Review

Soilless Growing Media for Cannabis Cultivation

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Abstract

Standardized pharmaceutical-grade cultivation of *Cannabis sativa* L. increasingly relies on soilless systems for precision, reproducibility, and regulatory compliance. This review examines the role of inert and semi-inert growing media in indoor cannabis production, focusing on their physical properties, agronomic performance, and sustainability. A systematic literature search was conducted using databases such as Scopus, Web of Science, and Google Scholar, emphasizing peer-reviewed original research, experimental trials, and relevant review articles. Evaluated substrates include rockwool, coconut coir, peat-based blends, perlite, vermiculite, expanded clay, foamed glass, phenolic foam, and biochar. Findings show that substrate selection strongly affects vegetative growth, rooting, and flower yield, while cannabinoid concentrations remain primarily genotype-driven under stable environmental and nutritional conditions. Substrate-specific traits such as aeration, water-holding capacity, and nutrient buffering significantly influence biomass production and resource-use efficiency. Rockwool remains the industry standard due to its uniformity and compatibility with fertigation systems, but renewable alternatives like coconut coir and biochar are gaining traction. This review underscores the importance of substrate selection in cannabis cultivation and identifies research gaps in genotype-specific responses and the development of sustainable growing media.

Keywords: *Cannabis sativa* L.; soilless cultivation; phytocannabinoids; inert media; THC; hydroponics; coconut coir; CBD; medicinal plants; sustainability

1. Introduction

In recent years, the cultivation of cannabis (*Cannabis sativa* L.) has undergone a rapid transformation from illicit practice to highly regulated pharmaceutical production [1]. This shift has been accompanied by increasing scientific interest in optimizing every aspect of the cultivation process, including the selection and management of growing media [2,3]. The production of cannabis for medicinal purposes imposes very strict requirements on the plant material. These requirements primarily concern the content and ratio of active compounds, as well as the cultivation environment. To meet such standards, growers must ensure consistency in phytochemical profiles, cleanliness of inputs, and reproducibility of environmental conditions [4]. Recent reviews also emphasize the economic dimension. The global cannabis market was valued at 47.3 billion US dollars in 2022 and is projected to grow to 444.3 billion US dollars by 2030, which corresponds to a compound annual growth rate of approximately 34 percent. Other market analyses converge on estimates of 60–100 billion US dollars within the next five to ten years, depending on legalization scenarios [5,6].

As a result, indoor cultivation in fully controlled environments has become the preferred approach in medical cannabis production, as it overcomes the limitations of outdoor systems. Outdoor cultivation is constrained by unpredictable environmental variability, which makes it practically impossible to produce a homogeneous product. In addition, it typically allows only a single harvest per year due to the uncontrolled photoperiod and further exposes plants to higher risks of diseases and pests as well contamination [7]. By contrast, modern cultivation facilities enable full control over photoperiod, temperature, humidity, and air circulation, allowing for multiple harvests per year and ensuring higher production stability [8]. Indoor cultivation can be implemented through different methods, but these generally fall into two primary approaches: (i) soil-based substrates, where fertilization is provided either through irrigation or pre-fertilized mixtures, and (ii) soilless systems, where plants are cultivated in non-soil media [9]. Scientific studies and surveys indicate that soilless systems dominate licensed indoor medical cannabis production, largely due to their precision, hygiene, and compatibility with fertigation systems. While soil-based cultivation persists in small-scale or traditional contexts, the majority of large-scale pharmaceutical cannabis is produced in inert or semi-inert substrates such as coir, peat–perlite mixes, and rockwool. Estimates suggest that more than two-thirds of controlled-environment production relies on soilless systems [2,6,10].

Soilless cultivation is currently one of the fastest-growing technologies in horticulture. Growers have widely adopted this method, especially for crops such as tomatoes and cucumbers [11]. Cannabis cultivation has, in turn, accelerated innovation in soilless growing systems, particularly in substrate development and fertigation strategies tailored to this high-value crop [2]. Many aspects of the techniques required for cannabis cultivation are similar to those used for other plant species [9]. Soilless cultivation serves as an alternative to conventional agricultural practices, delivering essential nutrients in aqueous solutions directly to the plant's root system [12]. With the potential for year-round growth in controlled environments, this method offers the capability to produce high-quality, homogeneous material [3]. In addition, soilless systems offer greater control over plant nutrition, reduce pathogen transmission through soil, and improve resource-use efficiency, contributing to sustainability goals [13]. Compared to soil-based systems, soilless media allow finer manipulation of root-zone parameters such as pH, electrical conductivity (EC), and moisture content, which are factors that directly influence plant performance and cannabinoid profiles [8,14]. The increasing popularity of soilless systems in cannabis cultivation reflects both the demand for higher yield and quality, and the ability to meet strict regulatory requirements in pharmaceutical applications [2,3]. Furthermore, regional regulatory frameworks often impose high-quality and traceability standards, which drive the adoption of advanced cultivation technologies [15].

These trends highlight the need for continued research into best practices, system design, and technological integration. A particularly underexplored area remains the systematic comparison of different soilless growing media, especially with respect to their physical, chemical, and biological properties and their impact on cannabis growth dynamics, yield potential, and secondary metabolite profiles. This literature review provides a comprehensive overview of the most commonly used soilless growing media in indoor cannabis cultivation. It includes an assessment of their physical properties (e.g., porosity, water retention), chemical characteristics (e.g., pH, cation exchange capacity), agronomic performance, and environmental sustainability. The focus is placed on inert and semi-inert substrates such as rockwool, coconut coir, peat-based mixes, phenolic foam, expanded clay, and foamed glass, which are currently used or hold strong potential for application in the production of cannabis for medicinal purposes. Original research articles, experimental

trials, meta-analyses, and review papers were evaluated. Studies focusing exclusively on soil-based systems, deep water culture (DWC), or aquaponics were deliberately excluded.

2. Soilless Cultivation and Growing Media

2.1. Historical Development of Soilless Cultivation

The origins of soilless cultivation date back to 1699, when English naturalist John Woodward conducted pioneering experiments with mint plants grown in different water sources—rainwater, water from the River Thames, and wastewater. Interestingly, the highest biomass was observed in plants grown in wastewater, leading Woodward to conclude that plant growth was not supported by water itself, but by nutrients dissolved within it [16]. This early observation laid the foundation for the concept that plants absorb mineral elements in ionic form, rather than deriving nutrition solely from soil [17]. Over a century later, in 1860, the first deliberate soil-free cultivation system was realized by German scientists Julius von Sachs and Wilhelm Knop, who formulated nutrient solutions composed of simple, soluble salts. Their work enabled the precise study of plant nutrition and paved the way for nutrient-controlled systems [18]. A major milestone followed between 1920 and 1930, when Dr. William F. Gericke from the University of California conceptualized and tested commercial-scale cultivation using nutrient solutions alone [19]. He introduced the term "hydroponics" and demonstrated its commercialization during World War II, when hydroponic systems were implemented to produce fresh vegetables for American troops stationed on remote islands [20].

In parallel with these developments in Europe and North America, Asia also made early contributions. Hydroponic farming in Shanghai during the 1930s successfully produced tomatoes on a commercial scale, marking one of the first soilless farms worldwide [21]. In the following decades, Japan emerged as a leader in nutrient solution science, developing the Yoshida solution for rice and the Enshi-shoho formula for vegetables, both of which became widely adopted [22,23]. Japan also pioneered the use of carbonized rice hulls as a lightweight, sustainable substrate, a practice later adopted internationally [24]. In South and Southeast Asia, particularly Sri Lanka and India, improvements in the processing of coconut coir during the 1980s and 1990s transformed this by-product into one of the most widely used substrates for greenhouse cultivation today [25]. At the same time, China developed innovative solar greenhouse designs that enabled year-round vegetable production under cold climates, later spreading to other countries [26].

Subsequent decades saw significant technological advances in this field. In the 1960s, the horticultural potential of mineral wool (rockwool) was recognized, novel synthetic fertilizers tailored for soilless systems were introduced, and durable plastics revolutionized containerization and irrigation control [27]. Together with Asian innovations in substrates, nutrient solutions, and protected structures, these advances contributed to the global spread of hydroponic and substrate-based systems, which today form a cornerstone of high-efficiency agriculture [28]. Recent global mapping indicates that China accounts for approximately 60 percent of worldwide greenhouse cultivation area, highlighting its leading position in soilless production systems [26].

2.2. Properties and Classification

In soilless cultivation, the substrate replaces the classical soil matrix and must fulfill multiple roles critical to root zone function [29]. It provides mechanical support for plant anchorage, retains moisture between irrigation cycles, facilitates gas exchange, and, depending on its physicochemical properties, may participate in nutrient buffering or microbiome establishment [14]. Substrates are often classified based on their water-holding capacity into water-retentive and freely draining types. However, further differentiation

is necessary based on parameters such as porosity, air-filled pore space, capillary conductivity, cation exchange capacity (CEC), microbial compatibility, chemical inertness, and biodegradability [30]. The optimal combination of these properties enables precise root zone control and high reproducibility, which are essential in intensive indoor cultivation of sensitive crops such as *C. sativa* L. [8].

Among the key substrates used in modern systems is rockwool, a sterile mineral fiber produced by melting and spinning basaltic rock. It is characterized by high porosity (typically 91–96%), low bulk density, and negligible CEC. These traits allow excellent air-to-water ratio control and consistent irrigation response [31]. From a cost–benefit perspective, rockwool is uniform and low-labor to deploy but is often treated as single-use in commercial practice; reuse is possible yet limited and accompanied by changes in physical properties after multiple cycles [32,33]. From a sustainability viewpoint, stone wool is energy-intensive to manufacture and non-biodegradable; life cycle assessments (LCAs) and environmental product Declarations (EPDs) consistently highlight its high embodied energy and disposal burden, despite its agronomic performance [34]. In contrast, coconut coir—a renewable organic material derived from the mesocarp of coconuts—offers high water retention and elevated CEC, enhancing nutrient buffering and microbial colonization, though its chemical variability and need for pre-treatment pose challenges [35]. Economically, coir is generally cost-competitive and can be reused for subsequent cycles after sanitation in some systems (reducing cost per crop), albeit with higher setup labor (hydration/expansion). Sustainability-wise, coir is a by-product and biodegradable; its overall footprint is typically lower than peat, though long-distance transport contributes to emissions [36]. Perlite, an expanded amorphous volcanic glass, is chemically inert, porous, and lightweight, making it suitable for aeration and drainage enhancement but less suitable as a stand-alone substrate due to low mechanical stability and high buoyancy when saturated. Perlite is low-to-moderate cost, sometimes reusable, but requires high-temperature expansion; it is inert and non-biodegradable at end-of-life (a space rather than toxicity issue) [37]. Another commonly used organic medium is peat moss, particularly sphagnum peat, which offers excellent water-holding capacity, acidic pH, and moderate CEC [38]. Despite its horticultural performance, concerns about peatland degradation and carbon emissions are driving the search for alternatives [39]. Scientifically, peat extraction is linked to substantial greenhouse gas releases; global emissions from drained peatlands are on the order of ~1.9 Gt CO_2-eq annually (~5% of anthropogenic greenhouse gases), and LCAs consistently show peat having among the highest climate impacts of growing-media constituents [40]. Phenolic foam, typically produced by polymerizing phenol with an aldehyde such as formaldehyde or its low-toxicity alternatives (e.g., furfural or glyoxal) into a rigid structure and expanding it with a foaming agent, represents a synthetic, dimensionally stable medium with predictable moisture dynamics and is primarily used in propagation systems, although its lack of biodegradability and higher cost limit broader adoption [41]. Supplementary materials such as vermiculite, expanded clay aggregates, biochar, or synthetic foamed glass may be employed in tailored mixes to adjust physico-chemical properties for specific cultivation strategies (Table 1) [42]. Expanded clay carries higher kiln energy at production but is highly durable and reusable across many cycles (improving cost per crop and reducing waste); foamed/recycled glass offers inert performance with recycled origin but may need more frequent irrigation; biochar can improve water/nutrient retention and, depending on feedstock/pyrolysis, contribute to favorable carbon balances [43–45].

Table 1. Key Soilless Substrates Summary.

Substrate	Origin	Key Properties	Limitations	Cost–Benefit/Sustainability
Rockwool	Mineral	High porosity, inert, consistent structure	Algae risk	Uniform, low setup labor; typically single-use → recurring cost; high energy in manufacture; non-biodegradable, limited recycling
Coconut Coir	Organic	High water retention, partial buffering	Variability, salt content, risk of pathogens and insect pests (e.g., fungus gnats)	Moderate price; possible reuse after sanitation; higher setup labor (hydration/drainage); renewable byproduct, biodegradable; transport adds emissions
Perlite	Mineral	Lightweight, excellent aeration, inert	Floats, limited mechanical support	Low cost; limited reuse; moderate embodied energy (thermal expansion); inert non-biodegradable end-of-life
Vermiculite	Mineral	High water retention, moderate CEC *	Waterlogging when used alone	Moderate cost; energy-intensive exfoliation; finite mineral resource; typically single-use in mixes
Expanded Clay (LECA)	Mineral	Durable, free-draining	Low water retention, floats when dry	Higher upfront cost offset by multi-cycle reuse (good cost per crop); kiln-fired (high energy) but inert and long-lived → reduced waste
Foamed Glass	Recycled Glass	Porous, inert	Needs frequent irrigation, friable	Recycled feedstock (sustainability plus); may be pricier; reusable to a point; inert end-of-life
Biochar	Carbon-based	Water/nutrient retention, microbial habitat	Variable quality, high pH risk	Potentially low cost if local; can improve nutrient/water efficiency; may offer favorable carbon balance depending on feedstock/pyrolysis
Peat (Peat Moss)	Organic	High water holding, acidic pH, natural	Hydrophobic when dry	Low upfront cost but strong sustainability downside: non-renewable, releases long-stored carbon, ecosystem loss; facing restrictions/phase-outs
Phenolic Foam	Synthetic Foam	Sterile, lightweight, consistent porosity	Mostly for propagation	Labor-saving in propagation; high unit cost; non-biodegradable synthetic waste → disposal burden

* Cation Exchange Capacity.

In addition to agronomic and sustainability factors, substrate selection in cannabis production is increasingly influenced by regulatory frameworks. In Europe, cultivation intended for the pharmaceutical market must comply with Good Agricultural and Collection Practice (GACP), which requires clean and contaminant-free substrates, and post-harvest handling must follow Good Manufacturing Practice (GMP) according to EudraLex Volume 4, Annex 7 for herbal medicinal products [46–48]. This framework directs growers toward substrates with low and controllable bioburden, reliable supplier documentation, and validated sanitation protocols if reuse is attempted, while also minimizing particulate shedding in post-harvest areas aligned with GMP cleanroom principles. In Canada, federally licensed production is governed by Health Canada's Cannabis Regulations (SOR/2018-144, Part 5) and associated good production practices (GPPs), which emphasize sanitation, contamination control, traceability, and detailed standard operating procedures (SOPs) rather than full EU-style GMP validation [49–51]. Substrate reuse is permissible under GPP provided

that validated procedures demonstrate control of microbial and chemical residues. In the United States, cannabis regulation is state-based, but common features include mandatory product testing for microbial and heavy metal contamination, approved-input lists, and requirements for hygiene SOPs, which indirectly encourage the use of inert, cleanable media. Voluntary standards such as the Foundation of Cannabis Unified Standards (FOCUS) cultivation guidelines further recommend sourcing substrates from sustainable and certified suppliers [52]. Israel has adopted one of the most stringent frameworks, mandating detached substrate cultivation under Israeli Medical Cannabis Good Agricultural Practice (IMC-GAP), effectively prohibiting soil-based cultivation and favoring inert or sterilized substrates that can be controlled and documented [53]. In Australia and New Zealand, cannabis must be cultivated under GACP principles for medicinal plants, with quality testing aligned with Therapeutic Goods Order No. 93 (TGO 93), which sets strict limits for heavy metals, pesticides, and microbial contamination [54]. Switzerland similarly enforces GACP and GMP through Swissmedic, and recently introduced a "Swiss Certified Cannabis" quality label aligned with EU standards [55].

Ultimately, the choice of inert or semi-inert medium must consider not only its stand-alone characteristics but also its interaction with the fertigation regime, climate control, crop genotype, and cultivation stage [42,56]. For cannabis, where yield and secondary metabolite expression are highly sensitive to root zone dynamics, optimizing substrate parameters such as air capacity, easily available water (EAW), and nutrient holding behavior becomes critical [2,10]. Consequently, the substrate is not a passive background component but an active determinant of cultivation success in controlled environment agriculture.

3. Characterization of Soilless Inert and Semi-Inert Media

A wide range of inert and semi-inert substrates are currently used in soilless cultivation, each exhibiting distinct physical, chemical, and biological properties that affect root development, nutrient availability, and overall plant performance [16,42,56]. This section provides a detailed overview of key media types employed across propagation and production stages, including both mineral and organic substrates as well as synthetic alternatives. Their advantages, limitations, and suitability for high-value crops such as *C. sativa* L. are critically evaluated in light of current knowledge and cultivation practices.

3.1. Rockwool

3.1.1. Production, Composition, and Physical Properties

Rockwool is a chemically inert, fibrous, and highly porous substrate derived from diabase, a type of volcanic rock rich in silicates. Its use in soilless horticulture began in the late 1960s in Denmark and has since become widespread due to its advantageous physical properties and ease of standardization [57]. The substrate is characterized by a total porosity of 91–96%, which provides an optimal air-to-water ratio essential for efficient gas exchange and moisture availability in the root zone. Rockwool contains virtually no free ions (EC = 50–100 μS/cm) and has a mildly alkaline pH of approximately 7.5 [58]. It remains chemically stable under typical cultivation conditions and only begins to degrade under strongly acidic conditions (pH < 5), where the silicate matrix may slowly dissolve. Despite its inertness, it exhibits a very low cation exchange capacity (CEC $\approx$ 0), meaning it does not retain or buffer nutrient ions [27]. This trait ensures full control over nutrient delivery via fertigation but also demands precise management, as nutrients are not retained within the substrate matrix [59].

Manufacturing rockwool involves melting diabase at temperatures around 1600 °C to produce a lava-like fluid, which is then spun into fibers using high-speed rotating discs. The fiber morphology—length, diameter, and orientation—is determined by spinning

velocity, melt viscosity, and the incorporation of additives such as calcium carbonate to modify hydrophobicity or hydrophilicity [58]. The fiber web is subsequently cured at 260 °C to ensure dimensional stability and sterility, and is then cut into standardized forms—slabs, cubes, or blocks (Figure 1). These formats provide flexibility for different crop systems, including seedling propagation, drip-irrigated slabs, and vertical stacking units [58,60,61]. Rockwool has a low bulk density (typically 50–100 kg/m^3), with block thicknesses commonly ranging from 7.5 to 10 cm. These dimensions offer a practical balance between capillary water retention and free air space, critical for supporting root respiration [62]. One of rockwool's major advantages is its homogeneity, which ensures consistency in water and nutrient distribution, as well as replicability across production cycles. Its physical stability allows for automation and precise irrigation control, particularly in recirculating hydroponic systems [13,63].

Figure 1. Various forms of rockwool.

3.1.2. Agricultural Use and Management Practices

In cannabis cultivation, rockwool is particularly valued for its uniform water and nutrient distribution and is widely used in high-density indoor systems utilizing drip irrigation. It supports rapid vegetative growth due to excellent root oxygenation and enables tight control of environmental and fertigation parameters [64]. Commercial growers frequently use Grodan-type cubes, typically 40 × 40 × 40 mm, for vegetative propagation [65]. These smaller cubes are inserted into larger cubes or blocks during the later vegetation phase, allowing for seamless root expansion. This modular system facilitates structured transitions between developmental stages and is highly compatible with high-frequency drip irrigation systems [2].

Although rockwool is initially sterile, microbial colonization occurs over time during cultivation. While this can include beneficial organisms that support plant health and nutrient solubilization, there is also the potential for pathogen buildup if sanitation protocols are not followed [63,66]. Moreover, despite its excellent moisture and air capacity, rockwool is not without limitations. Salts tend to accumulate at the upper surface, especially in open systems without drainage recirculation. This can interfere with nutrient uptake and root-zone osmotic balance. Mitigation requires periodic flushing, which, if excessive, risks water saturation and subsequent oxygen limitation [67,68]. Algal growth on the surface is another common issue, particularly under high humidity and continuous lighting. Algae

can harbor phytopathogens, attract pests such as fungus gnats, and impede water infiltration from emitters [65,69]. Rockwool's tendency to become hydrophobic when completely dry adds to management complexity. Once dried, it is difficult to re-wet uniformly, and irrigation water may preferentially channel through low-resistance pathways without saturating the substrate. Therefore, high-frequency, low-volume fertigation is employed to maintain substrate moisture within the EAW zone and to avoid preferential flow [2,61].

Cannabis plants grown in well-managed rockwool typically exhibit rapid growth and high yields due to vigorous root respiration supported by the substrate's high air-filled porosity (~95%) [65,70]. However, this inertness also means the substrate offers no buffering; deviations in pH or EC are quickly reflected in plant health. This high degree of controllability is often used for "crop steering"—an irrigation and nutrient management strategy that modulates plant morphology and directs resource allocation between vegetative and generative development [2,70]. During the vegetative phase, rockwool is typically kept near full saturation to promote canopy expansion. In contrast, small intentional dry-back periods during the flowering phase can enhance flower formation. Furthermore, rockwool's inert nature facilitates pre-harvest leaching (i.e., flushing), which enables rapid reduction in substrate EC when nutrient solutions are replaced with water [71].

3.1.3. Environmental Impact and Sustainability

Environmentally, rockwool presents significant challenges. It is non-biodegradable and difficult to recycle due to its mineral composition and fibrous structure. Used material often accumulates in landfills, contributing to the long-term waste burden [72]. Although it is considered inert and pathogen-free when disposed, the energy-intensive manufacturing process and post-use handling raise concerns in the context of sustainable agriculture. As a result, efforts have increased to identify more sustainable alternatives or to develop methods for rockwool recycling and reprocessing [73,74]. Despite these drawbacks, rockwool remains a dominant substrate in soilless cultivation due to its uniformity, root-zone control, and compatibility with precision fertigation technologies [2,57].

3.2. Coconut Coir

3.2.1. Production, Composition, and Physical Properties

Coconut coir, commonly referred to simply as "coir," is a fibrous organic substrate derived from the thick mesocarp of mature coconut fruit (*Cocos nucifera* L.). It is made from the unused husks of mature coconuts [75]. During the processing of coconut husks, long fibers are separated and used for industrial applications such as mats, brushes, and ropes, while shorter fibers and the dust-like fraction known as coconut pith were historically discarded [76]. Around the late 1980s, the potential of this residual material as a horticultural substrate was recognized. Approximately 25% of coconut fibers are too short for industrial use and are now utilized in growing media. Its adoption as a horticultural medium gained momentum due to its renewable origin and favorable properties. The processed coir is typically compressed into blocks, mats, pellets, or cubes for transportation, expanding up to eight to nine times their original volume upon hydration [24]. Coir is primarily exported from coconut-producing regions such as India, Sri Lanka, Vietnam, the Philippines, Mexico, and Ivory Coast [77]. In some facilities, raw coir is aged or composted for up to six months to enhance its structural stability and reduce phytotoxicity. This step is critical to prevent contamination by weed seeds and human pathogens, ensuring microbiological safety [78,79].

As a naturally derived substrate, coir exhibits substantial variability in both its physical and chemical composition, largely influenced by the environmental conditions under which the coconut palms were grown and the specifics of the post-harvest treatment. Before

use, the coconut husks are typically soaked in water for at least two weeks to soften the material and facilitate grinding [80]. The water used is often brackish, which increases concentrations of sodium (Na^+), chloride (Cl^-), and potassium (K^+) in the final product. Excess Na^+ and K^+ pose a particular challenge, as they compete with calcium (Ca^{2+}) and magnesium (Mg^{2+}) for root uptake, potentially leading to deficiencies in these essential nutrients. In early usage, leaching was done only with water, but it was later discovered that some Na^+ and K^+ ions are in exchangeable form [81]. For this reason, modern protocols use calcium nitrate solutions to leach coir, which significantly reduces monovalent elements in the substrate [82].

Coir's high CEC allows it to adsorb and gradually release cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+. While this feature offers buffering capacity and supports nutrient retention, it also requires careful substrate preparation. Particularly in systems using reverse osmosis (RO) water devoid of natural buffering ions like Ca^{2+} and Mg^{2+}, coir can absorb these critical nutrients from the first fertigation, destabilizing ion equilibrium and causing abrupt pH shifts [83]. To mitigate this, the coir must first be thoroughly leached to remove residual Na^+ and K^+. Subsequently, a buffering process involving immersion in a CalMag solution (1.3–2.0 mL/L, EC ~ 2.0) for 6–8 h is recommended. This ensures that the CEC sites are pre-saturated with Ca^{2+} and Mg^{2+}, improving nutrient availability and stabilizing the rhizosphere chemistry [24,84].

Physically, coconut coir is characterized by high porosity, excellent moisture retention, and favorable hydraulic properties, including high total pore space, air volume, EAW, and water buffering capacity. These attributes support optimal root aeration, prevent waterlogging, and provide a stable environment for root zone processes [85]. Its pH typically ranges from 5.2 to 6.8, and EC < 1000 μS/cm. The bulk density allows sufficient mechanical support for plants while facilitating gas exchange and microbial colonization. The fibrous matrix is composed predominantly of lignin, cellulose, pectin, and tannins. The high lignin content, in particular, confers microbial resistance and structural integrity, enabling the substrate to be reused across multiple cropping cycles [86].

3.2.2. Agricultural Use and Management Practices

In cannabis cultivation, coir has gained popularity as a renewable alternative to rockwool and peat. It is used from propagation to harvest, with seeds or cuttings often started in fine-grade coco plugs and later transplanted into coir-based containers. Coir's organic matrix supports beneficial microbes, including *Trichoderma* spp., which can improve root health and resilience. Pre-inoculated coir products are commercially available [87,88].

Reuse across cultivation cycles is possible if proper sanitization is performed, and disposal presents a lower environmental impact than mineral-based media. Nevertheless, the very properties that make coir advantageous, namely, its high water-holding capacity and organic content, can also predispose it to excessive moisture retention, increasing the risk of fungal proliferation under suboptimal environmental conditions [36,75]. To counter this, coir is often blended with inert, fast-draining materials such as perlite, expanded clay, or vermiculite, typically in ratios ranging from 70:30 to 50:50 (coir–inert material) depending on crop type and irrigation strategy. Additionally, the coir is frequently incorporated into composite systems with rockwool in horizontal "sandwich" configurations to combine the water-buffering and sustainability benefits of coir with the structural stability and uniformity of rockwool. This combination also reduces the environmental impact associated with substrate disposal after cultivation [2,89].

Nutrient dynamics in coconut coir are closely tied to plant developmental stages. During the vegetative phase, plants tend to prefer ammonium (NH_4^+) over nitrate (NO_3^-) as the nitrogen source. Ammonium uptake releases H^+ ions into the rhizosphere, resulting

in acidification and a drop in pH. This effect is compounded by high uptake of phosphate ($H_2PO_4^-$) and K^+, which further promote rhizosphere acidification [70,90]. However, ammonium should not exceed 30% of total nitrogen, as higher concentrations may be phytotoxic [91]. As the plant transitions to the generative (flowering) phase, nitrogen demand decreases overall, but the preferred form shifts to NO_3^-, whose assimilation is associated with OH^- exudation, leading to pH elevation. This phase is also marked by increased uptake of Ca^{2+} and K^+, which can intensify the rise in substrate pH. The resulting alkalization may reduce the solubility and availability of essential micronutrients such as iron (Fe), manganese (Mn), and zinc (Zn), potentially affecting flower quality and cannabinoid synthesis [88,92,93].

3.2.3. Environmental Impact and Sustainability

Coir is considered one of the more sustainable soilless substrates due to its organic nature and renewability. Its biodegradability stands in contrast to mineral substrates such as rockwool, and it has a significantly lower carbon footprint. However, environmental sustainability can be affected by water usage, brackish water contamination, and transport distance from producing regions. Standardizing quality and mitigating salinity remain key challenges for its widespread adoption [51,75,89].

3.3. Perlite
3.3.1. Production, Composition, and Physical Properties

Perlite is a highly porous, inert, and thermally expanded mineral substrate. It is derived from volcanic glass, a category of naturally occurring amorphous rocks with high silica content, among which obsidian is the most well-known example [94]. The raw material is typically an amorphous alumino-silicate, composed primarily of silicon dioxide (SiO_2, ~73%) and aluminum oxide (Al_2O_3, ~15%), with smaller proportions of potassium oxide, sodium oxide, ferric oxide, calcium oxide, and traces of magnesium oxide (Table 2) [57]. The production process involves crushing the volcanic glass and heating it rapidly to around 1000 °C. At this temperature, entrapped water molecules within the mineral matrix vaporize, expanding the material to approximately 4–20 times its original volume. This process results in a sterile, lightweight, and highly porous aggregate with a white-gray appearance and extremely high surface area. The final product has a bulk density of approximately 100 kg/m^3, and its particle size is typically graded for horticultural use [95]. For hydroponic systems or other soilless cultivation setups, a granule size between 1.5 and 3.0 mm is preferred, with a packing density between 80 and 100 kg/m^3 [96].

Table 2. Chemical Composition of Expanded Perlite.

Substance	Content [%]
Silicon dioxide (SiO_2)	73.06
Aluminum oxide (Al_2O_3)	15.30
Potassium oxide (K_2O)	4.50
Sodium oxide (Na_2O)	3.65
Ferric oxide (Fe_2O_3)	1.05
Calcium oxide (CaO)	0.80
Magnesium oxide (MgO)	0.05

Loss on ignition—1.92%.

Perlite exhibits several desirable physical properties: it is chemically inert, with a nearly neutral pH (7.0–7.5), does not release soluble elements, and has no cation exchange capacity (CEC ≈ 0). This means it does not bind nutrients from the fertigation

solution and does not interfere with nutrient availability. Water is retained not only on the particle surfaces due to capillarity, but also within the micropores formed during expansion, allowing the perlite to hold up to four times its own weight in water [97,98]. However, unlike fibrous media such as coconut coir or peat, perlite has very limited ability to retain nutrients and water, which makes precise and frequent irrigation essential to maintain optimal plant growth. Its structure promotes excellent drainage and aeration, which allows for a stable and oxygenated root environment regardless of temperature or crop growth stage [99].

3.3.2. Agricultural Use and Management Practices

In cannabis systems, perlite is most often used as an amendment in soilless mixes (typically 10–50% perlite blended into coco coir, peat, or soil), where it reduces compaction, improves aeration, and prevents overwatering, especially in fine-textured substrates. Pure perlite can also be used in hydroponic setups, including passive "Hempy buckets," where it is combined with vermiculite, and a lower reservoir of nutrient solution ensures continuous moisture and oxygenation, as well as in active systems such as Dutch buckets, where perlite serves as the primary substrate in a recirculating or drain-to-waste configuration [2,100,101]. Due to its mechanical properties and low density, pure perlite is more suitable for propagation than full-cycle crop production. One common application is in vegetative propagation, where perlite supports optimal moisture conditions for rooting cuttings. Its structure enables easy removal of rooted cuttings without damaging the root system, which is particularly valuable for clonal propagation. In cannabis, propagation in perlite beds or perlite/vermiculite blends promotes healthy lateral root growth and rapid rooting, reducing transplant shock [70,100].

However, in full-cycle crop cultivation, pure perlite's low weight can become a disadvantage. Under high irrigation volumes, it tends to float, disrupting plant anchorage and irrigation uniformity. To mitigate this, perlite is often combined with heavier or more cohesive media. A commonly used mixture is perlite and vermiculite in a 2:1 ratio, which combines the drainage capacity of perlite with the water-holding capacity and cation exchange potential of vermiculite [102,103].

3.3.3. Environmental Impact and Sustainability

Perlite is reusable over multiple growing cycles, assuming proper sanitation is maintained. After flushing with clean water and provided no pathogen contamination occurred during prior use, it can be reused for two to three crop cycles. However, perlite gradually degrades with time and handling, which leads to loss of structure and porosity. After repeated use, it may no longer offer adequate physical support or drainage [37]. As with other inert substrates such as rockwool, perlite is prone to algal growth when exposed to continuous moisture and light. Algae can interfere with emitter function and increase the risk of pest attraction or disease harboring. To prevent this, the top layer of the perlite substrate is often covered with opaque materials to block sunlight [13].

Despite being mineral-based, perlite is not biodegradable and contributes to horticultural waste accumulation. However, compared to other substrates, its mining and processing footprint is relatively low in terms of chemical inputs, and its reusability contributes to its sustainability profile [37,104].

3.4. Vermiculite

3.4.1. Production, Composition, and Physical Properties

Vermiculite is a thermally expanded, hydrated alumino-silicate mineral of the mica group that forms accordion-like granules when rapidly heated. Its name derives from the Latin "vermicularis" (meaning worm-like), referring to the elongated, curved shapes

formed during exfoliation [105]. This process increases its volume by approximately 15–30 times and creates a lightweight, porous structure with high water-holding capacity and moderate-to-high CEC. Horticultural-grade vermiculite typically has a bulk density of 90–130 kg/m^3 and a pH ranging from neutral to slightly alkaline (~7.0–7.5). Its specific gravity ranges from 2.2–2.5, and it is chemically inert with a phyllosilicate structure composed mainly of SiO_2 (37–42 wt%), MgO (12–14 wt%), Al_2O_3 (10–13 wt%), Fe_2O_3 (5–17 wt%), and structural H_2O (8–18 wt%) [106]. Exfoliated vermiculite particles are typically golden-yellow or brown with a nacreous luster, although their color may vary depending on iron content (e.g., Fe_2O_3 can impart a reddish tint) [107].

3.4.2. Agricultural Use and Management Practices

In cannabis cultivation, vermiculite is not commonly used as a stand-alone medium due to its very high moisture retention and low air porosity, which can promote waterlogging and root hypoxia. However, it plays an important role as a supplemental component in soilless mixes, most often in combination with perlite, coco coir, or peat. In these mixes, vermiculite provides stable moisture and nutrient buffering, while the accompanying aerating material ensures sufficient drainage and oxygenation of the root zone [70,108]. As a 2:1 clay mineral, vermiculite has a layered phyllosilicate structure that enables it to adsorb essential nutrients (e.g., K^+, Ca^{2+}, Mg^{2+}) from the fertigation solution and release them gradually [109]. This buffering effect helps stabilize nutrient availability and rhizosphere pH, especially in inert systems or when RO water is used. Some growers start seeds in pure vermiculite or in mixtures where vermiculite predominates (e.g., 70–100% vermiculite), and later transplant into more aerated substrates [70,110].

For cannabis, this translates to reduced risk of nutrient fluctuations, improved turgor pressure, and consistent growth across developmental stages. In passive hydroponic systems like the Hempy bucket, vermiculite is commonly blended with perlite (1:1 or 1:2 ratio) to combine its water-wicking properties with perlite's aeration. The vermiculite draws nutrient solution upward by capillarity, ensuring continuous hydration of the roots, while perlite prevents oversaturation. Such setups support robust vegetative and generative growth, particularly when managed with frequent fertigation [111]. In propagation, vermiculite is valued for its fine texture and high moisture retention, which create a gentle environment for cannabis seed germination and rooting of cuttings. Its sterile nature and moderate alkalinity reduce the risk of damping-off and promote uniform root development. One practical consideration is that horticultural vermiculite may contain native levels of potassium and magnesium due to its mineral origin [112]. These nutrients can be slowly released into the medium, so fertilizer regimens may require minor adjustments, particularly during early growth. If needed, leaching of new vermiculite with RO water can reduce excess soluble salts prior to use [2].

3.4.3. Environmental Impact and Sustainability

While vermiculite is reusable if thoroughly cleaned and sterilized between cycles, its relatively soft structure degrades over time, leading to smaller particles and reduced air capacity. Like perlite, it can be prone to algal growth if exposed to light and moisture at the surface, so a top layer of mulch or opaque cover is recommended [11,111]. It is important to note that excessive heating (above 1000–1100 °C) during processing can cause vermiculite to undergo structural changes into clinoenstatite, which reduces not only its thermal and insulating properties but also its ability to retain water and exchange nutrients, which are key characteristics relevant for horticultural use [111,113].

Such ion exchange properties have also been exploited in environmental technologies for removing heavy metals and pollutants from water, highlighting the mineral's chemical

versatility [114]. From an environmental standpoint, vermiculite is a non-renewable mined material, but its ability to be reused and safely incorporated into soil post-cultivation (as a soil amendment) enhances its sustainability profile [115]. Major global sources of vermiculite include South Africa, the United States, Brazil, Zimbabwe, Bulgaria, and India, which together account for over 95% of worldwide production [116].

3.5. Expanded Clay

3.5.1. Production, Composition, and Physical Properties

Expanded clay aggregate, commonly referred to as lightweight expanded clay aggregate (LECA), is a granular, inert growing medium produced through the high-temperature sintering of selected clays with minimal lime content. The thermal process conducted in rotary kilns at temperatures ranging from 1100 to 1200 °C induces pyroplastic expansion, wherein gases formed during heating become trapped within the clay matrix, resulting in the formation of vesicular, spherical to ellipsoidal granules with a honeycomb-like internal structure [117]. This process increases the volume of the clay up to five- to six-fold, producing lightweight particles that exhibit high structural stability and porosity. The final product consists of ceramic pellets typically ranging from 4 to 16 mm in diameter, though horticultural variants may span 0.1 to 25 mm. These granules have a rough, porous surface that supports both gas exchange and microbial colonization. Depending on kiln conditions and raw material, LECA exhibits variation in pore size distribution, color (brown, red, or gray), and crushing resistance [13,118].

Bulk density typically ranges from 250 to 710 kg/m^3, and total porosity reaches ~70–80%, enabling water absorption capacities of 20–30% by weight over 24 h. Its thermal conductivity remains low (0.097–0.123 $W\ m^{-1}\ K^{-1}$), making it suitable for controlled environment systems [119]. Chemically, LECA is composed primarily of silicon dioxide (SiO_2, 53–70 wt%), aluminium oxide (Al_2O_3, 15–27 wt%), and varying amounts of iron (Fe_2O_3), calcium (CaO), and alkali oxides (Na_2O, K_2O). It is considered chemically inert, with a near-neutral pH (6.0–7.0) and a negligible cation exchange capacity (CEC $\approx$ 0) [118]. This inertness, similar to that of rockwool or perlite, ensures full fertigation control while avoiding nutrient adsorption or ion exchange within the substrate matrix. However, unlike fibrous or organic media, LECA exhibits superior mechanical durability and resistance to compaction, allowing it to be reused across multiple crop cycles with minimal physical degradation [119,120].

3.5.2. Agricultural Use and Management Practices

In cannabis cultivation, LECA is particularly valued for its exceptional aeration properties and structural stability, making it well suited for DWC, recirculating drip irrigation, and ebb-and-flow systems [97,121,122]. Its high air-filled porosity enhances root respiration and reduces hypoxic stress, especially under high-transpiration or high-density canopy conditions [123]. The porous structure also allows for anchorage of developing root systems while preventing water stagnation, thus lowering the incidence of root-borne pathogens such as *Pythium* spp. and *Fusarium* spp. Expanded clay pebbles are frequently pre-soaked prior to use to improve initial water retention and are often placed in net pots or containers situated on drainage tables [124].

Although LECA retains less water than coir or vermiculite, its structural pores provide excellent oxygenation, which supports vigorous root development. Due to its lower water-holding capacity compared to coir or peat-based substrates, fertigation frequency must be carefully calibrated to plant size, light intensity, and environmental conditions [98]. Frequent irrigation events are particularly critical during warm seasons

or the generative phase, when optimized nutrient and oxygen availability is essential for cannabinoid biosynthesis [125].

However, to prevent excessive dry-back, especially, in high-light, high-transpiration environments, irrigation schedules must be adjusted accordingly. A practical concern is that LECA may float in poorly designed ebb-and-flow systems, potentially destabilizing plant anchorage; this issue can be mitigated by using heavier grades or embedding root balls in net baskets [126].

3.5.3. Environmental Impact and Sustainability

Expanded clay can be sterilized and reused across multiple cycles if free from pathogens. Its environmental footprint is moderate, as it is produced from abundant clay deposits without requiring synthetic additives, but the high-temperature firing process is energy-intensive [127]. After cultivation, spent LECA can be incorporated into soil as a long-term aeration enhancer or used in green infrastructure applications (e.g., green roofs, stormwater filters), adding to its sustainability profile [128].

3.6. Foamed Glass

3.6.1. Production, Composition, and Physical Properties

Foamed glass, also referred to as cellular glass or expanded glass aggregate, is a lightweight, porous, and chemically inert substrate manufactured through the sintering of finely ground recycled glass mixed with foaming agents at temperatures between 700 and 900 °C [129]. Common foaming agents include carbon black, glycerol, and silicon carbide, often in combination with oxidizing agents such as iron(III) oxide (Fe_2O_3), and in some cases, crystallization inhibitors like calcium phosphate to ensure uniform pore structure and suppress devitrification. During thermal treatment, gas evolution—predominantly CO_2—induces the expansion of the glass matrix, resulting in closed- or open-cell vesicular particles with high porosity and structural stability [130,131].

The resulting granules typically range in size from 2 to 20 mm and display bulk densities between 100 and 450 kg/m^3, with total porosity values of 70–90% and water-holding capacities around 10–25% by weight. Thermal conductivity remains low (~0.04–0.08 $Wm^{-1}K^{-1}$), enhancing root zone insulation in controlled environment cultivation [132]. Chemically, foamed glass consists primarily of silicon dioxide (SiO_2, ~65–75 wt%), sodium oxide (Na_2O, 10–15 wt%), calcium oxide (CaO, 6–12 wt%), and smaller amounts of Al_2O_3, Fe_2O_3, and MgO—reflecting the composition of the original soda-lime-silicate glass. The material is pH-neutral to mildly alkaline (6.5–7.5), resistant to microbial degradation, and has negligible cation exchange capacity (CEC $\approx$ 0), making it similar to other inert substrates such as rockwool or perlite in terms of fertigation control [131,133].

3.6.2. Agricultural Use and Management Practices

The high air-filled porosity and mechanical strength of foamed glass support excellent root aeration and drainage, critical in preventing hypoxic stress and root-borne diseases. The material's rough surface may also facilitate microbial colonization in the rhizosphere, though its relatively smooth pore walls might limit biofilm adhesion compared to organic substrates [134]. Foamed glass has been successfully applied in hydroponic horticulture systems, including green roofs, vertical farming, and flood-and-drain or recirculating drip irrigation setups, where lightweight, non-compacting media are preferred [135].

Although peer-reviewed studies specifically evaluating foamed glass in cannabis cultivation are currently lacking, its physicochemical properties suggest potential suitability for high-aeration growing systems or as an additive to substrate blends where improved drainage and reduced bulk density are desired [44]. However, due to its lower water

retention compared to coir or peat, careful management of irrigation frequency and nutrient delivery is essential. Pre-soaking prior to transplantation can enhance initial wettability, and different particle size grades may be tailored for propagation or generative-phase growth. The inert nature of the substrate also facilitates reuse after sterilization, although mechanical attrition may occur over repeated cycles [134,136].

3.6.3. Environmental Impact and Sustainability

From a sustainability perspective, foamed glass is produced from post-consumer glass waste, providing an environmentally friendly alternative to mined mineral media. While its production is energy-intensive due to the required sintering temperatures, the long service life, chemical stability, and potential for post-cultivation reuse in civil engineering or as a soil amendment contribute positively to its overall ecological profile [44,134,137].

3.7. Biochar

3.7.1. Production, Composition, and Physical Properties

Biochar is a porous, carbonaceous substrate produced by pyrolysis of organic biomass under limited oxygen supply, typically at temperatures between 500 and 650 °C, which is optimal for generating physically stable, low-volatile material suitable for soilless cultivation. In these systems, biochar is used as a sustainable additive, provided it is properly conditioned and free of phytotoxic residues, due to its physical stability, high specific surface area, and ability to retain both nutrients and water [138]. Depending on the feedstock used (e.g., wood, coconut shells, bamboo, agricultural residues) and pyrolysis temperature, biochar differs in physicochemical properties such as pH, CEC, porosity, and ash content [139]. Typical bulk densities of biochar range from 200 to 600 kg/m^3, total porosity reaches 50–85%, and pH values are mildly alkaline (6.5–9.5), which can positively influence the buffering capacity of the substrate. The high specific surface area (often exceeding 200 m^2/g) and the stable carbon content (~60–80%) contribute to its ability to retain nutrients (especially K, Ca, Mg) and to support the colonization of the rhizosphere by beneficial microorganisms [140]. Biochar particles are commonly mixed at a 5–20% volume ratio with other media such as coir, compost, or perlite [141].

3.7.2. Agricultural Use and Management Practices

In the context of soilless plant cultivation, including hydroponics, biochar has been tested as an additive that improves aeration, pH buffering, and water-holding capacity of the substrate. Studies have demonstrated improved growth, increased chlorophyll content, and greater biomass accumulation in species such as lettuce (*Lactuca sativa*) [142], tomato (*Solanum lycopersicum*) [143], and celery (*Apium graveolens*) when biochar was applied in the root zone [144]. In cannabis cultivation, biochar has been tested as an additive to coir- or peat-based mixtures at doses of 5–20% (*v/v*) [100]. While specific studies on cannabinoid content remain limited, data from other crops suggest that moderate biochar additions—typically, around 10%—can enhance plant growth, nutrient uptake, and root development [145,146]. Furthermore, biochar has been shown to stimulate beneficial rhizospheric microorganisms, particularly when combined with biocontrol agents such as *Trichoderma harzianum* or *Bacillus* spp., leading to improved plant vigor and pathogen suppression. For example, in tomato cultivation, the combination of biochar and *Trichoderma* under reduced N–P–K fertilization resulted in a 101% yield increase compared to half-strength fertilizer alone, and an 11% increase compared to full-strength fertilization [147]. Similarly, in eggplant and chickpea, co-application of biochar and *T. harzianum* enhanced root biomass, increased antioxidant enzyme activity, and reduced pathogen incidence by 27–33% [148,149]. In other studies, biochar also supported the pro-

liferation of *Bacillus* spp. and *Trichoderma* spp. in the rhizosphere, especially at amendment rates between 1–20% (*w/w*) [146].

A significant advantage of biochar is its ability to suppress pathogens—either directly by altering chemical parameters of the environment or indirectly by supporting antagonistic microorganisms [150]. However, its effects vary depending on the type of feedstock. For instance, manure-derived biochar is rich in nutrients but may exhibit high EC and require leaching or dilution. In contrast, wood-derived biochar is more structurally stable, has lower nutrient content, but is suitable for long-term substrate aeration [151]. Biochar is not typically used as a stand-alone substrate but as an amendment to optimize the physical and chemical properties of the growing medium. It is advisable to pre-wash or age biochar prior to use to minimize risks of phytotoxicity caused by volatile compounds or extreme pH levels. Due to its mechanical durability and biological stability, biochar is suitable for reuse after sterilization, which further enhances its sustainability [152].

3.7.3. Environmental Impact and Sustainability

From an environmental perspective, biochar represents an attractive option. It is produced from renewable or waste biomass, contributes to carbon sequestration, and its use reduces the need for the extraction of non-renewable substrates such as peat or perlite. The use of biochar in closed-loop nutrient systems or in organic farming supports the long-term sustainability of cultivation [153,154].

3.8. Peat

3.8.1. Production, Composition, and Physical Properties

Peat is a partially decomposed organic material formed in waterlogged, anaerobic environments over thousands of years, composed primarily of sphagnum moss, sedges, and other hydrophilic vegetation [155]. It is one of the most widely used substrates in soilless cultivation systems due to its favorable physical and chemical properties, including high water retention capacity, limited air-filled porosity in highly decomposed forms, and moderate nutrient buffering ability. These features make peat highly suitable for crops with rapid growth cycles and high moisture demands [57].

The classification of peat is based on botanical origin and the degree of humification, which affects its physical consistency, porosity, and nutrient content. Types include fibric (lightly decomposed sphagnum), hemic (intermediate), and sapric (highly decomposed black peat) [156]. Horticultural applications predominantly use sphagnum peat (blond peat), harvested from bogs in Northern Europe and Canada [157]. Peat typically exhibits bulk densities ranging from 50 to 300 kg/m^3, total porosity between 80–95%, and water holding capacities of 600–1200% (*w/w*). Its native pH is acidic (3.0–5.0), requiring pre-treatment with ground chalk or dolomitic limestone to adjust it to horticulturally optimal levels (5.5–6.5) [57,158]. CEC is generally moderate to high, typically 100–200 cmol(+)/kg depending on the decomposition stage, enabling the retention of essential nutrients such as Ca^{2+}, Mg^{2+}, and K^+. Organic matter content typically exceeds 90%, though ash content varies between 1–8% [159].

3.8.2. Agricultural Use and Management Practices

Peat is rarely used alone due to its tendency to compact and become hydrophobic upon drying. Instead, it is blended with coir, perlite, or vermiculite to improve structure, drainage, and air-filled porosity [160]. These blends are commonly applied in bags, modules, troughs, or containers. Various bag formats such as 100 × 11 × 4 cm units with 25 L of compressed peat are rehydrated before planting and used with drip fertigation systems ("spaghetti tubes") to deliver water and nutrients efficiently [161].

In cannabis cultivation, white peat-based substrates have demonstrated superior performance in plant growth and cannabinoid production when compared to just coir and dust-based alternatives [93]. Key improvements include greater root biomass, higher chlorophyll content, increased photosynthetic efficiency, and overall fresh and dry weight [100,125]. This performance is partly attributed to peat's consistent physical texture, buffering ability, and compatibility with beneficial microbial consortia such as *Trichoderma* and *Bacillus* spp. [162,163]. Peat is not sterile, and pre-treatment such as pasteurization or composting may be applied to reduce pathogen risk. Fertilization remains essential, as natural nutrient levels, especially, nitrogen, phosphorus, and potassium, are low [164].

3.8.3. Environmental Impact and Sustainability

While horticultural peat offers reliable agronomic performance, its extraction raises environmental concerns. Peatlands are carbon sinks, and their degradation contributes to CO_2 emissions and loss of biodiversity. Consequently, regulatory restrictions are emerging across the EU, with some countries phasing out peat in commercial horticulture [165,166]. Alternatives such as coconut coir, composted bark, or synthetic fibers are being investigated to partially replace peat. Nonetheless, trials have shown that peat-based media still outperform many substitutes in terms of plant growth and uniformity in controlled environments [24].

3.9. Phenolic Foam

3.9.1. Production, Composition, and Physical Properties

Phenolic foam is a rigid, semi-inert, and highly porous synthetic substrate composed mainly of phenol-aldehyde resins. Originally developed for insulation due to its excellent fire resistance and thermal stability, phenolic foam has gained attention in horticultural practices, especially for seedling propagation in soilless systems. Its homogeneous structure, high porosity, and sterility make it a viable alternative to rockwool or peat-based substrates during the propagation and early vegetative stages (Figure 2) [167,168].
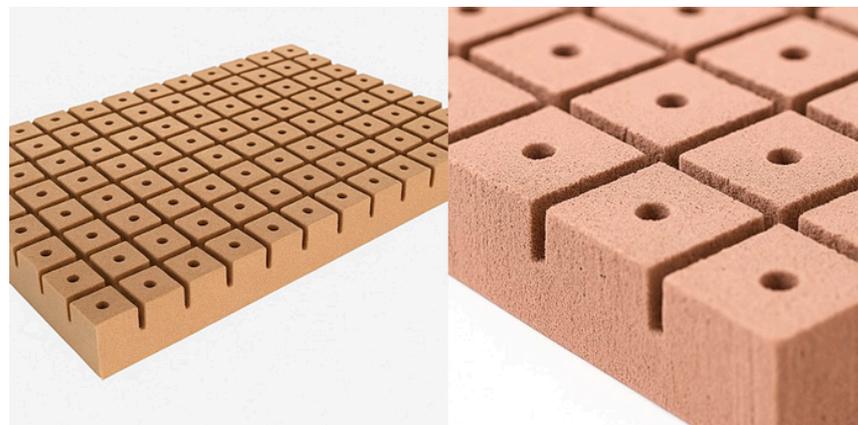
Figure 2. Phenolic foam propagation blocks.

The foam is synthesized through the polymerization of phenol with an aldehyde— in traditional formulations, most commonly formaldehyde—in the presence of blowing agents, catalysts, and curing agents. However, due to formaldehyde's classification as a carcinogen and its environmental persistence, its use is increasingly discouraged in applications involving food or plant production. In response, researchers and manufacturers have begun exploring alternative cross-linkers such as glyoxal, furfural, and hydroxymethyl-furfural, which offer lower toxicity and a reduced ecological footprint [168,169]. This process produces a lightweight material with a closed- or open-cell structure depending on formulation, typically exhibiting a density of 50–65 kg/m^3 and thermal conductivity

between 0.024–0.034 W m^{-1} K^{-1}. The microcellular, honeycomb-like structure enables excellent water retention, several times its own weight, while retaining sufficient air-filled porosity to support root respiration. However, under full saturation, reduced aeration may occur, necessitating careful irrigation control [170,171].

Phenolic foam is low in CEC and has minimal buffering capacity, allowing precise control of nutrient and pH management. The substrate typically has a pH between 5.8–6.8 and very low EC, although residual additives may cause slight variation. Most commercial propagation foams (e.g., OASIS® Rootcubes®) are preconditioned for optimal pH and require only thorough wetting prior to use [2,171]. Mechanical properties present both advantages and limitations. In the dry state, the material is lightweight and relatively strong; however, it becomes fragile and structurally unstable when wet and is prone to crumbling (friability) under pressure. Unlike fibrous substrates such as rockwool, phenolic foam must be handled with care, though it is easily shaped and cut to desired dimensions with consistent physical properties across all units [2,172].

3.9.2. Agricultural Use and Management Practices

Phenolic foam is widely used in plug seedling production, particularly for vegetables (e.g., tomato, pepper) and ornamentals [173]. Produced as small blocks or plugs arranged in perforated trays, it facilitates uniform germination and rooting due to its stable structure and sterile, inert nature. Empirical studies have shown over 90% germination success in crops like pepper, with seedling performance including plant height, biomass, and root development comparable to or better than that achieved in rockwool [174]. Its compatibility with mechanized seeding, precision irrigation (e.g., misting, ebb-and-flow), and ease of transplanting supports efficient propagation workflows [13].

While no peer-reviewed studies to date have evaluated phenolic foam specifically for medical cannabis cultivation, its properties suggest potential use in early-stage propagation, such as seed germination and cutting (clone) rooting. Some manufacturers, including Oasis Grower Solutions, already market their foam products for cannabis propagation [2,171]. The foam's inertness and uniformity allow for tight control over nutrition and root-zone conditions, which are critical in cannabis hydroponics. Nevertheless, challenges must be addressed. The high water retention can increase the risk of stem or root rot if over-watered, particularly in sensitive crops like cannabis that require a precise oxygen-water balance. Excess moisture around the hypocotyl or root collar may predispose seedlings to damping-off diseases. Thus, irrigation strategies must maintain the medium in a moisture state that ensures both capillary water and aeration [3,8,65,70]. Moreover, due to its mechanical fragility, phenolic foam lacks the structural support required for mature cannabis plants. As a result, it is best suited as a propagation substrate before transplanting into more robust media or systems such as coco coir, rockwool blocks, or deep water culture [2,8].

3.9.3. Environmental Impact and Sustainability

Traditional phenolic foams are non-biodegradable and contribute to long-term plastic waste. Derived from fossil-based phenol and formaldehyde, they persist in the environment and can break down into microplastics over time [175]. Studies report that a single block of florist-grade foam can release microplastic loads equivalent to several plastic bags, posing ecological risks, particularly in aquatic environments [176,177].

To mitigate these impacts, recent innovations in phenolic foam technology have prioritized sustainability and safety. Alternative aldehydes such as glyoxal and furfural are both less toxic and more environmentally benign, and these are under increasing consideration as replacements for formaldehyde [178,179]. In parallel, renewable feedstocks such as lignin (from pulp industry) [180], tannins (from bark extracts) [181], and cardanol

(from cashew nut shell liquid) are being used to partially substitute petroleum-derived phenol [182]. These bio-based foams maintain comparable physical performance while lowering environmental footprint [178]. A commercial example of this transition is the introduction of plant-based phenolic foams marketed for horticultural use, which are reported to offer comparable physical properties to conventional phenolic foams, while reducing carbon footprint by over 50%. Though still in development, these innovations suggest that phenolic foams could evolve into a more sustainable category of soilless substrates, suitable even for sensitive crops like cannabis, once performance and biodegradability are validated [183,184].

4. Effects of Medium on Cannabis Growth, Yield, and Cannabinoid Content

The choice of growing medium is a key factor influencing both the early vegetative phase and the generative phase of inflorescence development [2–4,9,10,93]. This section summarizes experimental findings on the effects of different soilless media on the development of cannabis plants, with emphasis on shoot and root biomass growth, nutrient uptake, flower yield, and cannabinoid content.

4.1. Vegetative Growth in Different Growing Media

During the vegetative phase, cannabis plants establish their architectural structure—stem development, leaf area expansion, and branching [185,186]. The rate of this growth is significantly influenced by the physical properties of the growing medium, particularly its water-holding capacity, aeration, and structural composition [3,24,30,42,56,98].

In controlled experiments with the cultivars "Janet's G" (chemotype IV) and "TJ's CBD" (chemotype III), aeroponically propagated cuttings exhibited enhanced early vegetative growth. For "TJ's CBD", shoot biomass-to-stem diameter ratios were significantly higher in aeroponics compared to rockwool and horticultural foam after 14 and 21 days. Plants were also consistently taller in aeroponics, with height advantages of up to ~15% over rockwool at 21 days post-propagation [65]. In longer vegetative trials, well-drained inorganic media also supported greater biomass accumulation than traditional organic mixes. Cannabis plants cultivated in rockwool exhibited superior leaf and stem dry mass accumulation compared to peat–perlite and coconut coir substrates. At 49 days after planting, leaf dry weight in rockwool reached ~25.8 g/plant and stem dry weight ~19.8 g/plant—values that were 20–23% higher than in the organic media. Similarly, the leaf area index in rockwool was significantly greater (12.8 m^2/m^2) than in peat or coir, indicating more vigorous canopy development [187]. These results demonstrate that well-drained and aerated media promote more rapid development of aboveground structures, which subsequently affects flower yield.

4.2. Root Development and Nutrient Uptake

The root system of cannabis plays a critical role in water and nutrient acquisition, and its development is strongly influenced by the properties of the substrate [70]. One key parameter to assess root proliferation is root length density (RLD), which quantifies the extent of root branching. In a comparative study, two phytocannabinoid-rich *C. sativa* genotypes—"KANADA" and "0.2x"—were grown in three substrates: a peat-based mix, a peat-based mix with 30% green fiber substitution (consisting of thermally treated coniferous wood chips), and pure coconut coir fiber [125]. Plants grown in the peat-based mix exhibited significantly higher RLD (4.32 cm/cm^3) than those in coconut coir (3.09 cm/cm^3), indicating a denser and finer root network in peat-based media. In coir, roots were fewer but thicker, likely due to its coarse structure and lower water retention capacity. Impor-

tantly, the addition of 30% green fiber to peat did not reduce RLD; on the contrary, it slightly increased it to 4.63 cm/cm^3, suggesting that partial substitution of peat with renewable wood-derived fibers can be achieved without compromising root development [125].

Aeroponic systems provide an extreme level of oxygenation in the root zone, leading to up to a 13-fold increase in root dry weight over 8 weeks compared to conventional substrate-based systems. Such a robust root system enables more efficient nutrient uptake, supporting overall plant growth [188]. Recent findings further confirm that aeroponically propagated plants exhibit superior root score, root length, and dry mass compared to those propagated in horticultural foam or rockwool. Treatments with frequent misting intervals (e.g., 1 min on/1 min off) have been shown to enhance lateral root initiation, nutrient uptake, and biomass accumulation due to optimized air–water balance at the root interface [65]. These conditions promote early transplant success and uniform root development across genotypes [189].

However, even among solid substrates, marked differences in root biomass have been observed. In a recent trial comparing rockwool, peat-perlite mix, and coconut coir fiber, significantly higher root dry weight was measured in plants grown in coconut coir (1.26 ± 0.04 g/plant), whereas root biomass was reduced by approximately 18% in rockwool and peat-perlite mix (common L_{max} estimate: 1.03 ± 0.03 g/plant). This finding correlates with differences in nitrogen availability and water retention between the substrates. Rockwool, despite its high water-holding capacity (2.6 L at container capacity) and the highest readily available water fraction (79%), supported the lowest root mass, which was probably due to luxury nitrogen consumption and reduced stimulation of root proliferation under non-limiting conditions. Conversely, coconut coir's higher buffering capacity and moderate water availability (1.4 L container capacity; 14% easily available water) may have triggered stronger root development to compensate for transient nutrient limitations. In contrast, peat-perlite mix exhibited both the lowest total water capacity (1.04 L) and the lowest fraction of easily available water (9%), which likely impaired both shoot and root development, particularly under conditions of low irrigation frequency [187].

Nitrogen uptake is another key factor significantly affected by the choice of growing medium. In the same trial, mean leaf nitrogen concentration in rockwool was significantly higher (52.6 ± 0.6 mg/g) compared with peat-perlite mix and coconut coir (both 48.6 ± 0.5 mg/g). This trend persisted across various tissues; e.g., sugar leaves in rockwool had 52.3 ± 1.2 mg/g N, while in coconut coir and peat-perlite mix it was 48.8 ± 0.9 and 46.5 ± 1.0 mg/g, respectively, reflecting greater nutrient accessibility in inert rockwool [187]. These findings contrast with earlier studies on cucumber and tomato, where coconut coir and peat–perlite mix outperformed rockwool in terms of nitrogen uptake [190,191], highlighting the importance of fertigation strategy. In the referenced study, the high irrigation frequency applied in rockwool likely enhanced nutrient mobility, while the organic substrates exhibited possible nitrogen immobilization and pH drops toward the end of the cycle (down to ~5.0 in peat-perlite mix), potentially reducing nitrogen availability [187].

In a complementary experiment with genotypes "KANADA" and "0.2x", grown in peat, peat + green fiber, and coir, the highest leaf nitrogen concentration was again observed in the green fiber–amended mix (52.24 mg/g), followed by peat (46.75 mg/g), and the lowest in coir (37.00 mg/g). These nitrogen levels correlated with significantly higher SPAD values, particularly in plants grown in the green fiber–amended mix (e.g., 56.10 in genotype "KANADA" and 52.77 in genotype "0.2x") compared to coconut coir (43.47 and 41.83, respectively), indicating enhanced chlorophyll content and photosynthetic capacity [125]. Additional studies have emphasized that substrate structure and irrigation frequency critically affect nutrient uptake efficiency. For example, coir-based substrates with higher air

capacity may require more frequent fertigation to prevent nutrient leaching and maintain optimal nutrient availability [90,92]. Conversely, peat-based mixes retain water and nutrients more effectively, supporting steady uptake. Furthermore, genotype-specific responses to substrate composition were observed, with "KANADA" showing more vigorous root growth and higher nutrient accumulation in peat-based media, while "0.2x" displayed greater tolerance to variable substrate conditions [125].

4.3. Generative Phase—Inflorescence Yield and Cannabinoid Content

During the generative phase, cannabis plants allocate energy toward flower production and the accumulation of secondary metabolites. Differences between substrates are most apparent in total flower biomass yield, while the concentrations of major cannabinoids tetrahydrocannabinol (THC) and cannabidiol (CBD) tend to be only minimally influenced by the substrate, assuming that nutritional and environmental conditions are stable.

CBD concentrations in inflorescence dry matter were not significantly affected by the growing medium in several studies. For instance, CBD levels ranged between 5.97% and 6.22% in genotypes ("KANADA" and "0.2x") cultivated in peat-based, peat with 30% green fiber, and coconut coir substrates, with no statistical differences reported [125]. Similarly, CBD concentrations ranged from 3.3% to 4.9% when plants were cultivated in rockwool, peat–perlite, and coco coir substrates, again showing no significant impact of the substrate on cannabinoid levels [187].

However, flower yield is influenced by the substrate, with results often reflecting differences in plant vigor established during the vegetative phase. In a comparative study, the "KANADA" genotype produced a significantly higher floral dry weight in peat (8.56 g/plant) compared to green fiber (4.94 g) and coco coir (3.84 g), while the "0.2x" genotype showed stable yields of 7.90–9.19 g/plant across all substrates [125]. A separate trial confirmed this pattern, as no significant differences in flower yield were observed between rockwool, peat–perlite, and coco coir (20.8–27.4 g/plant). Nonetheless, rockwool and coco coir supported greater vegetative biomass than peat–perlite, which likely contributed to the higher absolute floral yields [187].

These findings underline that while cannabinoid concentrations did not differ significantly between substrates, cannabinoid yields can be affected by physical substrate properties. In a study comparing two coir-based substrates differing in water-holding capacity, the substrate with lower water retention led to 22% and 20% higher yields of tetrahydrocannabinolic acid (THCA) and cannabigerolic acid, respectively. These differences were likely due to increased irrigation frequency and improved oxygen availability in the root zone of the drier substrate [92]. Genotypic differences also contribute to yield responses. The contrasting performance of "KANADA" and "0.2x" under identical fertigation and nutrient regimes suggests that cultivars vary in their sensitivity to substrate properties, underscoring the importance of genotype-specific substrate optimization [125].

A favorable substrate that reliably supplies water, nutrients, and oxygen can maximize total flower biomass, thus increasing overall cannabinoid yield via sheer mass. Conversely, substrates that impose mild constraints (e.g., lower nutrient buffering or intermittent water stress) may elevate cannabinoid concentrations in tissues without reducing yield, as demonstrated when controlled drought stress increased THCA by 12% and cannabidiolic acid by 13%, with cannabinoid yield per area rising by 43–67% [192]. Excessive stress, however, reduces both growth and yield, negating such benefits. Nutrient deprivation during flowering likewise maintained CBD yield at 95% while using one-third less fertilizer [193]. Hence, the key lies in maintaining an optimal balance. Media with high porosity and moderate cation exchange capacity allow frequent fertigation and high oxygenation of

roots [14]; under careful management, this environment supports both robust growth and high cannabinoid levels [10].

5. Conclusions and Future Perspectives

Soilless media that optimize the air–water balance are the principal drivers of vegetative vigor and inflorescence biomass. Across the literature synthesized in this review, aeration (air-filled porosity) and water-holding characteristics (including easily available water) consistently predict plant development and yield. Rockwool remains widely used because its uniform porosity and low CEC enable precise fertigation and high oxygen availability, although its non-biodegradability raises sustainability concerns. Coconut coir provides a renewable alternative with strong moisture retention and buffering but requires pretreatment and tighter process control to manage batch variability. Peat-based blends continue to deliver reliable physical performance yet face growing regulatory and environmental constraints. Inert aggregates such as expanded clay and foamed glass excel at gas exchange and reusability but have low water storage, demanding higher irrigation frequency and careful dry-back management. Phenolic foam and biochar are promising in specific roles (propagation; amendment-driven water/nutrient buffering), but they require validation of durability, friability, and process standardization in cannabis workflows. Overall, the physical hydraulics of the medium rather than chemistry per se most strongly governs biomass outcomes under stable nutrition and climate (Table 3).

Table 3. Physicochemical Characteristics and Usage of Soilless Growing Media.

Substrate	pH	CEC *	Water Holding Capacity	Aeration	Standalone Use	Mixes/Notes
Rockwool	~7.5	Very low (~0)	High	Excellent	Yes	Used alone or with coir
Coconut Coir	5.2–6.8	High	High	Moderate	Yes	Mixed with perlite or clay (70:30)
Perlite	7.0–7.5	None (~0)	Low–moderate	Excellent	No	Mixed with coir or vermiculite (10–50%)
Vermiculite	7.0–7.5	Moderate–high	High	Low–moderate	No	Mixed with perlite, coir, or peat
Expanded Clay (LECA)	6.0–7.0	None (~0)	Low	Excellent	Yes	Sometimes mixed for weight or retention
Foamed Glass	6.5–7.5	None (~0)	Low–moderate	Excellent	Yes	May be mixed for better retention
Biochar	6.5–9.5	Variable (low to high)	Moderate	Moderate	No	Mixed into coir or peat (5–20%)
Peat	3.0–4.5 (raw), 5.5–6.5 (adjusted)	Moderate–high (100–200 cmol(+)/kg)	Very high (600–1200%)	Low–moderate	No	Mixed with perlite or coir
Phenolic Foam	5.8–6.8	Very low	High	Moderate	No	Used in propagation, not final stage

* Cation Exchange Capacity.

When environmental and nutritional regimes are well controlled, cannabinoid concentrations (e.g., THC, CBD) are predominantly genotype-determined. Substrate choice rarely causes statistically robust shifts in major cannabinoid percentages; instead, media effects manifest indirectly via growth rate, canopy architecture, and harvest index. Thus, substrate selection should target reproducible biomass and resource-use efficiency first, with chemotype stability safeguarded mainly through genetics and environmental consistency.

Within this genotype-led ceiling, root-zone oxygenation, moisture dynamics, and microbial interactions can fine-tune quality traits. Media that sustain high oxygen availability and stable pH/EC reduce abiotic stress and may modulate secondary metabolism in sensitive cultivars. Organic matrices (e.g., coir) can host beneficial consortia (e.g., *Trichoderma*, *Bacillus*), while amendments such as biochar may enhance water/nutrient buffering and microbial habitat; these effects are context-dependent and require standardized assays to link rhizosphere function with terpene and minor-cannabinoid expression.

Abbreviations

The following abbreviations are used in this manuscript:

CBD	Cannabidiol
CEC	Cation exchange capacity
DWC	Deep water culture
EAW	Easily available water
EC	Electrical conductivity
EPD	Environmental product declaration
FOCUS	Foundation of Cannabis Unified Standards
GACP	Good agricultural and collection practice
GMP	Good manufacturing practice
GPP	Good production practice
IMC-GAP	Israeli Medical Cannabis Good Agricultural Practice
LECA	Lightweight expanded clay aggregate
LCA	Life cycle assessment
RLD	Root length density
RO	Reverse osmosis
SOP	Standard operating procedure
TGO 93	Therapeutic Goods Order No. 93
THC	Tetrahydrocannabinol
THCA	Tetrahydrocannabinolic acid

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