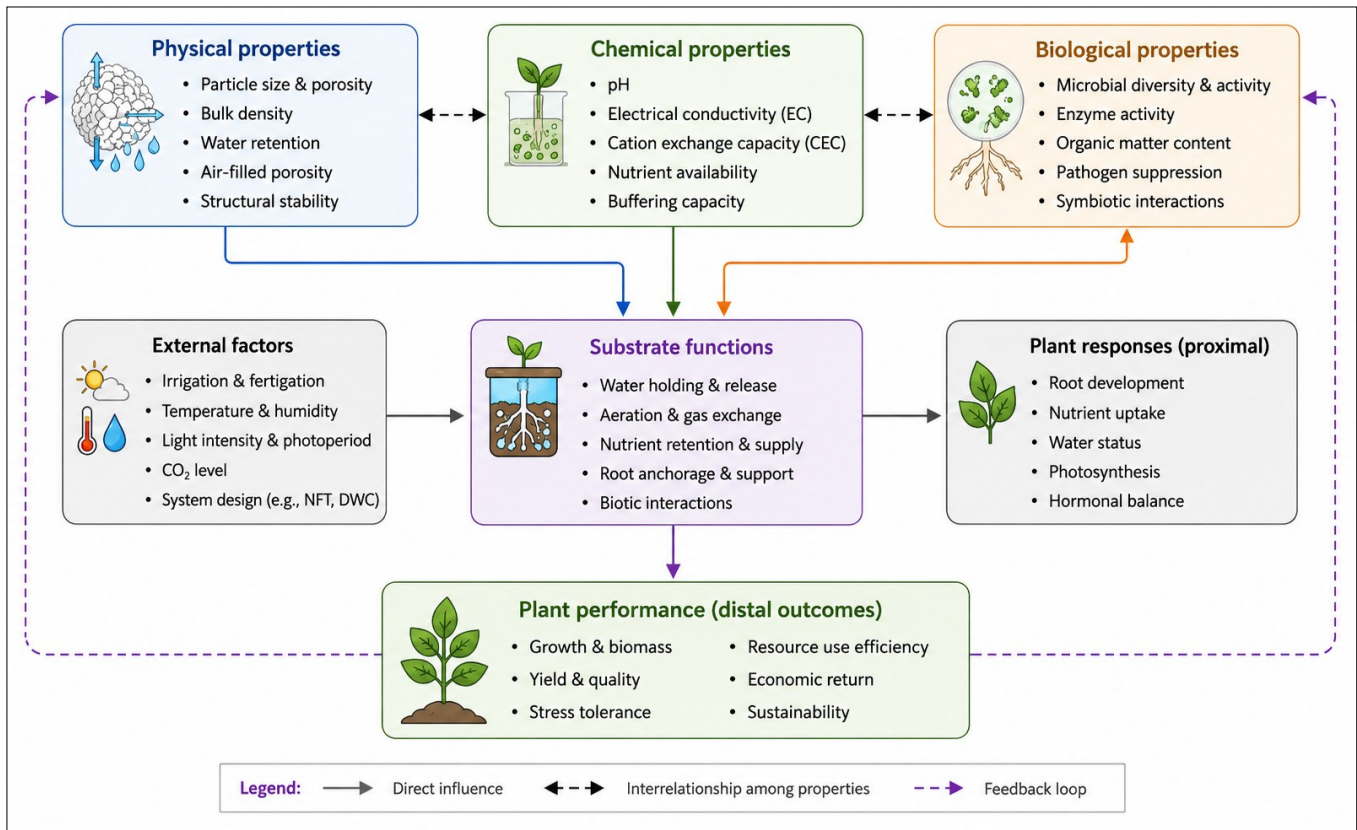


Fig. 2. Conceptual model illustrating the interactions among physical, chemical and biological properties of growing media and their effects on substrate functions, plant responses, crop performance, resource-use efficiency and sustainability.

moisture retention and aeration are critical. A group of researchers observed an improvement in the agronomic performance of maize, sunflower and cotton after using a vermiculite-based rock fertilizer in sandy soils (63). Vermiculite application rates of 5 t ha⁻¹ and 10 t ha⁻¹ enhanced leaf dimensions, along with fresh and dry matter yields of *Brassica napus* (69).

Biostrate

Biostrate is a recently developed, bio-based fabric designed specifically for hydroponic microgreens and baby salad greens. This woven mat felt material is widely available on the market and is made from biodegradable materials like wood fibres, providing ideal conditions for plant roots. Its lightweight design and efficient moisture and nutrient retention make it particularly well-suited for hydroponic applications, including microgreen production (70, 71). Its commercial use is mainly associated with small-scale indoor and commercial microgreen production, where its lightweight and ready-to-use form can simplify handling and substrate disposal.

The application of plant bio stimulants can further enhance the utilization of Biostrate, improving crop quality and nutrient absorption. Despite these benefits, Biostrate tends to be about 50 % more expensive than quality soil in small quantities and requires a nutrient supplement to achieve satisfactory yields. Thus, its economic feasibility depends on crop value, production scale, substrate cost and the savings associated with convenient handling and disposal. Some crops may struggle to thrive on this medium, necessitating careful monitoring of watering to prevent dehydration, as it can dry out quickly (72). While Biostrate is convenient for those who lack space for soil disposal, its accessibility may be limited, as it is not always readily available in local stores (73). However, it is more affordable than alternatives like hemp and coco coir and its easy disposability makes it practical for indoor gardening, particularly in kitchens. Compared with conventional soil and commonly used

substrates such as coco coir, Biostrate offers lower weight, convenient handling and easier disposal, but may have lower moisture-buffering capacity and greater dependence on controlled irrigation and nutrient supplementation.

Its ability to decompose naturally adds to its appeal as an environmentally friendly option. Because it is composed primarily of biodegradable plant-derived fibres, Biostrate can decompose after use, potentially reducing persistent substrate waste compared with non-biodegradable synthetic materials; however, the rate and environmental benefits of biodegradation depend on disposal conditions. Biostrate is a newly emerging medium for microgreen cultivation and is readily available in the market. But there is no literature evidence related to the usage of Biostrate as a medium for microgreen cultivation. However, despite its commercial availability, independent scientific evidence on its long-term performance, biodegradation behaviour, cost-effectiveness and suitability across different crops remains limited (70).

Expanded clay pellets

The lightweight and aerating properties of expanded clay pellets, also referred to as hydroton or clay pebbles or grow rocks, making them highly popular in the hydroponics field (74). Expanded clay balls are produced by various brands in different countries, such as Hydroton in Australia, Keramzit in Russia and Blaehton in Germany. Additionally, these pellets have been noted to provide effective drainage. They exhibit a pH value of 7, indicating a neutral nature. Furthermore, it displays a notable resistance to degradation and does not undergo breakdown over extended periods. Using clay pellets is prevalent in hydroponic systems that operate through flood and drain (ebb and flow) mechanisms (75). The water-holding capacity of these materials is limited, which may necessitate more frequent irrigation (76). However, they are recommended only for short-term growth periods, ideally under 4 weeks. This limitation is

due to reduced control over nutrient delivery, as the medium can encourage light-driven algal growth and high evaporation rates in the trays (77). Unlike plastic fragments, these substrates are not chemically inert and may release mineral ions into the solution or change nutrient availability, making them less suitable for studies on mineral element deficiencies and toxicities. These pellets are filled with tiny air pockets, giving them excellent drainage and aeration, which are crucial for maintaining oxygenated root zones and supporting healthy root development.

Clay pebbles work particularly well in systems with frequent watering, such as ebb and flow setups, since their structure prevents clogging while promoting water flow and retention of air bubbles around the roots. One of the key advantages of expanded clay pebbles is their reusability and cost-effectiveness, making them a sustainable choice for both home and commercial growers (78). Compared with rockwool and perlite, expanded clay pellets have a greater potential for repeated reuse because of their durability, although they require thorough cleaning and sanitation between production cycles to remove accumulated roots, algae, pathogens and salts. Perlite is also reusable but can generate dust and gradually lose structural integrity during handling, whereas rockwool is generally more difficult to reuse and dispose of because of its fibrous structure. Although the initial cost of expanded clay pellets may be higher than some disposable substrates, their long service life and repeated use can reduce the cost per production cycle. However, water, labour and energy requirements for cleaning and sanitation should also be considered when evaluating their lifecycle cost.

Wood fibre

The term "wood fibre" encompasses materials derived from both fresh sources, such as pine chips and waste sources, like shredded pallets, but lacks a clear definition in existing literature. Wood fibre is emerging as a sustainable alternative to peat in growing media, effectively addressing the significant environmental concerns associated with peat extraction, such as habitat destruction, biodiversity loss and carbon dioxide emissions (79, 80). Wood fibre alone or mixed with peat is a viable alternative, although not entirely accepted due to challenges with nitrogen immobilization during microbial decomposition and low water retention capacity. Wood fibre alone or mixed with peat is a viable alternative, although not entirely accepted due to challenges with avoiding nitrogen immobilization and low water retention capacity (43). It improves the water-holding capacity of growing media, promoting consistent moisture levels for plant roots. As reliance on peat diminishes due to its classification as a fossil fuel and non-renewable resource, wood fibre serves as an effective supplement in horticulture, although it cannot fully replace peat (81, 18).

The quality of wood fibre is crucial for its effectiveness as a Growing media; poor-quality fibres can harbour pathogens and harmful substances detrimental to plant health. To ensure high standards, obtaining RHP (Registration of Growing Media) certification is essential, as this guarantees compliance with strict quality control standards, including particle size, nutrient content and water retention, while ensuring the medium is free from contaminants. In commercial soilless growth media, wood fibres are predominantly created through intensive secondary processing, often extruded from debarked softwoods like pine or spruce (82). Because wood fibre has a high carbon-to-nitrogen ratio, microbial decomposition can temporarily immobilize mineral nitrogen, reducing its availability to plants during early cultivation. To mitigate

microbial nitrogen immobilization and enhance stability, the material is frequently saturated with nitrogen. However, due to its tendency to compress and hold insufficient plant-available water, wood fibre is rarely utilized as a standalone growth medium component. A combination of 75 % of wood fibre and 25 % of compost tended to produce the highest marketable yield (83).

Rockwool

Rockwool (RW) is a widely used substrate in hydroponic systems for seed and clone propagation (84, 85). It is primarily composed of diabase and limestone melted at around 1600 °C, producing a stable, porous structure with high water retention suitable for crop cultivation (85). Its inert nature provides no nutrient charge (zero ppm or EC), allowing precise control over nutrient delivery and feeding regimes (86, 87). RW combines high water retention with adequate aeration, creating favourable conditions for root development, while its sterile nature reduces the risk of pests and diseases (88). However, its inorganic and non-biodegradable nature creates disposal challenges, with used RW frequently accumulating in landfills and posing potential environmental concerns. It is available in different sizes and forms, allowing its use from seed establishment to mature crop production. Although not infinitely reusable, rockwool can be cleaned and reused for multiple growing cycles, improving its cost-effectiveness over time.

Growstone

Growstones (GS), an innovative and environmentally sustainable Growing media derived from recycled glass, are increasingly utilized in hydroponic systems and container gardening as a viable alternative to traditional substrates such as perlite, pumice and rockwool (89). Rowstones were created by finely grinding waste glass and mixing it with calcium carbonate, which was then heated in a kiln. The heating process caused the glass particles to fuse, releasing carbon dioxide and trapping air pockets within the glass. This process resulted in a lightweight, expanded material. Their highly porous structure allows for exceptional drainage and aeration, reducing the risk of waterlogging and root rot by facilitating excess water flow while enabling optimal air circulation around the root zone (90). Moreover, the use of recycled glass in their production underscores growstones' alignment with circular economy principles, providing a sustainable and eco-conscious solution that minimizes environmental impact.

Pumice

Pumice, a highly porous, lightweight and silica-rich glassy rock formed by explosive volcanic eruptions, is commonly found in volcanic regions globally and has emerged as a viable inorganic option for plant growth. However, since the physical properties of pumice can vary significantly across different volcanic regions (91, 92). Pumice, a lightweight and porous volcanic rock, is increasingly recognized as an effective inorganic growth medium in vertical farming due to its high silica content and excellent water retention and aeration properties. Its physical characteristics can vary based on volcanic origin, which influences crop performance (92). Research shows that pumice significantly enhances the quality of crops like muskmelons (*Cucumis melo* L.) and tomatoes (*Solanum lycopersicum* L.), improving visual and flavour characteristics, total soluble solids, flowering acceleration and fruit ripening (93–95). Additionally, pumice helps suppress pathogens and supports beneficial biocontrol agents, promoting plant health (93, 96, 97). Its inert, pH-neutral nature allows for precise nutrient and

pH management, while its durability ensures structural integrity over multiple growth cycles, making it a sustainable and cost-effective option. The incorporation of pumice into soilless systems thus not only supports efficient water and nutrient delivery but also contributes to a healthier growing environment, ultimately leading to more resilient crops in vertical farming applications (98). Although pumice may be preferable for heavier or taller plants needing additional weight for stability.

Sand

Sand, one of the oldest known hydroponic substrates, is less commonly used today due to its low water-holding capacity and considerable weight. However, sand can be effective in vertical farming when used in techniques such as sandponics or the Integrated Aqua-Vegeticulture System (IAVS). Its excellent drainage, root aeration, affordability and reusability provide advantages, particularly where other substrates are expensive (99). However, its low cation exchange capacity and limited water retention require frequent nutrient supplementation and careful irrigation management. In commercial stacked vertical farms, the high bulk density of sand increases structural load and handling requirements, while frequent irrigation and limited suitability for automated water management reduce its practical advantage compared with lightweight engineered substrates. Mixing sand with perlite or coir can improve water retention and nutrient availability.

Gravel

Gravel was one of the earliest commercially used substrates in hydroponic systems and remains affordable, readily available, durable and reusable (100). Its high porosity provides good root aeration, but its poor water retention can cause rapid drying if irrigation is interrupted. Its high weight also increases structural load and makes handling and automated substrate management more difficult in stacked vertical systems. Although gravel can be reused after washing and sterilization between crop cycles, these additional

cleaning and handling requirements can increase labour and operational costs in commercial production. Consequently, gravel is less commonly preferred than lightweight substrates in modern automated vertical farming systems. Overall, the major growing media differ considerably in their resource requirements, environmental impacts, biodegradability, reusability and lifecycle considerations (Fig. 3).

Oasis cube

Oasis cubes provide a convenient, low-maintenance hydroponic medium ideal for vertical farming. They are easy to irrigate and handle, with adjustable heights to support various plants, including vegetables, herbs and flowers. Highly absorbent and able to retain 30–40 times their weight in water, oasis cubes deliver consistent moisture and nutrients to plant roots while maintaining good oxygen flow. Additionally, their neutral pH offers a healthy environment for plants, reducing risks of harmful microbes (101). However, oasis cubes have limitations. Their foam structure holds fewer nutrients, requiring additional fertilizers for nutrient-demanding plants. They may also compact over time, which can reduce root oxygenation and impact growth. Oasis cubes tend to be pricier than other hydroponic media, potentially adding to costs for larger setups.

Rice hulls

Rice hulls are a lesser known and underutilized substrate in most parts of the world, but they have proven to be as effective as perlite to produce a range of crops (102). Rice hulls are a by-product of rice production and have the potential to be an inexpensive, effective medium in rice production areas. This free-draining substrate has low to moderate water-holding capacity, a slow rate of decomposition and low level of nutrients. Rice husk, with its slight acidic pH and high potassium levels, offers benefits for plant growth (103). As a renewable and readily available resource, it serves as a promising alternative to conventional substrates like peat. Del Amor

Substrate type	Renewable resource use  (Use of renewable materials)	Manufacturing energy demand  (Energy required for production)	Water Use  (Water footprint in production)	Use phase performance  (Durability, reusability & plant productivity)	End-of-life impact  (Biodegradability/recyclability)	Overall Sustainability score (out of 15)  (Higher score = more sustainable)
 Coco coir	●●●	●●	●●	●●●	●●●	13 (High)
 Perlite	●	●●	●●	●●●	●	8 (Moderate)
 Expanded clay pellets	●	●●	●●	●●●	●●	9 (Moderate)
 Rockwool	●	●●●	●	●●●	●	6 (Low)
 Biochar composite	●●●	●●	●●	●●●	●●●	13 (High)
 Biodegradable polymer (substrate)	●●●	●●	●●	●●	●●●	12 (High)

Scoring guide (per indicator)

●●● High (3) = More sustainable impact
●● Moderate (2) = Medium impact
● Low (1) = Less sustainable impact

Notes:

- Assessment is relative and based on published data and general literature.
- Scores consider cradle-to-grave impacts: resource use, manufacturing, use phase, and end-of-life.
- Actual impacts may vary with source, processing, transportation, system design, and region.

Score interpretation (out of 15)

12–15 = High sustainability
7–11 = Moderate sustainability
0–6 = Low sustainability

Abbreviations: ● = Low (1) ●● = Moderate (2) ●●● = High (3)

Fig. 3. Comparative sustainability assessment of major growing media based on resource use, environmental impacts, reusability, biodegradability and lifecycle considerations.

and associates (104) demonstrated that adding rice husk ash (RHA) to substrate notably boosts dry matter and chlorophyll levels in pepper seedlings. Additionally, tomato yields have been observed to improve significantly when grown in substrate mixes that include rice husk (105).

RHA 40 (Rice husk ash: peat: vermiculite: perlite = 4:4:1:1) improved cucumber and melon growth by enhancing stem diameter, root activity, chlorophyll content and fruit quality, while boosting sucrose and soluble protein levels (102).

Polyurethane Grow Slabs

Polyurethane grow slabs are lightweight, synthetic growing media made from foam, developed specifically for hydroponic production. Comprising 75–80 % air space and 15 % water-holding capacity, these slabs offer excellent water retention, aeration and nutrient flow, promoting healthy root growth (106). They are sterile, inert and pH-neutral, reducing the risk of pests and diseases (107). Easy to handle and reusable, polyurethane slabs are a sustainable choice for vertical farming systems. However, they require regular monitoring of nutrient levels due to their limited nutrient retention. Overall, polyurethane grow slabs provide an efficient and cost-effective solution for vertical farming, though more research is needed due to their relatively new development (108).

Recent advancements in growing media

Recent advancements in growing media for vertical farming emphasize sustainability, efficiency and high performance to address the challenges of limited space and resources. Innovations in substrates are improving key properties like water retention, nutrient delivery and aeration, which are critical for maximizing plant health and productivity in confined environments (109, 110). A prominent development is the use of renewable materials, such as coco coir, which serves as a sustainable alternative to peat and is renowned for its excellent water retention and aeration capabilities. Often blended with additives like perlite or vermiculite, coco coir creates an ideal environment for root health by optimizing moisture levels.

Studies by Dede and Ozer (26) further underscore the benefits of such blends; they found that adding 25 % perlite to raw peat and hazelnut husk improved the porosity of the growing media by 68.25 % and increased air capacity by 30.03 %, while hazelnut husk helped fine-tune air capacity by lowering it to more optimal levels. Hydroponic growing systems have also seen advancements in media such as expanded clay pellets, perlite and rock wool, which provide consistent support while ensuring efficient moisture retention and nutrient absorption. Additionally, bio-based materials like algae-based media and recycled inputs (e.g., rice husks, straw and coffee grounds) are gaining popularity due to their potential to reduce waste, improve water retention and enhance nutrient cycling. Biochar-based composites are also emerging as multifunctional substrates because their porous structure can improve water retention, nutrient adsorption and microbial habitat while enabling the utilization of agricultural residues. Similarly, engineered biodegradable polymers and polymer-biomass composites are being explored to provide controlled porosity, structural stability and gradual biodegradation as alternatives to persistent synthetic materials.

The integration of smart technologies is another step forward, enabling real-time monitoring of water, nutrient levels and pH for precise control over the growing environment. The Internet of

Things (IoT) enhances vertical farming by optimizing growing media management for efficient resource use and improved crop health (111). By embedding sensors in the media, IoT enables real-time monitoring of moisture, nutrient levels, temperature and other vital factors, allowing automated systems to deliver precise irrigation and nutrients, minimizing waste (112, 113). Additionally, IoT helps maintain ideal aeration and root health by adjusting humidity and CO₂ levels, preventing issues like waterlogging and nutrient imbalance (114, 115). Increasingly, artificial intelligence (AI) and machine-learning approaches are being combined with sensor data to predict moisture and nutrient requirements and optimize irrigation and fertigation according to crop growth stage. This development is moving substrate management from fixed media formulations toward precision substrate design, in which particle size, porosity, water-holding capacity, nutrient retention and root-zone conditions can be tailored to specific crops and production systems. This approach reduces the need for frequent media replacement, promoting sustainability by conserving resources and minimizing waste.

Another emerging approach is the incorporation of beneficial microbial inoculants, including plant-growth-promoting bacteria and fungi, into growing media. These microorganisms can improve nutrient mobilization, root development and plant resilience while supporting biological processes in otherwise low-microbial soilless systems. Similarly, in hydroponics system Nutrient Film Technique (NFT) offering efficient nutrient and water delivery with minimal waste. Nutrient Film Technique supports steady nutrient uptake, resulting in healthier and more productive crops. New materials, like hydrogels and engineered substrates, are also promising in water retention. For instance, specific hydrogel formulations, such as nanocomposite-calcium montmorillonite (NC-MMt), have demonstrated enhanced plant growth, as shown in tomato seedlings (116), highlighting their potential as a sustainable potting medium for vertical farms. Nanomaterial-based substrates and nanocomposite hydrogels are further being investigated for their ability to improve water and nutrient retention and provide controlled release of essential inputs, although their long-term environmental and biological safety requires careful evaluation (118, 119). The key physical, chemical and sustainability characteristics of the major growing media used in vertical farming are comparatively summarized in Table 3.

Recent research is also increasingly adopting circular-economy approaches by converting agricultural and food-processing residues into growing media, thereby reducing waste and dependence on non-renewable substrates. However, the sustainability of novel media cannot be assessed solely from their biodegradability or renewable origin. Lifecycle assessment (LCA) is increasingly important for evaluating energy consumption, processing requirements, transportation, durability, reuse, waste generation and end-of-life impacts. Such assessments can identify whether apparently sustainable substrates provide genuine environmental benefits over their complete production and use cycles. Altogether, biodegradable mats, microbial-enhanced substrates, hydrogels, biochar composites, nanomaterial-based substrates and precision-controlled hydroponic innovations contribute to resource-efficient, high-yield vertical farms. The integration of advanced materials, biological inputs, sensor-based monitoring and AI-driven optimization therefore represents a shift from conventional substrate selection toward multifunctional and

Table 3. Comparison of key properties and sustainability metrics of various growing media for vertical farming

Growing media	CEC	Water holding capacity	pH	Nutrient retention capacity	Porosity	Rewetting capacity	Renewability	Cost effectiveness	Nutrient content	Microbial activity	Carbon footprint	Degradability	References
Peat	High	High	Acidic (3.5–5.5)	High	Moderate	Poor	Non-renewable	Moderate to High	Moderate to High	High	High (non-renewable)	Moderate	(23)
Coco Coir	Moderate	High	Neutral to slightly acidic (5.5–6.5)	Moderate	High	Good	renewable	Moderate	Moderate	High	Low to Moderate	High (biodegradable)	(23,49)
Perlite	Low	Low to Moderate	Neutral (7)	Low	Very high	Good	Non-renewable	Low to Moderate	Very low	low	High (energy-intensive)	Low	(50,51)
Vermiculite	Moderate to High	Very high	Neutral to slightly alkaline (6.5–7.5)	High	Moderate	Good	Non-renewable	Moderate	Moderate	High	High (energy-intensive)	Moderate	(64,65)
Biostrate	Low	Moderate	Neutral (6–7)	Low	Moderate to low	Moderate	renewable	High	Low to Moderate	Low	Low	High (biodegradable)	(70)
Expanded Clay Pellets	Very Low	Low	Neutral (7)	Very low	Very high	Good	Renewable	Moderate – high	Very Low	Low	High (energy-intensive)	Low	(74,75)
Wood fibre	Low	Moderate to High	Neutral to slightly acidic (5.5–6.5)	Low to Moderate	Moderate to High	Good	Renewable	Moderate	Moderate to High	High	Low to Moderate	High (biodegradable)	(79,117)
Rockwool	Very Low	High	Neutral (7)	low	High	Moderate	Non-renewable	Moderate to High	Very Low	Low	High (energy-intensive)	Low	(88)
Sand	Very Low	Very Low	Neutral (6.5–7.5)	Very Low	High	Good	Non-renewable	Low	Very Low	Low	Very Low (mined)	Low	(100)
Gravel	Very Low	Very Low	Neutral (7)	Very Low	Very High	Excellent	Renewable	Low	Very Low	Low	Very Low (mined)	Low	
Pumice	Low	Moderate	Neutral to slightly acidic (6–7)	Low	High	Good	Non-renewable	Moderate to High	Low to Moderate	Moderate	Low	Low	(92)
Growstone	Low	Moderate	Neutral (6.5–7.5)	Low	High	Good	Recycled material	Moderate to High	Low	Moderate	Low	Low	(89)
Rice hulls	Low to Moderate	Moderate	Slightly acidic (6–7)	Moderate	High	Moderate	Renewable	Low	Moderate to high	High	Low	High (biodegradable)	(102,103)

precision-designed growing media. These eco-conscious substrates showcase the potential of vertical farming to support sustainable food production with minimal environmental impact. These developments indicate a shift toward biodegradable, multifunctional, biologically integrated, digitally optimized and circular growing-media systems for future vertical farming (Fig. 4). Despite recent advances in sustainable growing media, several knowledge gaps remain regarding substrate standardization, long-term environmental performance, crop-specific design, microbial integration and AI-assisted optimization; these gaps and corresponding future research priorities are summarized in Table 4.

Conclusion

Vertical farming, supported by advances in growing media and integrated technologies, offers a promising approach to food production under limited land and resource availability. Among existing substrates, coco coir and coir-based blends provide a favourable balance of water retention, aeration, renewability and crop performance, while perlite and expanded clay pellets offer advantages in drainage, structural stability and reuse. However, no single substrate is optimal across all crops and production systems. Emerging biochar composites, biodegradable polymers, hydrogels, nanocomposites and microbial-enhanced substrates show considerable promise, although their long-term performance, safety, scalability and environmental impacts require further validation.

The integration of IoT, automation and environmental control systems enables precise management of moisture, nutrients and aeration, improving resource-use efficiency. Future research should focus on biodegradable alternatives to rockwool, standardized substrate evaluation, long-term life-cycle assessment, AI-assisted optimization, crop-specific substrate design and

beneficial microbial integration. Researchers should develop standardized evaluation protocols, growers should consider performance and lifecycle costs, manufacturers should prioritize sustainable and reusable materials and policymakers should support standards and incentives for low-impact substrates. Overall, the future of vertical farming depends on integrating optimized growing media, biological inputs, smart technologies and circular resource management to achieve productive, economically viable and environmentally sustainable systems.

Acknowledgement and Funding

The authors sincerely acknowledge the Department of Agronomy, Tamil Nadu Agricultural University for their valuable support, guidance and encouragement. Their constant assistance and the opportunity to undertake and develop this article have been instrumental in bringing this work to fruition. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' contributions

KS and VS prepared the manuscript. Guidance and supervision for the work were provided by RK, RAIP, AA and SG. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to declare.

Ethical issues: None

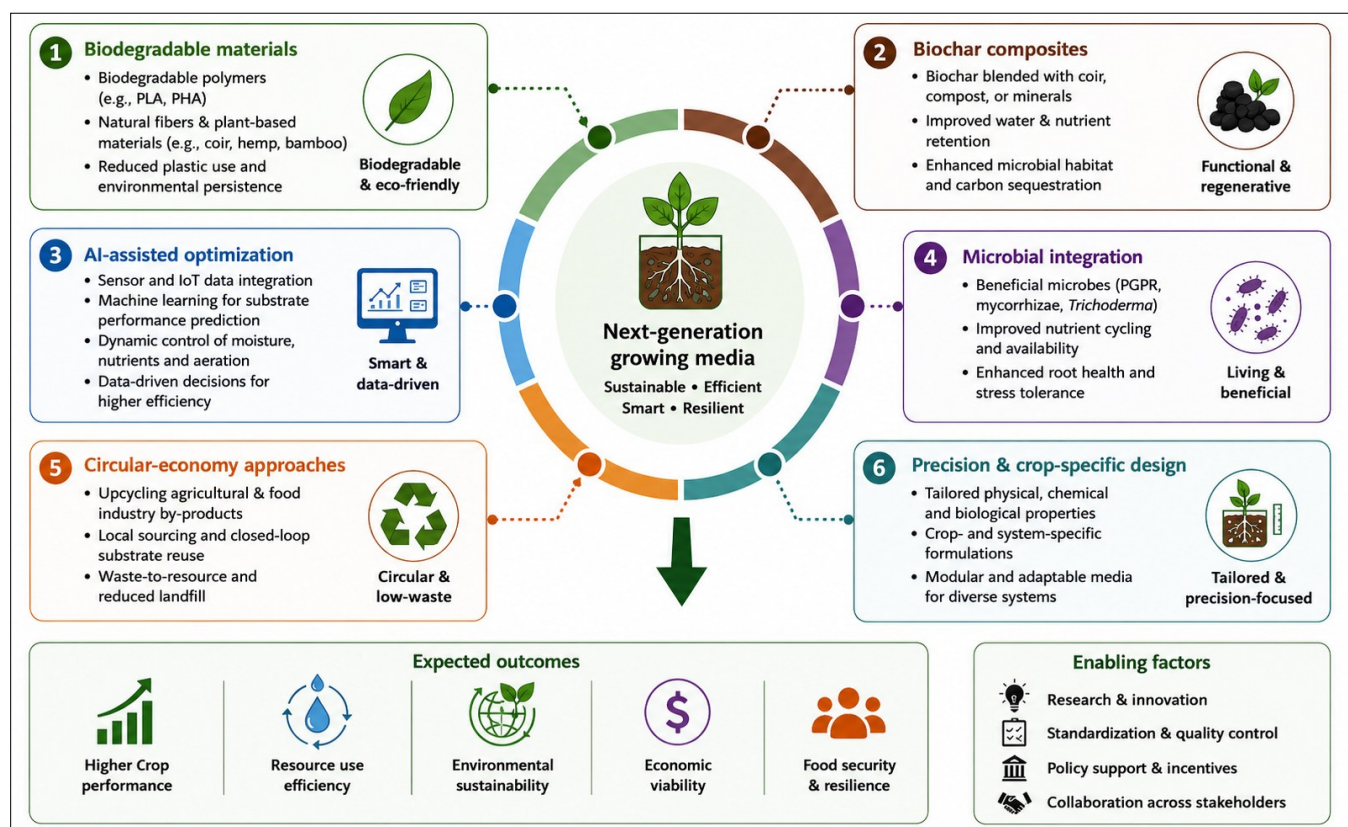


Fig. 4. Future trends in sustainable growing media, highlighting biodegradable materials, biochar composites, microbial integration, AI-assisted optimization, precision substrate design and circular-economy approaches.

Table 4. Summary of current knowledge gaps and recommended future research priorities for sustainable growing media in vertical farming

Knowledge gap	Current limitation	Recommended research priority	Expected outcome
Lack of standardized substrate evaluation	Different studies use varying methods and parameters, making comparisons difficult	Develop standardized protocols for physical, chemical, biological and agronomic evaluation	Improved comparability and reliable substrate selection
Limited biodegradable alternatives to rockwool	Many alternatives have insufficient durability or commercial validation	Develop and test biodegradable substrates with adequate structural stability and root support	Reduced non-biodegradable waste from vertical farming
Insufficient long-term sustainability data	Environmental benefits of novel substrates are often assessed only during production or use	Conduct long-term life-cycle assessments covering production, transport, reuse and disposal	Better understanding of actual environmental performance
Limited crop-specific substrate design	Most substrates are evaluated across broad crop groups rather than specific crop requirements	Develop crop-specific substrate formulations based on root characteristics and growth requirements	Improved crop performance and resource-use efficiency
Limited understanding of microbial interactions	Soilless systems often have poorly characterized microbial communities	Integrate beneficial microorganisms and study their effects on nutrient cycling, root health and plant growth	Improved nutrient availability and plant resilience
Limited AI-assisted substrate optimization	Substrate selection and irrigation are often based on fixed recommendations	Use AI and sensor-based data to optimize moisture, nutrient availability and substrate properties	Precision substrate and irrigation management
Limited validation of novel materials	Nanomaterials, hydrogels, biochar composites and biodegradable polymers require further validation	Evaluate long-term performance, safety, scalability and environmental effects	Identification of safe and commercially viable alternatives
Limited circular-economy integration	Many substrates are discarded after use, generating waste	Develop reusable, recyclable and residue-based substrates and establish effective end-of-life strategies	Reduced waste and improved resource circularity
Economic feasibility remains uncertain	Initial cost, replacement frequency and processing costs vary among substrates	Assess whole-cycle costs, reuse potential, labour and energy requirements	Improved economic decision-making for commercial vertical farms
Limited large-scale commercial validation	Many promising substrates are tested mainly under laboratory or small-scale conditions	Conduct multi-cycle and commercial-scale trials across crops and hydroponic systems	Improved scalability and practical adoption

References

- Conforti P, editor. Looking ahead in world food and agriculture: perspectives to 2050. Rome: Food and Agriculture Organization of the United Nations; 2011.
- Food and Agriculture Organization of the United Nations. FAOSTAT database. Rome: Food and Agriculture Organization of the United Nations; 2016.
- AbdelRahman MAE. An overview of land degradation, desertification and sustainable land management using GIS and remote sensing applications. *Rend Fis Acc Lincei*. 2023;34:767–808. <https://doi.org/10.1007/s12210-023-01155-3>
- Beacham AM, Vickers LH, Monaghan JM. Vertical farming: a summary of approaches to growing skywards. *J Hortic Sci Biotechnol*. 2019;94(3):277–83. <https://doi.org/10.1080/14620316.2019.1574214>
- Gokul A, Sheeja P. Vertical farming: a novel farming technology. *Int J Mod Trends Eng Res*. 2016;3:7–11. <https://doi.org/10.21884/ijmter.v3.i7.gx2J5WU9>
- Albadwawi MAO, Ahmed ZFR, Kurup SS, Alyafei MA, Jaleel A. A comparative evaluation of aquaponic and soil systems on yield and antioxidant levels in basil, an important food plant in Lamiaceae. *Agronomy (Basel)*. 2022;12:3007. <https://doi.org/10.3390/agronomy12123007>
- Wu S, Wei Y, Head B, Zhao Y, Chen J, Hanna S, et al. The development of ancient Chinese agricultural and water technology from 8000 BC to 1911 AD. *Palgrave Commun*. 2019;5:77. <https://doi.org/10.1057/s41599-019-0282-1>
- Despommier D. Vertical farms, building a viable indoor farming model for cities. *Field Actions Sci Rep*. 2019;20:68–73.
- Bailey GE. Vertical farming. Baltimore: Lord Baltimore Press; 1915.
- Jackson W. New roots for agriculture. In: Coates GJ, editor. *Resettling America: energy, ecology and community*. London: Routledge; 2023. p. 498–515. <https://doi.org/10.4324/9781003425168-26>
- Sowmya C, Anand M, Indu Rani C, Amuthaselvi G, Janaki P. Recent developments and inventive approaches in vertical farming. *Front Sustain Food Syst*. 2024;8:1400787. <https://doi.org/10.3389/fsufs.2024.1400787>
- Despommier D. The vertical farm: feeding the world in the 21st century. New York: Thomas Dunne Books/St. Martin's Press; 2010.
- Nájera C, Gallegos-Cedillo VM, Ros M, Pascual JA. LED lighting in vertical farming systems enhances bioactive compounds and productivity of vegetable crops. *Biol Life Sci Forum*. 2022;16:24. <https://doi.org/10.3390/IECHo2022-12514>
- de Kreijl C, Voogt W, Baas R. Nutrient solutions and water quality for soilless cultures. Naaldwijk: Applied Plant Research, Division Glasshouse Horticulture; 2003. 42 p. (PPO-Glas Brochure; 191).
- Klassen SP, Bugbee B, Monje O. Aeroponic and hydroponic systems for the cultivation of plants. In: Moo-Young M, editor. *Comprehensive biotechnology*. 3rd ed. Amsterdam: Elsevier; 2020. p. 330–44.
- Naskali AT, Pinarer O, Tolga AC. Vertical farming: under climate change effect. In: *Environment and climate-smart food production*. Cham: Springer; 2022. p. 259–84. https://doi.org/10.1007/978-3-030-71571-7_8
- Benke K, Tomkins B. Future food-production systems: vertical farming and controlled-environment agriculture. *Sustain Sci Pract Policy*. 2017;13(1):13–26. <https://doi.org/10.1080/15487733.2017.1394054>
- Schmilewski G. The role of peat in assuring the quality of growing media. *Mires Peat*. 2008;3:1–8. <https://doi.org/10.19189/001c.128252>
- Gruda N. Current and future perspective of growing media in Europe. *Acta Hortic*. 2012;960:37–43. <https://doi.org/10.17660/ActaHortic.2012.960.3>

20. Barrett GE, Alexander PD, Robinson JS, Bragg NC. Achieving environmentally sustainable growing media for soilless plant cultivation systems: a review. *Sci Hortic*. 2016;212:220–34. <https://doi.org/10.1016/j.scienta.2016.09.030>
21. Sabatino L. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems: an editorial. *Agronomy*. 2020;10:1384. <https://doi.org/10.3390/agronomy10091384>
22. Konappan S, Ramanujam K, Saitheja V, Subramanian S, Govindan SK, Ettiyagounder P, et al. Polyhalite as a next generation chloride-free multi-nutrient fertilizer for sustainable agriculture: a review. *J Plant Nutr*. 2025;48(20):3784–814. <https://doi.org/10.1080/01904167.2025.2523539>
23. Mariotti B, Martini S, Raddi S, Oliet JA, Maltoni A. Coconut coir as a sustainable nursery growing media for seedling production of the ecologically diverse *Quercus* species. *Forests*. 2020;11(5):522. <https://doi.org/10.3390/f11050522>
24. Alexander PD, Bragg NC, Meade R, Padelopoulos G, Watts O. Peat in horticulture and conservation: the UK response to a changing world. *Mires Peat*. 2008;3:8. <https://doi.org/10.19189/001c.128260>
25. Schmilewski G. Growing media constituents used in the EU. *Acta Hortic*. 2009;819:33–46. <https://doi.org/10.17660/ActaHortic.2009.819.3>
26. Dede OH, Ozer H. Improving physical properties of plant growing media using perlite. *Sak Univ J Sci*. 2018;22(5):1346–50. <https://doi.org/10.16984/saufenbilder.382895>
27. Paleckiene R, Navikaite R, Slinksiene R. Peat as a raw material for plant nutrients and humic substances. *Sustainability*. 2021;13:6354. <https://doi.org/10.3390/su13116354>
28. Gruda N. Sustainable peat alternative growing media. In: *Book of abstracts: new and innovative techniques in soilless cultivation*. 2010. p. 33.
29. Cao S. Environmental impact of vertical farming systems. *IOP Conf Ser Earth Environ Sci*. 2019;384:012174. <https://doi.org/10.1088/1755-1315/384/1/012174>
30. Bonn A, Reed MS, Evans CD, Joosten H, Bain C, Farmer J, et al. Investing in nature: developing ecosystem service markets for peatland restoration. *Ecosyst Serv*. 2014;9:54–65. <https://doi.org/10.1016/j.ecoser.2014.06.011>
31. Dunn C, Freeman C. Peatlands: our greatest source of carbon credits? *Carbon Manag*. 2011;2(3):289–301. <https://doi.org/10.4155/cmt.11.23>
32. Michiels P, Hartmann R, Coussens C. Physical properties of peat in an ebb/flood irrigation system. *Acta Hortic*. 1993;342:205–19. <https://doi.org/10.17660/ActaHortic.1993.342.23>
33. Clymo RS, Fogg GE. The limits to peat bog growth. *Philos Trans R Soc Lond B Biol Sci*. 1984;303:605–54. <https://doi.org/10.1098/rstb.1984.0002>
34. Hirschler O, Thrän D. Peat substitution in horticulture: interviews with German growing media producers on the transformation of the resource base. *Horticultrae*. 2023;9:919. <https://doi.org/10.3390/horticultrae9080919>
35. Lindholm T, Heikkilä R. Destruction of mires in Finland. In: Lindholm T, Heikkilä R, editors. *Finland-land of mires*. Helsinki: Finnish Environment Institute; 2006. p. 179–92.
36. Steiner C, Harttung T. Biochar as a growing media additive and peat substitute. *Solid Earth*. 2014;5:995–99. <https://doi.org/10.5194/se-5-995-2014>
37. Schmilewski G. Growing media constituents used in the EU in 2013. *Acta Hortic*. 2017;1168:85–92. <https://doi.org/10.17660/ActaHortic.2017.1168.12>
38. Emmanuel G, Brimmo A, Chiesa M, Olukan T. The suitability of unprocessed coconut coir as nursery growth media for seedling production in hydroponic system. *SSRN Electron J*. 2022. Ppapers.ssrn.com. <https://doi.org/10.2139/ssrn.4055161>
39. Rosairo HSR, Kawamura T, Peiris TLGS. The coir fiber industry in Sri Lanka: reasons for its decline and possible turnaround strategies. *Agribusiness*. 2004;20(4):495–516. <https://doi.org/10.1002/agr.20071>
40. Nemati R, Fortin JP, Craig J, Donald S. Growing medias for medical cannabis production in North America. *Agronomy*. 2021;11:1366. <https://doi.org/10.3390/agronomy11071366>
41. Sangian HF, Kristian J, Rahma S, Dewi HK, Puspasari DA, Agnesty SY, et al. Preparation of reducing sugar hydrolyzed from high-lignin coconut coir dust pretreated by recycled ionic liquid and alkaline combination. *Bull Chem React Eng Catal*. 2015;10:8–22. <https://doi.org/10.9767/bcrec.10.1.7058.8-22>
42. Purnomo AS, Sariwati A, Fatmawati S, Puspitasari FE. Effect of coconut coir (*Cocos nucifera*) as a growth medium for *Pleurotus ostreatus* on mineral and vitamin B contents. *HAYATI J Biosci*. 2023;30(1):95–104. <https://doi.org/10.4308/hjb.30.1.95-104>
43. Gruda NS. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy*. 2019;9:298. <https://doi.org/10.3390/agronomy9060298>
44. Surya K, Sanbagavalli S, Somasundaram E, Renukadevi A, Panneerselvam S. Effect of potassium and foliar nutrition on yield and economics of kodo millet under irrigated condition. *Biol Forum Int J*. 2022;14(3):42–46.
45. Blok C, Wever G. Experience with selected physical methods to characterize the suitability of growing media for plant growth. *Acta Hortic*. 2008;779:239–50. <https://doi.org/10.17660/ActaHortic.2008.779.29>
46. Thomas GV, Palaniswami C, Prabhu SR, Gopal M, Gupta A. Co-composting of coconut coir pith with solid poultry manure. *Curr Sci*. 2013;104(2):245–50.
47. Paul RAI, Arthanari PM, Peramaiyan P, Kumar V, Bagavathiannan M, Surya K. Comparative analysis of UAV and electric backpack sprayers for herbicide efficacy and crop-weed nutrient dynamics in direct-seeded rice. *J Agric Food Res*. 2025;23:102307. <https://doi.org/10.1016/j.jafr.2025.102307>
48. Lizabeni MK, Somasundaram E, Murali AP, Kannan R, Janaki P, Sunitha R, et al. Non-chemical approaches for effective weed management and productivity of transplanted rice (*Oryza sativa* L.). *Plant Sci Today*. 2025;12(2). <https://doi.org/10.14719/pst.9374>
49. Both AK, Linderman JA, Madireddy G, Helle MA, Cheung CL. Valorization of coco coir into biocomposite materials through water-based chemistry. *Ind Crops Prod*. 2022;178:114563. <https://doi.org/10.1016/j.indcrop.2022.114563>
50. Grillas S, Lucas M, Bardopoulou E, Sarafopoulos S, Voulgari M. Perlite based soilless culture systems: current commercial applications and prospects. *Acta Hortic*. 2001;548:105–14. <https://doi.org/10.17660/ActaHortic.2001.548.10>
51. Londra PA, Paraskevopoulou AT, Psychoyou M. Evaluation of water-air balance of various substrates on begonia growth. *HortScience*. 2012;47:1153–58. <https://doi.org/10.21273/HORTSCI.47.8.1153>
52. Kingston PH, Scagel CF, Bryla DR, Strik BC. Influence of perlite in peat- and coir-based media on vegetative growth and mineral nutrition of highbush blueberry. *HortScience*. 2020;55(5):658–63. <https://doi.org/10.21273/HORTSCI14640-19>
53. Alkan M, Dogan M. Surface titrations of perlite suspensions. *J Colloid Interface Sci*. 1998;207:90–96. <https://doi.org/10.1006/jcis.1998.5694>
54. Bilderback TE, Warren SL, Owen JS, Albano JP. Healthy substrates need physicals too! *HortTechnology*. 2005;15:747–51. <https://doi.org/10.21273/HORTTECH.15.4.0747>
55. Zhang MX, Kelly PM. The morphology and formation mechanism of pearlite in steels. *Mater Charact*. 2009;60(6):484–89. <https://doi.org/10.1016/j.matchar.2009.01.001>

56. Varuzhanyan AA, Varuzhanyan AA, Varuzhanyan H. A mechanism of perlite expansion. *Inorg Mater.* 2006;42:1039–45. <https://doi.org/10.1134/S0020168506090202>
57. Fields JS, Fonteno WC, Jackson BE, Heitman JL, Owen JS. Hydrophysical properties, moisture retention and drainage profiles of wood and traditional components for greenhouse substrates. *HortScience.* 2014;49:827–32. <https://doi.org/10.21273/HORTSCI.49.6.827>
58. Kingston PH, Scagel CF, Bryla DR, Strik BC. Suitability of sphagnum moss, coir and Douglas-fir bark as soilless substrates for container production of highbush blueberry. *HortScience.* 2017;52(12):1692–99. <https://doi.org/10.21273/HORTSCI12374-17>
59. Daza A, Santamaría C, Rodríguez-Navarro DN, Camacho M, Orive R, Temprano F. Perlite as a carrier for bacterial inoculants. *Soil Biol Biochem.* 2000;32(4):567–72. [https://doi.org/10.1016/S0038-0717\(99\)00185-6](https://doi.org/10.1016/S0038-0717(99)00185-6)
60. Markoska V, Spalevic V, Lisichkov K, Atkovska K, Gulaboski R. Determination of water retention characteristics of perlite and peat. *Agric For.* 2018;64:113–26. <https://doi.org/10.17707/AgricForest.64.3.10>
61. Maaswinkel RHM, Gunadi N. Improving sweet pepper yields in Indonesia. *Fruit Veg Tech.* 2009;9(4):14–15.
62. Choi E, Lee Y, Kim J. Nutrient uptake, growth and yield of cucumber cultivated with different growing substrates under a closed and an open system. *Acta Hortic.* 2001;548:543–49. <https://doi.org/10.17660/ActaHortic.2001.548.66>
63. Pavlou GC, Ehaliotis CD, Kavvadias VA. Effect of organic and inorganic fertilizers applied during successive crop seasons on growth and nitrate accumulation in lettuce. *Sci Hortic.* 2007;111:319–25. <https://doi.org/10.1016/j.scienta.2006.11.003>
64. Patil ST, Kadam US, Mane MS, Mahale DM, Dhekale JS. Hydroponic growth media (substrate): a review. *Int Res J Pure Appl Chem.* 2020;21(23):106–13. <https://doi.org/10.9734/irjpac/2020/v21i2330307>
65. Fixen P, Paul E, Bruulsema T, Jensen RM, Murrell TS, Brouder S, et al. The fertility of North American soils. *Better Crops.* 2010;94:6–8.
66. Khalaj MA, Amiri M, Sindhu SS. Response of different growing media on the growth and yield of gerbera in hydroponic open system. *Indian J Hortic.* 2011;68(4):583–86.
67. Safaei M, Panahandeh J, Tabatabaei SJ, Motallebi Azar AR. Effects of different nutrients solutions on nutrients concentration and some qualitative traits of lettuce in hydroponics system. *J Sci Technol Greenh Cult.* 2015;6(2):1–8. <https://doi.org/10.18869/acadpub.ejgcs.6.2.1>
68. Bai G, Luo F, Zou Y, Liu Y, Wang R, Yang H, et al. Effects of vermiculite on the growth process of submerged macrophyte *Vallisneria spiralis* and sediment microecological environment. *J Environ Sci.* 2022;118:130–39. <https://doi.org/10.1016/j.jes.2021.08.038>
69. Pisa C, Parwada C, Chiripanyanga S, Dunjana N. Evaluation of vermiculite application rates on growth and yield of *Brassica napus*. *Sci Herit J.* 2020;4(2):46–50. <https://doi.org/10.26480/gws.02.2020.46.50>
70. Rajan P, Lada RR, MacDonald MT. Advancement in indoor vertical farming for microgreen production. *Am J Plant Sci.* 2019;10:1397–408. <https://doi.org/10.4236/ajps.2019.108100>
71. Di Gioia F, Petropoulos SA, Ozores-Hampton M, Morgan K, Roszkopf EN. Zinc and iron agronomic biofortification of Brassicaceae microgreens. *Agronomy.* 2019;9:677. <https://doi.org/10.3390/agronomy9110677>
72. Lada RR, Majiers W, Nieboer S. Innovative indoor horticultural systems (iHort) for the 21st century. *Curr Investig Agric Curr Res.* 2018;4:576–81. <https://doi.org/10.32474/CIACR.2018.04.000194>
73. Pinto E, Almeida AA, Aguiar AA, Ferreira IMPL. Comparison between the mineral profile and nitrate content of microgreens and mature lettuces. *J Food Compos Anal.* 2015;37:38–43. <https://doi.org/10.1016/j.jfca.2014.06.018>
74. Mlih R, Bydalek F, Klumpp E, Yaghi N, Bol R, Wenk J. Light-expanded clay aggregate (LECA) as a substrate in constructed wetlands: a review. *Ecol Eng.* 2020;148:105783. <https://doi.org/10.1016/j.ecoleng.2020.105783>
75. Rajaseger G, Chan KL, Tan KY, Ramasamy S, Khin MC, Amaladoss A, et al. Hydroponics: current trends in sustainable crop production. *Bioinformation.* 2023;19(9):925–38. <https://doi.org/10.6026/97320630019925>
76. Forster BP, Pakniyat H, Macaulay M, Matheson W, Phillips MS, Thomas WTB, et al. Variation in the leaf sodium content of the *Hordeum vulgare* cultivar Maythorpe and its derived mutant cv. Golden Promise. *Heredity.* 1994;73(3):249–53. <https://doi.org/10.1038/hdy.1994.130>
77. Shavrukov Y, Genc Y, Hayes J. The use of hydroponics in abiotic stress tolerance research. In: Asao T, editor. *Hydroponics: a standard methodology for plant biological researches.* Rijeka: InTech; 2012. p. 39–66. <https://doi.org/10.5772/35206>
78. Gorham J, Bristol A, Young EM, Wyn Jones RG, Kashour G. Salt tolerance in the Triticeae: K/Na discrimination in barley. *J Exp Bot.* 1990;41(9):1095–101. <https://doi.org/10.1093/jxb/41.9.1095>
79. Muro J, Irigoyen I, Samitier P, Mazuela P, Salas MC, Soler J, et al. Wood fiber as growing media in hydroponic crop. *Acta Hortic.* 2005;697:179–85. <https://doi.org/10.17660/ActaHortic.2005.697.22>
80. Verhagen J, Boon H. Classification of growing media on their environmental profile. *Acta Hortic.* 2008;779:231–38. <https://doi.org/10.17660/ActaHortic.2008.779.28>
81. Jackson BE, Wright RD, Alley MM. Comparison of fertilizer nitrogen availability, nitrogen immobilization, substrate carbon dioxide efflux and nutrient leaching in peat-lite, pine bark and pine tree substrates. *HortScience.* 2009;44:781–90. <https://doi.org/10.21273/HORTSCI.44.3.781>
82. Grigatti M, Giorgioni ME, Ciavatta C. Compost-based growing media: influence on growth and nutrient use of bedding plants. *Bioresour Technol.* 2007;98:3526–34. <https://doi.org/10.1016/j.biortech.2006.11.016>
83. Aurdal SM, Woznicki TL, Haraldsen TK, Kusnierik K, Sønsteby A, Remberg SF. Wood fiber-based growing media for strawberry cultivation: effects of incorporation of peat and compost. *Horticulturae.* 2023;9:36. <https://doi.org/10.3390/horticulturae9010036>
84. Bunt AC. Media and mixes for container-grown plants: a manual on the preparation and use of growing media for pot plants. 2nd ed. London: Unwin Hyman; 1988. <https://doi.org/10.1007/978-94-011-7904-1>
85. Sonneveld C. Rockwool as a substrate for greenhouse crops. In: Bajaj YPS, editor. *Biotechnology in agriculture and forestry.* Berlin: Springer; 1993. p. 285–312. https://doi.org/10.1007/978-3-642-76415-8_17
86. Alsanius BW, Wohanka W. Root zone microbiology of soilless cropping systems. In: Raviv M, Lieth JH, Bar-Tal A, editors. *Soilless culture: theory and practice.* 2nd ed. Amsterdam: Elsevier; 2019. p. 149–94. <https://doi.org/10.1016/B978-0-444-63696-6.00005-0>
87. Thomas P, Knox OGG, Powell JR, Sindel B, Winter G. The hydroponic rockwool root microbiome: under control or underutilised? *Microorganisms.* 2023;11(4):835. <https://doi.org/10.3390/microorganisms11040835>
88. Zheng Y, Huber J, Zhang P, Dixon M. Searching for recyclable or biodegradable growing media. *Acta Hortic.* 2009;819:435–42. <https://doi.org/10.17660/ActaHortic.2009.819.53>
89. Eksi M, Rowe DB. Green roof substrates: effect of recycled crushed porcelain and foamed glass on plant growth and water retention. *Urban For Urban Green.* 2016;20:81–88. <https://doi.org/10.1016/j.ufug.2016.08.008>

90. Evans MR. Physical properties of and plant growth in peat-based root substrates containing glass-based aggregate, perlite and parboiled fresh rice hulls. *HortTechnology*. 2011;21(1):30–34. <https://doi.org/10.21273/HORTTECH.21.1.30>
91. Lenzi A, Oggiano N, Maletta M, Bolaffi A, Tesi R. Physical and chemical characteristics of substrates made of perlite, pumice and peat. *Italus Hortus*. 2001;8:23–31.
92. Gizas G, Savvas D. Particle size and hydraulic properties of pumice affect growth and yield of greenhouse crops in soilless culture. *HortScience*. 2007;42(5):1274–80. <https://doi.org/10.21273/HORTSCI.42.5.1274>
93. Nishimura Y, Fukumoto Y, Shimasaki K. Effects of reservoir depth at the bottom of bed on plant growth and fruit quality of muskmelon (*Cucumis melo* L.) in pumice substrate. *Environ Control Biol*. 2005;43(4):267–74. <https://doi.org/10.2525/ecb.43.267>
94. Mitsanis C, Aktopoglu DC, Koukounaras A, Tsouvaltzis P, Koufakis T, Gerasopoulos D, et al. Functional, flavor and visual traits of hydroponically produced tomato fruit in relation to substrate, plant training system and harvesting time. *Horticulturae*. 2021;7:311. <https://doi.org/10.3390/horticulturae7090311>
95. Tzortzakis NG, Economakis CD. Impacts of the substrate medium on tomato yield and fruit quality in soilless cultivation. *Hortic Sci*. 2008;35(2):83–89. <https://doi.org/10.17221/642-HORTSCI>
96. Van der Gaag DJ, Wever G. Conduciveness of different soilless growing media to *Pythium* root and crown rot of cucumber under near-commercial conditions. *Eur J Plant Pathol*. 2005;112(1):31–41. <https://doi.org/10.1007/s10658-005-1049-7>
97. Khalili S, Hultberg M, Alsanius BW. Effects of growing media on the interactions between biocontrol agents and tomato root pathogens in a closed hydroponic system. *J Hort Sci Biotechnol*. 2009;84(5):489–94. <https://doi.org/10.1080/14620316.2009.11512553>
98. Zhao R, Sofkova-Bobcheva S, Cartmill DL, Hardy D, Zernack A. Comparative evaluation of pumice as a soilless substrate for indoor *Rubus idaeus* L. cultivation. *N Z J Crop Hortic Sci*. 2024;52(3):280–97. <https://doi.org/10.1080/01140671.2024.2358885>
99. Konlan S, Opoku-Agyeman MO, Acheampong K, Opoku-Ameyaw K, Anim-Kwapong GJ, Addo G. Evaluation of river sand as a medium for raising cocoa (*Theobroma cacao* L.) seedlings. *Am J Agric For*. 2014;2(4):114–20. <https://doi.org/10.11648/j.ajaf.20140204.13>
100. Mehmood T, Ahmad W, Ahmad KS, Shafi J, Shehzad MA, Sarwar MA. Comparative effect of different potting media on vegetative and reproductive growth of floral shower (*Antirrhinum majus* L.). *Univ J Plant Sci*. 2013;1(3):104–11. <https://doi.org/10.13189/ujps.2013.010308>
101. Fravela DR, Larkin RP. Reduction of Fusarium wilt of hydroponically grown basil by *Fusarium oxysporum* strain CS-20. *Crop Prot*. 2002;21(6):539–43. [https://doi.org/10.1016/S0261-2194\(01\)00143-0](https://doi.org/10.1016/S0261-2194(01)00143-0)
102. Li M, Ning X, Gao T, et al. Rice husk ash-based growing media impact on cucumber and melon growth and quality. *Sci Rep*. 2024;14:5147. <https://doi.org/10.1038/s41598-024-55622-4>
103. Susana IGB, Alit IB. Rice husk as sustainable waste energy for small farmers: a review. *World J Adv Eng Technol Sci*. 2021;3(2):1–6. <https://doi.org/10.30574/wjaets.2021.3.2.0063>
104. del Amor FM, Gómez-López MD. Agronomical response and water use efficiency of sweet pepper plants grown in different greenhouse substrates. *HortScience*. 2009;44(3):810–14. <https://doi.org/10.21273/HORTSCI.44.3.810>
105. Adebajo SO, Akintokun PO, Ojo AE, Ajamu IA. Effects of rice husk biochar on the growth characteristics, rhizospheric microflora and yield of tomato plants. *J Agric Sci Environ*. 2019;19:60–72. <https://doi.org/10.51406/jagse.v19i1.2015>
106. Hardgrave M. An evaluation of polyurethane foam as a reusable substrate for hydroponic cucumber production. *Acta Hortic*. 1995;401:205–10. <https://doi.org/10.17660/ActaHortic.1995.401.24>
107. Gunawan NR, Tessman M, Schreiman AC, Simkovsky R, Samoylov AA, Neelakantan NK, et al. Rapid biodegradation of renewable polyurethane foams with identification of associated microorganisms and decomposition products. *Bioresour Technol Rep*. 2020;11:100513. <https://doi.org/10.1016/j.biteb.2020.100513>
108. Wright HC, Cameron DD, Ryan AJ. Rational design of a polyurethane foam. *Polymers*. 2022;14(23):3511. <https://doi.org/10.3390/polym14235111>
109. Djidonou D, Simonne AH, Koch KE, Brecht JK, Zhao X. Nutritional quality of field-grown tomato fruit as affected by grafting with interspecific hybrid rootstocks. *HortScience*. 2016;51:1618–24. <https://doi.org/10.21273/HORTSCI11275-16>
110. Carlen C, Ançay A, Christ B. Optimization of the root environment for raspberry production on substrate. *Acta Hortic*. 2020;1277:283–86. <https://doi.org/10.17660/ActaHortic.2020.1277.41>
111. Rathor AS, Choudhury S, Sharma A, Nautiyal P, Shah G. Empowering vertical farming through IoT and AI-driven technologies: a comprehensive review. *Heliyon*. 2024;10:e34998. <https://doi.org/10.1016/j.heliyon.2024.e34998>
112. Siregar RRA, Seminar KB, Wahjuni S, Santosa E. Vertical farming perspectives in support of precision agriculture using artificial intelligence: a review. *Computers*. 2022;11(9):135. <https://doi.org/10.3390/computers11090135>
113. Madushanki AAR, Halgamuge MN, Wirasagoda WAHS, Syed A. Adoption of the Internet of Things (IoT) in agriculture and smart farming towards urban greening: a review. *Int J Adv Comput Sci Appl*. 2019;10(4):11–28. <https://doi.org/10.14569/IJACSA.2019.0100402>
114. Udanor CN, Ossai NI, Ogbuokiri BO, Nweke OE, Ugwoke PO, Ome UK. A pilot implementation of remote IoT sensors for aquaponics system datasets acquisition. *J Comput Sci Its Appl*. 2022;28(2):1–8. <https://doi.org/10.4314/jcsia.v28i2.1>
115. Priya GL, Baskar C, Deshmane SS, Adithya C, Das S. Revolutionizing holy basil cultivation with AI-enabled hydroponics system. *IEEE Access*. 2023;11:82624–39. <https://doi.org/10.1109/ACCESS.2023.3300912>
116. Melo RAC, Jorge MHA, Bortolin A, Boiteux LS, Ribeiro C, Marconcini JM. Growth of tomato seedlings in substrates containing a nanocomposite hydrogel with calcium montmorillonite (NC-MMT). *Hortic Bras*. 2019;37(2):199–203. <https://doi.org/10.1590/s0102-053620190210>
117. Gruda NS, Hirschler O, Stuart J. Peat reduction in horticulture: an overview of Europe. *Acta Hortic*. 2024;1391:545–60. <https://doi.org/10.17660/ActaHortic.2024.1391.75>
118. Surya K, Sornam G, Asritha M, Paul RAI, Easwaran C, Sri BK, et al. Unraveling approaches of silica nanoparticles for next-generation agricultural sustainability. *Front Sustain Food Syst*. 2025;9:1677788. <https://doi.org/10.3389/fsufs.2025.1677788>
119. Surya K, Krishnan R, Saitheja V, et al. Phytochrome-mediated shade avoidance responses and its impact on growth and physiology in crops-a review. *Photochem Photobiol*. 2026;48:1–27. <https://doi.org/10.1111/php.70098>