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Review

Increasing Sustainability of Growing Media Constituents and Stand-Alone Substrates in Soilless Culture Systems

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Abstract: Decreasing arable land, rising urbanization, water scarcity, and climate change exert pressure on agricultural producers. Moving from soil to soilless culture systems can improve water use efficiency, especially in closed-loop systems with a recirculating water/nutrient solution that recaptures the drain water for reuse. However, the question of alternative materials to peat and rockwool, as horticultural substrates, has become increasingly important, due to the despoiling of ecologically important peat bog areas and a pervasive waste problem. In this paper, we provide a comprehensive critical review of current developments in soilless culture, growing media, and future options of using different materials other than peat and rockwool. Apart from growing media properties and their performance from the point of view of plant production, economic and environmental factors are also important. Climate change, CO_2 emissions, and other ecological issues will determine and drive the development of soilless culture systems and the choice of growing media in the near future. Bioresources, e.g., treated and untreated waste, as well as renewable raw materials, have great potential to be used as growing media constituents and stand-alone substrates. A waste management strategy aimed at reducing, reusing, and recycling should be further and stronger applied in soilless culture systems. We concluded that the growing media of the future must be available, affordable, and sustainable and meet both quality and environmental requirements from growers and society, respectively.

Keywords: biochar; compost; climate change; hydroponics; growing medium; life cycle analysis; organic bioresources; peat alternatives; renewable raw materials; rockwool; waste; wood fibers

1. Introduction

According to the United Nations, the current world population of 7.79 billion people will increase to 9.77 billion people by 2050 [1], while the arable land per capita continues to be reduced. This development is following the same pattern in all countries, although the rate varies between countries. For instance, in North America there were 1.06 ha, and in the European Union 0.32 ha, per person available in the year 1961, while in 2015 only 0.55 ha and 0.21 ha per person, respectively. This is nearly to 2× and more than 1.5× reduction for North America and the European Union, respectively (Figure 1) [2].

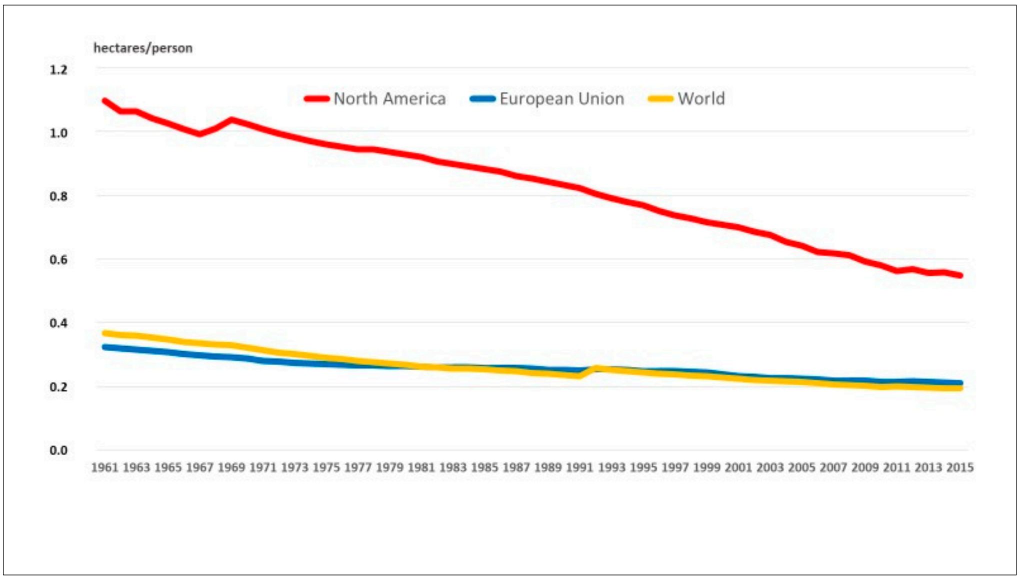

Figure 1. The arable land per person has been continuously reduced in the recent past. Arable land in hectares per person from 1961–2015 for North America, the European Union, and worldwide, according to World Bank [2].

In addition, worldwide urbanization is increasing rapidly. In 2008, the global urban population overtook the rural population for the first time in history. Today, over 50% of the world's population lives in cities; by 2030, this number is projected to increase to 70% [3].

Future climate change scenarios predict more frequent occurrence of extreme conditions, such as drought years and the uneven distribution of precipitation during the year [4]. The possible increase in water shortage and extreme weather events may cause lower yields and higher yield fluctuations [5]. These disadvantages will be predominately in warmer regions worldwide. Therefore, besides securing sufficient water, it will become increasingly important to improve the use efficiency of this resource [6–8]. Water, as a valuable resource, can be used more efficiently in protected vegetable production, which is considered less dependent on weather conditions than open field production, because micro-climates can be manipulated [6,7].

Decreasing arable land, rising urbanization, water scarcity, and climate change exert pressure upon agricultural producers. One of the most promising approaches to tackle this challenge is termed "sustainable intensification", which tries to combine increased production without damaging its supporting ecosystem. Examples for this approach are protected, soilless culture systems (SCS) [9]. "Soilless culture" is defined as the cultivation of plants in systems without soil in situ [10]. The percentage of SCS to the total commercial horticultural protected cultivation area varies from country to country. For instance, in the Netherlands and Almeria, Spain, soilless culture represents the main cultivation system used [11]. In Europe, Canada, and in the large horticultural industry complexes in the US, 95% of greenhouse tomatoes are produced in SCS [12,13].

Growing media, "substrates" or "plant substrates" provide a root environment that is initially free of plant pathogens and properties that ensure an adequate aeration, water, and nutrient supply. In the horticultural industry, generally, mixtures of growing media constituents and additives are used. Organic or inorganic materials can be used as constituents, while additives include fertilizers, liming materials, and bio-control or wetting agents [14–16].

Blok and Urrestarazu [17] estimated an area of more than 10,000 ha cultivated in rockwool slabs worldwide, including 6000 ha greenhouse area in Europe, mainly in Northern Europe. Rockwool has a low volume weight, is inert, and has a buffering capacity, limited to the quantity of nutrients and water held within the pore space of the medium [18]. To feed the plant with water and fertilizer a complete nutrient solution is supplied through the irrigation system (Figure 2).

(**a**) (**b**)

Figure 2. Tomato production in soilless culture with rockwool as a growing medium: (**a**) Transplants in rockwool cubes, shortly before the start of greenhouse cultivation; (**b**) tomato plants in rockwool slabs (photos: Gruda, private collection).

However, it is important to note that the disposal problem for mineral wool has led to criticism of its current usage. Some authors, such as Bussell and Mckennie [19], showed some options to reuse rockwool, but when analyzing the life cycle assessment of horticultural growing media, Quantis [20] reported that mineral wool has the highest negative impacts on human health. In addition, freight costs are relatively high.

Besides rockwool, other inorganic substrates, such as perlite, volcanic rock, tuff, expanded clay granules, vermiculite, zeolite, pumice, sand, and synthetic materials could be used directly or in combination with other materials as a growing medium.

Of all organic materials, peat is the most used substrate constituent in horticulture [7]. The leading peat-production countries are Finland, Ireland, Germany, Sweden, Belarus, Canada, and Russia, which account for 80% of the world's production. Commercial applications include lawn and garden soil amendments, potting soils, and turf maintenance on golf courses [21]. The extensive use of peat as a basic and main component of substrates is due to relatively low costs in these areas, its excellent chemical, biological, and physical properties with low nutrient content, low pH, a unique combination of high water-holding capacity by high air space and drainage characteristics, light weight, and freedom from pests and diseases [14,16,21]. The unique microporous properties of *Sphagnum* peat and its resistance to degradation are matched by few other growing medium constituents [22].

However, peat is a limited resource with a great demand, and the extraction of peat bogs causes negative impacts on environment. Peatlands are areas with a layer of dead plant materials (peat) at the surface. The water-saturated and oxygen-free conditions prevent peat from fully decomposing. Peatlands are a habitat with special ecological value with the most important long-term carbon sinks and one of the most effective eco-systems in the terrestrial biosphere, providing different environmental services, such as biodiversity, carbon (C) storage, regulation of the local water quality, and local hydrology conditions, including flood protection [23–25]. Covering only about 3% of Earth's land area, they may store 21% [26] to 33% [27] of the total world's terrestrial organic carbon. In the long-term, peatlands are the largest stores of organic carbon of all terrestrial ecosystems [28]. However, when peat bogs are drained or destroyed, i.e., used in agriculture, forestry, and/or horticulture, they no longer act as carbon sinks. Degraded peatlands contribute disproportionally to global greenhouse gas emissions, with approximately 25% of all CO_2 emissions from the land use sector [29]. Annual emissions equivalent of 15 million tons of carbon are estimated [23,24,30,31]. In addition, the renewal process of peatlands takes a very long time, and in arid areas peat is imported, with an impact both in environmental and economic terms. Therefore, Quantis [20] indicates that peat has the highest impact on "climate change" and "resources" of all commonly-used substrate materials.

Recently, the energy use and carbon emissions in horticultural production systems have moved into the public spotlight. Thus, retailers increased the pressure and are now requiring not only traceable healthy and safe horticultural products, but also "clean and green" produce with a low carbon footprint. On the other hand, due to limited natural resources and waste recycling issues, environmentally acceptable solutions are needed for materials used as growing media constituents.

The objective of this paper is to critically review and expand the knowledge of impacts of soilless culture and growing media on the environment, targeting an improvement of sustainability of all horticultural systems. First, an overview on the pros and cons of soilless culture and growing media use is provided. Second, different important economic and environmental factors are analyzed. Moreover, different organic materials are explored with the objective to recognize successful alternatives for peat and rockwool.

2. Results and Discussion

2.1. Soilless Culture and Growing Media: Pros and Cons

Soilless culture systems are commonly integrated in controlled environment agriculture, i.e., heated greenhouses, that in turn are associated with environmental concerns and the production of high amounts of greenhouse gases (GHGs). Indeed, major studies conducted showed that from an environmental point of view, plants cultivated directly in soil in tunnels or greenhouses without using auxiliary systems perform better than those with heating in SCS [32–34]. However, even if the heated protected cultivation systems present a good opportunity to move from soil to SCS, we do not have to associate SCS only with heated greenhouses. The specific features along the entire production system in these structures include the large amount of energy consumption for heating during the cold season, artificial lighting, the greenhouse structure itself [35], the use of fertilizer and growing media [7], postharvest transport, and packaging [36]. The equipment of SCS contribute to some degree to an increase of the energy needed together with growing media used in these systems. But, on the other hand, SCS contributes to a reduction of many problems associated with traditional cultivation on soil in situ, such as soil-borne diseases and pests, and to an exact control of water and fertilizer supplies. As a consequence, higher yields at a reasonable production cost and high product quality can be attained in these systems [13,37]. Recently, the greenhouses production is increasingly carried out with machines as an "unmanned working model" in some soilless systems [38].

Moreover, high precision in modulating nutrient solution composition, the exact dosage and controlled exposure, make SCS a good instrument to predict the product supply and enhance the organoleptic plant parameters and bioactive quality components. Moderate salinity and/or nutritional stress and the biofortification of vegetables with beneficial micronutrients to human health, such as iodine, iron, molybdenum, selenium, silicon, and zinc are well known methods that have been successfully used to enhance the health-promoting phytochemicals in vegetables [13,39–42].

Therefore, in general, growing plants in soilless media is a sustainable production manner. This is due to the inherent space, nutrient, and water use efficiencies of this production method; all of which are higher than soil-grown crops [9]. At present, life cycle analysis (LCA) is used for the classification of growing media constituents, based on their environmental impact and sustainability, environmental protection, and the application of "green technologies" for their production [7,16]. Mugnozza et al. [43] determined, using LCA, that soilless cultivation reduced the environmental impact by more than double, due to lower levels of fertilizers and pesticides emitted to the environment, compared to soil cultivation. The total GHG emissions from a tomato rockwool culture averaged 853 g (exp. 1) and 999 g CO_2 equivalent (exp. 2), and from a soil-based production averaged 1303 g (exp. 1) and 1509 g CO_2 equivalent (exp. 2), respectively. In addition, 16S ribosomal ribonucleic acid gene abundance in soil samples was 10-fold higher than in rockwool samples [44].

Every year, the majority of freshwater, approx. 87%, is used worldwide for agricultural production [45]. The lack of freshwater resources is an acute issue for arid and semiarid areas in Africa, the Middle East, Southern Europe, and South America that may not only threaten economic development, but also lead to drastic environmental and social problems. One of the major advantages of using SCS is water economization. For instance, lettuce nutrient film technique (NFT) production in South-East Spain requires 62% less water than soil cultivation [46]. In this context, sometimes a comparison between local and imported products is discussed. Stoessel et al. [47] studied a wide range of vegetables, including tomatoes, and concluded that, from a carbon footprint viewpoint, it is often better to import vegetables produced in warm Southern countries during periods when Northern production requires heating. However, surprisingly, sometimes LCA studies, e.g., for tomato production in different Mediterranean countries, have been carried out without considering the impacts of freshwater use [48–51]. Webb et al. [52] also did not address the impacts of freshwater use in their comparison of locally produced tomatoes in the UK and imported tomatoes from Spain [53].

Tomato is the most important vegetable crop in the world [54] and the most cultivated in SCS. When comparing water consumption and water use efficiency (WUE), defined as the obtained yield per unit of irrigation water, vast improvements in WUE are made, with varying degrees, when moving from traditional, soil-based production to protected SCS cultivation methods (Figure 3). For instance, for one kilogram of tomatoes produced in the field, on average about 200 ± 100 L of water are needed. Using drip irrigation, this amount is reduced to about 60 L/kg [55,56]. Moving from soil to SCS can further improve WUE.

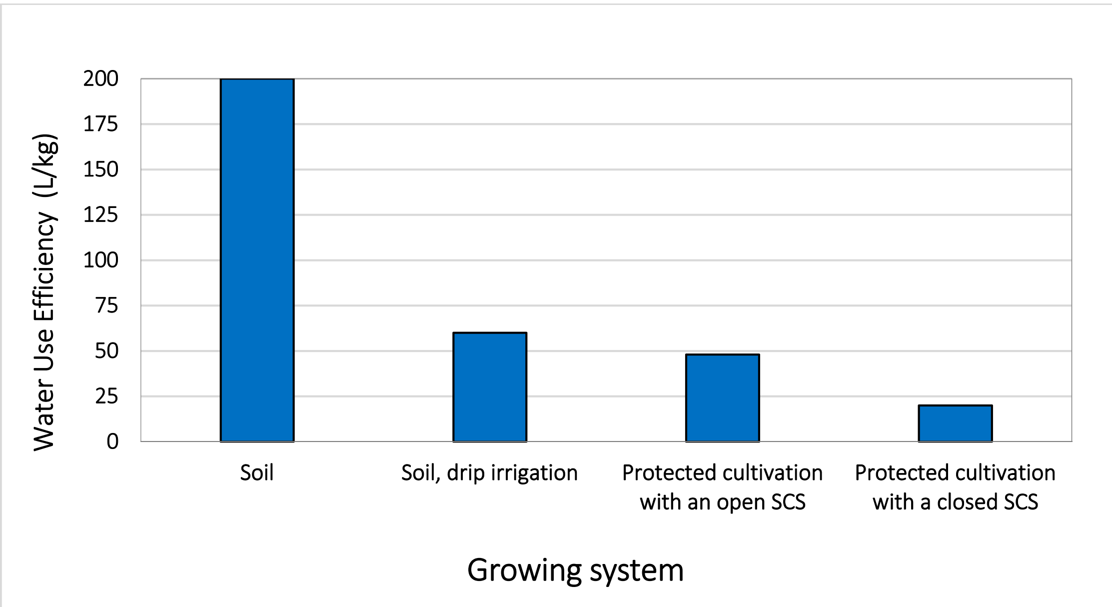

Figure 3. Applying new techniques and new irrigation systems can significantly improve water use efficiency, here calculated as L/kg tomatoes, using different growing systems. Soilless culture system (SCS).

The SCS could be either open-loop or closed-loop cultivation systems. The latter, which involves re-using any drainage solution, can substantially reduce potential pollution of water resources by nitrates and phosphates, while contributing to an appreciable reduction in water and fertilizer consumption [10], even if an ion accumulation (Na^+ and Cl^-) is a challenge in these systems [57]. Comparing data from a commercial tomato farm in Italy and referring to one summer growing season, the savings from a closed irrigation system were 25%, 40%, 24%, and 11% in water, nitrogen (N), phosphorus (P), and potassium (K), respectively [58]. In an open system, where drainage water is not captured and recycled, 10–20% water and fertilizers can be saved, while production and quality can be improved [59]. However, in closed-loop or recirculating water systems that recapture the drainage water for reuse [13], the average use is between 14 and 20 L/kg, i.e., reduced by a factor of up to 5–10 [51,55,60] (Figure 3). By combining a modern irrigation system with modern environmental management, such as the use of closed/semi-closed greenhouses [8] with the regaining and reusing of condensed evaporated water [55], the use of light selective shading and evaporative cooling systems [60,61] make more water savings possible. To come back to our example regarding tomatoes, according to van Kooten et al. [55], it is possible to achieve WUE of 1.5 L water per kg tomato. Under practical conditions, the levels of WUE are rather higher than this. However, these values are possible to achieve and every reduction in water consumption is a step in the right direction. Moreover, under the expected climate change scenarios and water limitation for agriculture, desalinated seawater coupled with hydroponic systems could be a valuable strategy to sustain a high productive agriculture [46].

WUE has a direct economic and environmental effect [8]. Apart from WUE, growing crops with high water requirements in water-scarce areas has important implications. Payen et al. [51] compared the production of tomatoes in Morocco with a production in France. They found that, although the water use efficiency was similar, Moroccan tomato freshwater deprivation was almost four times higher, with 28.0 L H_2O eq kg^{-1} for Moroccan tomatoes and 7.5 L H_2O eq kg^{-1} for French tomatoes. This was explained by the high-water stress index of the cultivation area. Therefore, the authors concluded that, from a water perspective, sourcing vegetables from water-scarce countries is questionable [51].

Because of their light weight and sustainability in terms of resource efficiency, soilless systems are especially suitable for urban areas as well as hobby gardening. These systems allow for an exact dosage and application of nutrients [3,62]. Nowadays, "vertical farming systems" in tower shapes have started to be applied. This system provides 10x more plants per unit area, a 50% reduction in the harvest period, water and fertilizer savings, clean production, and all year-round production [38].

The major disadvantages of soilless cultures are the high investment and energy costs that are required for the initial installation, as well as the increased technical skills that are needed. Other advantages and disadvantages by using certain organic materials as growing media constituents and stand-alone substrates are analyzed below.

2.2. *Organic Materials Other than Peat Used as Growing Media Constituents*

Different organic materials may play an important role in decreasing the C footprint of the horticultural industry by fully or partly replacing peat-based substrates. Compost, coir, bark, and wood fiber are some organic materials that are already being used in a commercial way as an alternative to peat [23]. In addition, some inorganic materials, such as vermiculite, perlite, clay granules, lava, and pumice are used instead of rockwool or in mixture with peat and other combinations, while new organic materials, such as *Sphagnum* moss, waste and digestates, biochars, and hydrochars are still in their test phase. Below, some of these organic materials and bioresources are briefly described.

2.2.1. Compost, as a Bioresource and Growing Media Constituent

Compost is a general term, describing all organic matter that has undergone thermophilic, aerobic decomposition. It represents a bioresource and a sustainable use case for a potential waste material [9,63]. Several materials are used as growth media after adequate composting. Abad et al. [64] created a database with 105 materials suitable for use as growing media for ornamental potted plant production in Spain. The authors differentiate between urban, sea, agricultural, forest, animal, industrial, and food waste. The disposal needs for waste materials is already an environmental problem, and their recycling in the form of potting media provides a suitable solution. However, some of these materials cannot be used directly. They either contain pathogens, are not stable, or have high water [65] or nutrients content. In some cases, the legal basis needs also be clarified.

Table 1 presents several waste materials used for compost production, which, afterwards, alone or in mixture with other materials, can be used as plant substrates. These include urban and municipal solid wastes, animal manure, grape marc, olive mill, and other food processing wastes; bark, sewage sludge, paper waste, greenhouse waste, pruning waste, spent mushroom compost, and green waste. Different nursery, ornamental, and vegetable plants can grow into these substrates (Table 1). Materials such as bark, wood, several shells or hulls, and coconut coir possess good physical properties after composting. However, being relatively resistant to decomposition, these materials should be subjected to long and well-controlled composting, which may be shortened using N and N-rich organic matter, such as animal manures [66]. According to Raviv [66], high temperatures may cause ashing of these materials, which leads to reduced porosity and increased bulk density. Therefore, temperatures above 65 °C are not desirable.

Table 1. Waste materials used for compost, which, in turn, is used as a plant substrate on its own or in a mixture with other materials.

Feedstock Waste	Use as Growing Medium for Plant Production	Reference(s)
Animal manures	Pot plant production, landscape nurseries, vegetables, and cut flowers production	[67]
Broccoli plants	Lettuce	[68]
Chestnut plants	Lettuce	[68]
Coconut coir dust	Gerbera	[69]
Dredged sediment co-composted with green waste	Ornamental plants	[70]
Corn cobs	*Anthurium*	[71]
Cotton gin	*Azalea*	[72]
Coffee pulp	Tomato seedling	[73]
Farm yard manure	Gerbera	[69]
Grape fruit with coir or vermiculite	Seedlings of lemon basil	[74]
Grapes	Lettuce	[68]
Green waste and sewage sludge	Ornamental bedding plant	[75]
Green/pruning; green/pruning wastes compost, vermicompost, and slumgum compost	Rosemary, Leyland cypress, lettuce, onion, petunia, and pansy	[76]
Olive mill [1], olive [2]	Melon, cress, and tomato plants [1]; lettuces [2]	[77] [1], [68] [2]
Plant leaves	Gerbera	[69]
Posidonia residues	Tomato [1], lettuce seedlings [2], melon, and tomato seedlings [3], pot basil [4], pot sea fennel [5]	[78] [1],[79] [2],[80] [3],[81] [4],[82] [5]
Pruning wastes; pruning waste and municipal solid, or sewage sludge	Ryegrass and cypress [1], Pistacia (nursery) [2]	[83][1], [84][2]
Sewage sludge	Ornamental conifer plants	[84]
Slumgum compost	Rosemary, Leyland cypress, lettuce, onion, petunia, and pansy	[76]
Spent mushroom	Ryegrass and cypress	[85]
Urban solid wastes	Tomato transplant	[86]

Superscripted reference numbers (e.g., [1, 2, 3, 4, 5]) link feedstock waste and growing media with the corresponding literature, applicable only within rows, not columns.

Some value-added benefits have to be highlighted here. These are based on specific properties, such as the potential to suppress some diseases and the capacity to control some plant pathogens. Biofertilization and biostimulation could be mentioned as well. However, composts are variable with respect to physical, chemical, and biological properties. Volume weight, air space, water retention, pH, and available plant nutrient elements can vary greatly from batch to batch as well as with the degree of microbiological degradation and primary organic material used. Even within the different green composts there are differences concerning the quality of the compost. For instance, only the use of selected raw material from greenhouse vegetables, nursery shrubs, and green wastes, i.e., plant trimmings, prunings, and crop residues, could contribute to the production of high-quality compost [87]. The selected green compost was found to be a valuable growing medium for peat substitution, while the green compost derived from mixed raw material negatively influenced *Pelargonium* plant nutrition and photosynthesis, thus significantly reducing plant biomass accumulation and quality. Raw material selection increases the production costs of compost. Therefore, according to Massa et al. [87], efforts should involve the adaptation of new technologies for tracking raw materials and supporting sustainable circular chains for compost production at a local level. In addition, strict quality control procedures are essential in preparing composts for use in growing media [22].

Composts produced from so-called green materials, such as prunings, shredded branches, plant debris, and waste from gardens and nurseries, are widely used as components of growing media in the Netherlands, the United Kingdom, Italy, and Germany, primarily in media for the hobby market [22]. However, they can be used as a component of a growing medium up to 50%, but not as stand-alone substrates [88]. The limiting factor regarding the use of composted green waste is its high electrical conductivity (EC) and potassium (K) concentration. There can also be a problem of plant pathogens, human pathogens, and weed contamination if the composting process is not properly conducted, i.e., if the temperature time exposure is not sufficient [14]. Moreover, compost has a low (5–10%) carbon efficiency, which is reflected in material mass and volume reduction and a relatively high pH.

The use of waste as composting material with a further use as growing media and/or growing media constituents is of a dual benefit. For instance, the removal and disposal of large volumes of plant biomasses of *Posidonia*, a marine phanerogam endemic of the Mediterranean Sea, represent, on one hand, a high cost for local administrations [79]. On the other hand, posidonia-based compost, produced from posidonia residues, may have a considerable potential as a peat substitute in horticultural substrates. Several studies evidenced its use for production of tomatoes [78], lettuce transplants [79], melon and tomato seedlings [80], pot basil [81], and pot sea fennel [82].

The same is true for mushroom substrates. Over three million tons of spent mushroom substrates are produced in Europe every year as a by-product of the cultivation of *Agaricus bisporus* [89]. Due to its physical properties and nutrient content, spent mushroom substrate has great potential to be employed as a growing medium in horticulture. However, spent mushroom substrate should be first matured and stabilized through a composting system [89] before being used, e.g., for vegetable production (Figure 4).

(**a**) (**b**)

Figure 4. Spent mushroom substrate used as growing media in simple soilless culture systems (SCS) in Shandong province in China. (**a**) Spent mushroom substrate. Mushroom production is usually placed in the North part of the greenhouse. (**b**) Tomato production in simple SCS in the South part of the greenhouse. Here, the spent mushroom substrate is utilized as a growing medium (Photos: Gruda, private collection).

Compost, when mixed into growing media, is a source of fiber, i.e., a rooting medium, as well as an important source of nitrogen (N), phosphorus (P), and potassium (K). Therefore, the substrate mixtures containing compost required adjusted fertigation due to nutrients supplied by the compost [90]. In addition, the degree of infection with powdery mildew and aphids was strongly positively correlated with the N status of the crop, pointing at the risks of high N supply for the crop [90].

As an alternative to conventional composting, the action of worms and their gut microorganisms can be used to break down organic waste materials to produce vermicompost. Particle-size distribution and fertility were superior in the vermicompost-based media than in the conventional compost-based media. The compost-based media showed an approx. 2.2× higher coarseness index than the vermicompost medium that possessed more fine particles as compost, due to the effect of earthworms [91]. Earthwoms increase the quantity of small particles by ingesting, mixing, grinding, and then egesting organic material [92]. In addition, the nutrient level was higher and the heavy metal concentration was lower in vermicompost [91,93,94]. Moreover, the supplement of additives could counteract some negative aspects of composting processes, such as emissions of GHGs and odorous molecules.

Due to the large range of raw materials used, composting durations and conditions leads to different compost qualities are produced. Concerning the reproducibility, this is a weakness. However, on the other hand, the diversity of final materials may be treated as a force. The use for plant growth and the properties of materials should meet plant biological requirements.

2.2.2. Coir, a Growing Media Constituent and Stand-Alone Substrate

Coir is the material that forms the middle layers or mesocarp of coconut fruits (*Cocos nucifera* L.). Coir pith, coir fibers, and coir chips are some of the most abundant plant-derived organic waste materials in many tropical and subtropical countries, notable as a rapidly renewable resource. The use of coir as and in growing media has vastly increased since 2004, particularly in Europe but also in the western United States [22].

Similar to peat, coir is used in mixtures for the potting industry as it is a lightweight material and has good air and water holding characteristics. Since coir contains more lignin and less cellulose than peat, it is more resistant to microbial breakdown and usually shrinks less; it is also more hydrophilic and easier to re-wet after drying than peat moss and tends to retain its basic structure when wet or dry [18,95,96].

Leaching of nitrogen is marginally higher and the total water-holding capacity is lower than in peat when comparing materials of a similar particle size, and sometimes natural higher total soluble salts, sodium, and chloride levels are found in coir, depending on their origin [96–98].

However, coir pith has the highest impact on "ecosystem quality", which is often due to land occupation during the coconut harvesting stage [20]. Therefore, efforts have been undertaken to investigate and develop growing media from locally sourced materials, such as, for instance, bark or other wood-based materials, co-products from a forest harvest, or wood processing industries [99–102].

2.2.3. Bark and Wood-Based Materials as Bioresources, Growing Media Constituents, and Stand-Alone Substrates

Bark is a major component of growing media, particularly in areas where peat is scarce or expensive [22], due to transportation cost. It is a lightweight material with a bulk density of 0.1–0.3 g cm^{-3} [63]. Similar to coir, bark can be produced in different particle sizes, which makes adjusting the air and water-holding capacities possible by varying the percentage of fine particles [103].

As with coir, pine bark is not produced specifically for use in growing media and tends to have variable physical, chemical, and biological properties [24]. Bark is usually used as a composted or aged material, in order to avoid potential problems with phytotoxicity, since the presence of phenolic compounds, terpenes, and tannins are typical in the chemical composition [30]. High manganese content, especially at low pH could also be a source of potential phytotoxicity [104]. In addition, N deficiency is a common issue, depending on the origin of the material used and the processing method. Recent studies showed that hydrothermal treatments were effective regarding phytotoxicity removal from industrial bark. After this treatment, bark maintains a very high air content that can be a plus in aeration improvement when added to commercial peat-based substrates [31].

Wood fiber, wood chips, and sawdust are renewable resources from the woodworking industry. All these products are characterized by low water retention and good air content. Depending of the initial material, they could sometimes contain phytotoxins that may affect the plant growth at the beginning of cultivation. In this case, a pretreatment with substrate washing would be recommended [105]. Particle-size distribution determines further physical properties, e.g., water retention and water-holding capacity [99,100,106]. A very good correlation was detected between the high percentage of particles <1 mm and max. water holding capacity, and therefore plant growth [101,107].

Wood fibers are further used to optimize the physical properties of other material components, e.g., reducing bulk density, increasing air space, improving re-wetting capacity [24,107,108] and/or as an organic mulch to reduce soil temperature fluctuations, and soil water evaporation and suppress weeds [109,110].

2.2.4. Biochar and Hydrothermal Carbonization Products as Bioresources and Growing Media Constituents

Different investigations have been carried out to search for methods that transform agricultural, industrial, and municipal wastes into materials that can be used in growing media. The benefit of diverting wastes from landfills and providing large quantities of organic growing media in the future is particularly important for arid and semiarid regions of the globe [22,23].

Biochar and hydrothermal carbonization (HTC) might play a more important role as constituents of growing media. Whereas biochar is manufactured by heating organic matter in an anoxic situation (pyrolysis), the HTC process requires only moderate temperatures [31] and pressures and is usually used for materials with high water content, e.g., plants. Both processes, pyrolysis and HTC, show great potential for the production of sustainable CO_2-neutral energy from biomass, because plants capture the sun energy and convert carbon dioxide from the atmosphere into carbohydrates via photosynthesis [23].

Biochar and HTC char have physical and chemical properties that are variable, depending on the raw material used and the carbonization technique. Usually, the electrical conductivity (EC) and pH values are similarly low in peat and HTC and are slightly increased in biochar [25].

Biochars contain various amounts of different micronutrients in addition to P and K. These nutrients are usually slowly available to plants much like slow release fertilizers, rather than being immediately available [65]. However, there are some problems that need to addressed. For instance, biochar usually contains about 1% nitrogen (N). A high N-immobilization occurs in hydrochar as well. This, and the presence of some phytotoxic substances, were the factors that lead to reduced growth of potted basil, even in mixtures of only 30% by volume [111]. After composting, N-immobilization was reduced and phytotoxic substances degraded within a few weeks [111]. However, as mentioned before, low carbon efficiency, high volume reduction, and time needed for composting make this process not particularly economically attractive. Therefore, apart from feedstock choice, carbonization processes seem to be important for future research.

2.2.5. Other Organic Materials as Bioresources and Growing Media Constituents

Apart from materials analyzed above, several more novel materials and bioresources are used at a small scale and/or have the potential to be used as growing media constituents. These include untransformed waste stream materials, which are affordable and available in certain areas. Waste materials can include, e.g., rice hulls [112–114], almond shell waste [115–117], hazelnut husks [118–120], and paper waste [121]. The main disadvantage of using these materials in commercial soilless media is that they are not produced specifically for horticultural applications; they can therefore be highly inconsistent. As such, they are almost always used in conjunction with more traditional materials [24].

Furthermore, peat moss (*Sphagnum*) from paludiculture has recently been used as a sustainable high-quality alternative to fossil white peat, i.e., as a raw material for plant substrates. *Sphagnum* farming refers to the cultivation of *Sphagnum* mosses to produce *Sphagnum* biomass sustainably [122].

Moreover, *Sphagnum* farming is a feasible large-scale, climate-friendly, and sustainable land use option for abandoned cutover bogs and degraded bog grassland [123]. It reduces human pressure on the remaining natural peatlands in surroundings areas [122].

In areas where forestry activity is minimal, but arable farmland is abundant, the development of soilless growing media from crops normally used as biofuels has been investigated [24]. *Miscanthus* is one such fast-growing crop. *Miscanthus* is a renewable raw material and a low-input crop that can be locally produced, providing ecosystem services, such as CO_2 mitigation and biodiversity [124]. Moreover, switchgrass (*Panicum virgatum* L.) [125,126], giant reed (*Arundo donax* L.) [127], reed canary grass (*Phalaris arundinacea* L.) straw [128], and willow (*Salix* spp.) [126] have been used in plant production alone or in mixtures with other materials.

2.3. Growing Medium Choice

The question as to which is the best growing medium does not have a single answer. This will depend on the location, the availability and cost of potential growing medium constituents, and the crop production system envisaged.

The materials for growing media have to fulfil different requirements: First, they should be available consistently from batch to batch and economically feasible, i.e., the materials and the production process should not be very expensive. Second, the physical, chemical, and biological properties of the growing medium should meet the biological plant requirement. However, there is no universal substrate or mixture that is valid for all plant species and in all situations of cultivation [11,14,23]. Gruda et al. [14], Barrett et al. [24], Savvas, and Gruda [16] also speak for the performance of growing media. Here, they included not only substrate properties, but also the ability to perform well in real growing conditions.

Third, the material used for production and growing media itself should be sustainable and environmentally friendly. Carbon footprint analyses show that the largest share of emissions from heated greenhouse farms results from energy consumption, followed by substrate, packing, and containers used [129]. The biodiversity concern and climate change emphasize the significance of peat bogs as carbon sinks. Generally, avoiding or reducing the use of peat as a growing media constituent, can substantially reduce the carbon footprint in horticulture [23,130]. Apart from extraction, processing, manufacturing, and transportation are important business factors to distinguish between materials from specific sources [131]. Therefore, the authors suggested a list of eight criteria that reflect current, and potentially future, social and environmental issues in relation to the use of growing media. These include the energy and water used in previously mentioned business factors, the social compliance, ensuring minimum labor standards, continuity of supply, habitat and biodiversity, pollution, renewability, and resource use efficiency. In order to guarantee a continued growth and sustainable development of soilless cultivation, it is important to identify effective and environmentally sustainable materials for growing media [24].

Selecting growing media is not an easy task because environmental issues and technical and financial implications must be considered [14,20]. The geographical location, the selection of plant cultivation and production types, the substrate cost and performance, as well as other societal concerns, govern which growing media has to be selected. In addition, the evidence indicates that growers and gardeners tend to favor the types of growing media they are accustomed to and know how to manage. Hence, inertia is also a barrier to change [132]. In the following, we identified two perspectives and functions that we found important to consider: Production systems and transportation distances.

2.3.1. Production Systems

2.3.1.1. Nursery Production

Peat-based growing media are mainly used for production of seedlings and transplants for vegetables and ornamental plants. Nowadays, efforts in the substrate industry are made toward peat reduction in the entirety of the components, used for growing media. Even 10% wood fiber mixed in pure black peat would significantly reduce the carbon footprint for lamb's lettuce, grown in 4 cm press pots [133]. Higher percentages of wood fiber can result in additional emission reductions. For instance, Gruda and Schnitzler [107] reported that, from a performance point of view, the optimal percentage of wood fiber for the prevention of considerable degradation of press pots was approximately 30% in volume. Similarly, biochars can be favorably used as an amendment to peat-based substrates for the development of sustainable greenhouse production [134]. The authors evaluated the effects of additional biochars at a rate of 15% (*v*/*v*) to a peat-based substrate and found that the biochar addition increased the C, decreased the N availability in fertigated peat-based growing media, and mitigated CO_2, CH_4, and N_2O emissions. To increase microbial activity, compost at a rate of 4% (*v*/*v*) was added. This reaction is similar to results reported for agricultural soils by an additional biochar application.

On the other hand, using the large definition of a plant nursery that includes the production of plants for gardens, agriculture, forestry and conservation biology, bark, and wood fiber substrates are the standards in nursery production. This sustainable way of production will remain steady in the near future.

2.3.1.2. Greenhouse Vegetable Production

Growing media have been used traditionally, mostly for plant propagation, bedding, and pot plant production, but this range of use has expanded to include the total production of many food crops, especially high-value crops grown under protection in greenhouses [14]. For instance, stand-alone substrates, such as rockwool and perlite are used for the commercial soilless production of vegetables [15,16].

The use of polythene-wrapped rockwool, originally produced as insulation in the construction industry, aided by its lightweight and ease of handling, has become the dominant soilless culture system for greenhouse vegetables worldwide and especially in Europe [10]. The advantages of rockwool are substrate uniformity, ease of handling, and ease plant production steering.

Materials which can be pressed in slabs, such as coir, can be successfully used instead of rockwool. The water-buffering capacity is lower in coir dust than in rockwool and peat, and the level of air space varies considerably depend on the origin of the material [97]. Hence, mixing different particle sizes and ratios together or adding other materials is recommended to meet crop-specific moisture and aeration requirements in order to use coir products as stand-alone substrates. For instance, adding perlite to coir improved the physical and hydraulic characteristics of the media, such as total porosity and wettability, by manipulating the porosity and capillarity [135]. However, while coir products can make excellent growing media, the long transportation distance makes this alternative less attractive for many areas, such as Northern Europe and North America (see Section 2.3.2. for more information).

White spruce and fir bark alone or mixed with low-grade peat showed high potential for greenhouse tomato production and represented an environmentally sound alternative to rockwool [136]. Moreover, pine bark can be successfully used as a stand-alone substrate for the cultivation of vegetables, such as bell pepper, cucumbers, and muskmelons [137–139]. An economic analysis determined that pine bark was nearly one-eighth the cost of perlite and could be reused for several consecutive crops, resulting in reduced production costs and greater profits. However, bark could become a limited resource due to the changing timber industry and the fact that it is an effective energy source [140], increasingly used as fuel.

Wood chips and fibers are also gaining traction as an alternative to rockwool for slab culture [141]. Depardieu et al. [142], stated that sawdust- and bark-based materials can be used for strawberry soilless culture production, as long as an initial basic fertilization is applied to avoid the initial tie up. Additional N fertilization from the beginning of plant cultivation is recommended to overcome N immobilization in wood fiber substrates [143].

Recently, Kraska et al. [124] found that cucumbers and tomatoes grown on different stand-alone Miscanthus substrates, such as shreds, chips, and fibers, obtained comparable cumulative yields to rockwool. Generally, by using rockwool alternative substrates, the plant cultivation technology has to be adapted to the growing medium's properties [7].

2.3.1.3. Greenhouse Ornamental Production

The standard substrate component used for the production of greenhouse ornamentals is peat moss. Several stand-alone substrates, such as perlite and volcanic lava are used to produce cut ornamentals. If SCS, such as ebb-and-flow bunches or floors, are applied, pot ornamentals could also be cultivated in alternative peat substrates. Other materials, such as bark, wood fibers etc., can be used up to 100% to produce plants. Since nutrient solution is used to supply the plants, the substrate function is vital to keep and support the plants.

However, depending on the crops and technologies used, the portion of usage of growing media constituents other than peat in pot ornamentals varies between 20–50%. Apart from porosity that is much higher in growing media, an important difference between soil and substrate culture is the limited volume of plant roots in a container. This provides a reduced root system for a comparable and sometimes much higher developed aerial part. According to Savvas and Gruda [16], the particle size of the growing media used and the container geometry have to be properly selected to balance water availability and aeration in the root zone. In addition, an adaptation in cultivation methods, mainly in irrigation systems, is required. Furthermore, investing in SCS demands excellent water quality, drainage water collection systems, and an increase in laborers' skills. A soilless crop is much more sensitive to mistakes as there is hardly any buffer [59].

Bark is used as stand-alone substrate in the production of orchids and as a growing media constituent in pot ornamentals, whereas wood fiber substrates are becoming more and more popular in ornamental plant production. Wood chips and sawdust are usually used in the proportion of 20−30% (volume basis) in mixtures with other substrate components. A reduction in particle size, an increase in volume weight, and an increase in the irrigation frequency is recommended [99,100,106]. Furthermore, clay is added, to increase the water holding capacity and nutrient buffer ability of potting mixes.

Álvarez et al. [144] showed that it is possible to grow container plants of geranium (*Pelargonium peltatum* (L.) L'Hér. ex Aiton) and petunia (*Petunia x hybrida* hort. ex E. Vilm.) using a peat-based substrate mixed with biochar and/or vermicompost. Plants in these substrates showed a similar or enhanced physiological response to those grown under control using a commercial peat-based substrate. When compost is used, perlite may be utilized as a growing medium constituent to increase the drainage and air content of the growing media mix.

Several studies reported that biochar in potting media results in the same ornamental plant growth as in peat-based standard substrates [65,145,146]. According to Kern et al. [25], char materials must not necessarily remain on the level of a minor ingredient, but have the potential to be used as major constituents. Furthermore, since they are characterized by a high porosity and a high water-holding capacity, these materials may also be usable as a substitute for constituents, which are already established in the growing media market, but which have a limited supply [25,147,148]. For instance, rice hull-derived biochar would be a practically applicable amendment to improve the properties of growing media, in terms of an increased cation exchange capacity and water content [149]. The typically high porosity and surface area of biochars promote the retention of water and the sorption of nutrients [25].

Non-decomposed *Sphagnum* has been used with great success in the cultivation of orchids as well as together with peat substrates for the cultivation of *Tagetes patula* L. [150]. These results were confirmed by investigations with *Pelargonium* and *Petunia* [151]. Adding *Sphagnum* fibers to peat increased water retention and hydraulic conductivity, but either reduced or had no impact on air-filled porosity. Moreover, the quality of brown peat can be improved by adding a minimum of 30% *Sphagnum* fibers to sieved peat. Therefore, Jobin et al. [151] stated that *Sphagnum* biomass production will most likely continue to develop, offering the growing mix industry an alternative material with a low carbon footprint and a better use of peatlands.

However, the chosen substrate has to be stable enough and possess a good bulk density within the entire cultivation period and after the sale to the end-consumer. For bed, balcony, bowl, and hanging basket plants, the irrigation management of the end-consumer is a challenge. Since the end-consumers are usually inexperienced, mistakes occur. Any incorrectness is frustrating and associated with product rejection. End-consumers think that they do not possess the "green fingers" and this in turn creates a great loss for horticulture, not only from the profit side.

2.3.2. Transportation Distances

The second perspective is a function of growing media use from distances from sources of primary raw materials to growers. Due to transportation ways, the cost of a growing medium is also a function of location. For instance, in peat-rich regions, such as Northern Europe and Canada, where the transportation distances are relatively short, peat may still be an economical option. Similar to peat, coconut coir is produced in specific locations (mainly South-East Asia) and, if not used locally, has to be transported to growers in other parts of the world, with unavoidable costs [9,23]. This is the reason why regional substrates, such as volcanic lava and pumice are and will certainly remain important in the South of Europe in the future. However, location is not only important from an economical point of view, but also from a sustainability perspective, due to the high CO_2 footprint. Therefore, compost, together with biochar and hydrochar, has good chances, since usually they are locally produced. Materials, whether sourced from industrial, agricultural, or municipal waste are being investigated as soilless substrate components [24]. A particular trend has been the use of renewable raw materials locally sourced, natural in occurrence and fast-growing, in particular in industrialized countries [16,30].

2.4. Disposal Concerns and Waste Management

The disposal issue is one of the biggest concerns of using soilless culture and growing media. The question is, what can be done with several fertilizer leachates and water waste during the cultivation period as well as the growing media after its end-of-life?

The generally accepted waste management hierarchy includes the three Rs: Reduce, reuse, and recycle [152]. Reducing the amount of growing medium per plant contributes to reducing CO_2 emissions in the production chain of plants [7].

In the seedling and transplant industry there has recently been a trend among producers towards more cells per tray, which decreases the need for growing medium and increases the number of seedlings or transplants produced per unit area [153]. However, the reduction of growing media amount is not always a viable option, due to a direct influence on yield and product quality parameters [9,13]. For instance, Gruda and Schnitzler [153] reported that a reduction of the pot size decreased the quality of the lettuce seedlings. However, no differences were found in the lettuce yield after transplanting to the field and this is of much importance. Certainly, culture methods, such as irrigation and a good root development of seedlings in wood fiber substrates, have been responsible for these results [153].

On the other hand, using SCS means using a reliabe and precise dosage of both fertilizer and water, and this is one of the advantages of using closed systems, at least theoretically. However, in practice, soilless culture vegetables are usually over-fertilized, and an excessive synthetic N fertilizer is applied to ensure that no nutrient deficiency occurs. Indeed, as Truffault et al. [154] reported, over-fertilized tomatoes provided an accumulation of N in leaves and stems. However, yield, leaf photosynthetic activity, and plant architecture were not significantly improved. In addition, the quality of tomato fruits decreased in terms of their sugar:acid ratio and dramatically decreased in the pericarp, whereas the locular gel composition remained similar [154]. Therefore, the reduction of fertilizer used, first and foremost the N fertilizer, is the first appropriate and sustainable step that should be undertaken. The impacts are not only related to the use of fertilizers itself but also to the amount of energy, materials, and transport processes involved in the production of fertilizers [155] and manufacturing facilities. As Gruda et al. [7,8] reported, the fertilizer reduction is directly linked with a reduction of N-emissions (N_2O, NH_3, and NO_x) that, in turn, have an enormous effect on GHGs.

One way to address the runoff nutrient wastewater pollution in open-loop hydroponic systems is the reuse of drained nutrient solutions to a second greenhouse crop. This system is called the "cascade cropping system" [156,157]. Muñoz et al. [157] reported that the N leachate from a soilless tomato system decreased by more than 60% when the nutrient solution was used in a tomato soil system. Moreover, intense and year-round crop production, high N-fertilizer application, suitable temperatures, and frequent irrigation make the greenhouse system an ideal environment for high N-emissions that are considered to be extremely damaging to the ozone layer [7]. The adoption of the cascade crop system reduced the environmental impact by 21%, but increased the eutrophication category by 10% because of the yield reduction [157]. Similarly, cherry tomatoes may be grown with an exhausted nutrient solution that is flushed out from a culture of a salt-sensitive tomato cultivar in semi-closed soilless systems [156]. Several other studies stated that nutrient solution discharged from hydroponic culturing systems can be reused for the production of several vegetables in indoor or outdoor conditions, such as Chinese cabbage [158], melon, and cucumber [159]. These results are in agreement with the growth promotion of poinsettias (*Euphorbia pulcherrima* Willd. ex Klotzsch) after reusing the waste nutrient solution from rose hydroponic cultures [160].

Growing media can be reused as well. Reuse is the best approach in terms of its environmental impact and the results of LCA [9]. For instance, multiple cucumber cycles can be produced on the same growing media in soilless or substrate culture systems, whereas a reuse of substrates in containers systems is generally not common. However, reusing could be associated with distributions of pathogen infections and the possible deterioration of substrate properties. Therefore, in accordance with the Directive EU2018/851 of the European Parliament and of The Council, "waste management in the European Union should be improved and transformed into sustainable material management, with a view to protecting, preserving, and improving the quality of the environment, protecting human health, ensuring prudent, efficient, and rational utilization of natural resources, promoting the principles of the circular economy ... " [161]. The directive further regulates how to reuse and prepare for reuse and recycling, in line with the waste hierarchy. With regards to growing media, the reuse of substrates may induce a higher compaction with increased volume weight (bulk density) and reduction of porosity, due to shrinkage [9,162], with a limited air and low water buffer capacity [101] accompanied by failures and a bottleneck situation of nutrients [163]. On the other hand, the gradual accumulation of nutrients in organic substrates during growing season may have adverse effects on plant development [148], and these effects are further increased by a substrate reuse. Xing et al. [164] identified a total of 358 differentially abundant proteins, including 11 mineral ion binding and transport related proteins, such as a calmodulin-like protein and a nitrate transporter 3.2 under peat-vermiculite and coir tomato cultivation. Xing et al. [164] suggested that these indicators could contribute to a better control of SCS and a waste reduction.

The investigations of crop response to the cultivation in reused growing media compared to virgin substrates show contradictory results: (a) Reduction of crop yield and/or produce quality in reused media, (b) minimal differences between virgin and reused substrates, or (c) even better results in reused materials [165]. Similar to virgin growing media, the reused materials have to possess good physical, chemical, and biological properties. Therefore, generally, some remediation steps are recommended to amend the substrate properties before reusing [9].

First, growing media should be free from any infection with pests and diseases, otherwise a disinfection process has to be undertaken. For instance, cleaning and disinfecting perlite with hot water at a temperature of 96 °C before reuse produced a better marketable tomato yield in comparison to a virgin one, due to the collective effect of salt reduction, medium disinfection, and the optimum level of nutrients [166]. Second, the nutrient level of growing media should be analyzed and eventually adjusted according to crop demands. This step is very important when a nutrient solution is not used in the second crop. Third, physical properties have to be amended by breaking up and sifting growing media as well as by removing older roots [165].

Further, organic substrates with high microbial activities, such as compost, are often added to used peat substrates, because of their suppressive properties against soilborne diseases, such as *Pythium*. In addition, an artificial inoculation with selected microorganisms or the introduction of microbial antagonists, preliminarily isolated from suppressive soils and/or used soilless media, could be used to increase the suppressive properties against root rot diseases [165,167]

Recycling is the final approach in the waste management hierarchy. To recycle something means that it will be transformed again into raw material, which can be shaped into a new item [152] for second or multiple life uses. Until recently, growing media were always the last step of the value chain, and usually it was all about how to dispose of them without further negative impact on the environment and climate. Composting offers a good option to drastically reduce this impact, as shown in Section 2.2.1. Organic substrates can be used immediately or after their composting as soil amendments. This method is highly evaluated in arid and semi-arid areas, increasing not only organic matter in soil but also improving water holding capacity. In addition, composted materials can be used to cultivate less-demanding crops, such as forest tree saplings [9]. Moreover, Kraska et al. [124] opted for a cascade way of recycling and found a subsequent use of *Miscanthus*-based growing medium for combustion feasible, after the production of cucumbers and tomatoes on different stand-alone *Miscanthus* substrates. As mentioned before, *Miscanthus* is a renewable raw material and a low-input crop that can be locally produced.

2.5. Other Factors Having an Impact on Sustainability

In temperate regions, controlled environment systems are characterized by large amounts of energy consumption for heating during the cold season. Large energy consumption is the greatest environmental concern [7,8]. As Eigenbrod and Gruda [3] stated, the motto for future plant production should not be "local at any price," but "as sustainable as possible." Therefore, Gruda et al. [7,8] recommend the implementation of so-called next generation culture methods: Better insulation thanks to double cladding and triple screens, following biological and nature-oriented culture techniques, dehumidifying the blown-in air, and, if necessary, humidifying (rewetting) and "harvesting" greenhouse existing heat amounts. In addition, the use of alternative energy sources can fundamentally increase and improve the sustainability of protected cultivation systems and nursery production. Replacing or recycling rockwool and plastic items are other important factors [7,8].

Plastic containers, pots, bags, and trays have been the predominant containers in greenhouse and nursery production. However, most plastics are derived from petroleum—a nonrenewable resource [168]. Therefore, different examples of alternative containers made from plantable and compostable materials, such as bamboo, coconut or wood pulp fiber, rice hulls, and recycled paper have been developed. The use of these containers will furthermore contribute to sustainable systems along with suitable growing media.

Moreover, the lifetime of structure materials, e.g., plastic covers and auxiliary equipment, e.g., drippers, should be further extended and manufactured out of biodegradable material to reduce waste. Better management of the nutrient supply as well as the reduction of fertilizer use is required [7].

Another way to reduce the amount of peat (not only for SCS), used as soil improvements for acidophilic plants, is the breeding of new varieties that have neutral requirements related to pH in the root zone. In addition, the use of plant biostimulants, such as humic substances, protein hydrolysates, seaweed extracts, and beneficial microorganisms, such as mycorrhizal fungi and nitrogen fixation bacteria [37,167,169], can contribute to improve effectiveness and interaction in the root zone of plants into growing media.

3. Conclusions

In conclusion, soilless culture is one of the best techniques to overcome local water shortages, while also producing high quality produce, even in areas with poor soil structure and problematic conditions. Reduce, reuse, and recycle issues should be more frequently applied in SCS. The application of these systems is likely to increase close to existing cities as well as in mega-cities worldwide in the near future.

In this paper, we reviewed different organic materials and bioresources used or intended to be used as growing media constituents in the future. All of these have their respective advantages and disadvantages. Different areas in the world, with different conditions and requirements, require different crops, different distances to sources of primary raw materials used as growing media components, and different technologies used to produce plants.

However, factors such as climate change, CO_2 emissions, and other ecological issues will determine and drive the adoption and influence of growing media in the near future. Materials that are easily available, financially feasible, environmentally friendly, and that can provide a high-quality growing medium will become replacements for rockwool and peat in the future.

Further research on the innovative approaches in SCS and materials used as growing media components is required.

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