Biochar Amendment in Green Roof Substrate: A Comprehensive Review of the Benefits, Performance, and Challenges

applied sciences

MDPI

Review

Biochar Amendment in Green Roof Substrate: A Comprehensive Review of the Benefits, Performance, and Challenges

Cuong Ngoc Nguyen [1], Hing-Wah Chau [1,2], Apurv Kumar [3], Ayon Chakraborty [3] and Nitin Muttil [1,*]

[1] Institute for Sustainable Industries & Liveable Cities, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia; ngoc.nguyen178@live.vu.edu.au (C.N.N.); hing-wah.chau@vu.edu.au (H.-W.C.)
[2] College of Engineering and Science, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia
[3] Institute of Innovation, Science and Sustainability, Federation University, Mt Helen, VIC 3353, Australia; apurv.kumar@federation.edu.au (A.K.); a.chakraborty@federation.edu.au (A.C.)
* Correspondence: nitin.muttil@vu.edu.au

Featured Application: Biochar, a carbon-rich material derived from organic matter through pyrolysis, enhances substrate quality by increasing water retention and nutrient availability, leading to healthier plant growth and increased biodiversity. It also plays a significant role in carbon sequestration, capturing and storing carbon that would otherwise be released into the atmosphere, thus contributing to climate change mitigation efforts.

Abstract: Green roofs (GRs) are a well-established green infrastructure (GI) strategy that have been extensively studied for decades to address a growing array of social and environmental challenges. Research efforts have been continuously made to contribute to the awareness of benefits of GRs and towards their widespread application. The substrate, which is one of the crucial layers of a GR system, plays a major role in the serviceability of GRs. Thus, several studies have been undertaken to alter the substrate characteristics by applying innovative substrate additives. Biochar, a carbon-rich material with a highly porous structure and large specific surface area, has been found advantageous in several areas such as agriculture, water filtration, environmental remediation, construction, and so on. However, the application of biochar in GRs has been insufficiently studied, partially because biochar amendment in GRs is a relatively recent innovation. Furthermore, a comprehensive review of the performance of biochar-amended GR substrates is lacking. This review paper aims to summarize the past performance of GRs enhanced with biochar by considering the various benefits that biochar offers. The results indicate that most of the reviewed studies observed increased retention of runoff and nutrients when utilizing biochar. Additionally, the capabilities of biochar in improving thermal insulation, plant performance, and microbial diversity, as well as its effectiveness in sequestrating carbon and controlling soil erosion, were mostly agreed upon. Notwithstanding, a definitive conclusion cannot yet be confidently made due to the limited research information from biochar–GR systems and the uneven research focus observed in the studies reviewed. The influence of biochar-related variables (including amendment rates, application methods, processed forms, and particle size) on the effectiveness of biochar was also discussed. Opportunities for future research were suggested to fill the research gaps and address challenges restricting the application of biochar in GRs. Detailed information from past research findings could serve as a foundation for further investigations into the large-scale implementation of biochar in GRs.

Keywords: biochar; green roof; review paper; soil additive; WSUD; green infrastructure

Citation: Nguyen, C.N.; Chau, H.-W.; Kumar, A.; Chakraborty, A.; Muttil, N. Biochar Amendment in Green Roof Substrate: A Comprehensive Review of the Benefits, Performance, and Challenges. *Appl. Sci.* **2024**, *14*, 7421. https://doi.org/10.3390/app14167421

Academic Editor: Mohamed M. Chehimi

Received: 14 July 2024
Revised: 19 August 2024
Accepted: 21 August 2024
Published: 22 August 2024

1. Introduction

Green roofs (GRs) are a well-established green infrastructure (GI) strategy to effectively tackle numerous social and environmental challenges caused by rapid urbanization and climate change. GRs have garnered significant attention from researchers and have been studied for decades. The ecosystem services offered by GRs include runoff retention; enhancement of runoff water quality; urban heat island effect reduction; lowered building energy costs; improved air quality; and various other economic, social, and environmental benefits [1,2]. Despite its huge potential, GR remains restricted in its widespread application due to several reasons. While a considerable number of GR studies have been undertaken by using various approaches, there are still inconsistent findings and research gaps that necessitate further investigation [3]. For instance, Vijayaraghavan and Raja [4] and Gong, et al. [5] observed positive results in GR runoff quality, while contrasting findings were found in the studies of Beecham and Razzaghmanesh [6] and Ferrans, et al. [7]. Besides runoff quality, the performance of GRs in temperature and runoff reduction has also been reported inconsistently. The reduction in runoff volume by GRs was less significant in regions with high annual precipitation, with only an 11.9% reduction observed in a humid subtropical climate [8] and 11% under 3110 mm of rainfall per year in the city of Bergen, Norway [9]. In addition, the benefits of GRs related to temperature and energy savings are also highly dependent on climatic conditions. Exceptional performance of GRs was observed in a hot climate in the city of Shanghai, China [10–12]. In contrast, GRs did not reduce energy consumption for cooling in several Mexican cities, where they actually led to increased energy use for heating [13]. Additionally, challenges in installing GRs such as high investment costs and added structural loads on existing buildings that were not initially designed for GR systems pose significant barriers [14,15]. Therefore, further research is essential to fully understand the benefits of GRs and thus facilitate their widespread adoption.

There are an increasing number of studies that have employed modeling software to further understand the effectiveness and benefits of GRs [16–19]. Furthermore, new technologies such as hybrid GR systems and innovative substrate materials have also been applied to enhance the multiple benefits of GR. For instance, GRs have been integrated with photovoltaic (PV) systems, resulting in enhanced thermal benefits for buildings and increased electricity production due to the cooling effect of GRs on PV panels [20–22]. The effectiveness of GRs in temperature reduction was also improved by integrating them with a radiant cooling system [23–25]. Additionally, an improved GR system called "Blue-green roof", which features a large water storage layer, has significantly reduced runoff [26–28]. Furthermore, new GR materials have also been utilized to enhance the effectiveness of GR systems. For instance, Carpenter, et al. [29] obtained an impressive average runoff retention rate of 96.8%, surpassing commonly reported values, due to the use of an effective drainage layer. Another innovative material, "biochar" has emerged as a promising solution to enhance GR benefits by modifying the characteristics of GR substrates. The term "biochar" refers to a carbon-rich material that is manufactured by burning biomass in an oxygen-deficient environment [30]. Biochar has garnered significant attention from researchers due to its positive effects on soil structure, along with its physiochemical properties such as high porosity and large surface area, which enable biochar to enhance soil water-holding capacity, nutrient retention, soil fertility, plant performance, and carbon sequestration, among other benefits [31].

Figure 1 illustrates an increasing trend in the number of studies on both biochar and biochar-based GRs from 2011 to 2023, based on data from the Scopus database. Notably, there has been a significant surge in research interest in biochar in recent years, especially from 2018 onwards. Moreover, Figure 1 also highlights that there has been relatively limited research on biochar in GRs compared to its application in other research areas. A Scopus-based search using different keywords further highlights the limitation of biochar–GR studies, as shown in Figure 2. Among 6200 search results for GRs, only 75 studies were found relevant to biochar. While biochar has been extensively studied with approximately 35,000 studies, research attempts specifically focused on biochar-amended GRs have been relatively limited. Although there is growing information on how biochar affects GR functions, there is a lack of comprehensive reviews on the performance of biochar-amended GRs. The Scopus database identified only five review papers. Four of them focus on green infrastructure and geotechnical engineering structures rather than specifically on GRs [30,32–34]. The study by Lee and Kwon [35] is the only review that focusses exclusively on examining the application of biochar in GRs. Although this review aimed to provide an overview of the impacts of biochar on GRs, it lacks an in-depth investigation and discussion on specific categories of benefits that biochar amendment brings to GRs. It also does not thoroughly address various barriers and limitations of biochar amendment in GRs. Therefore, this review aims to comprehensively quantify and qualify the performance of previous studies and application of biochar amendment in GR systems across various benefit categories. It also seeks to identify research opportunities by highlighting gaps in the current understanding of the benefits provided by GR–biochar systems. Additionally, the review thoroughly examines barriers to biochar amendment in GRs, including environmental concerns, economic challenges, and policy-related hurdles. By doing so, the review can accurately highlight limitations and offer recommendations for future research. Furthermore, it provides directions for future studies by identifying optimal biochar-based variables, such as biochar application methods, amendment rates, and particle sizes. Despite the limited research available, the significant potential of biochar highlighted by preliminary studies could attract the interest of researchers and garner attention from authorities and the community, thereby promoting the recognition and adoption of biochar in GRs. Moreover, detailed information from past research findings could work as a foundation for further investigation of biochar in GRs. The selection of papers for this review was based on the following criteria: (1) the presence of numerical or quantifiable results that were reported, (2) inclusion of primary GR performance parameters such as runoff retention rate, temperature reduction, and concentrations of total phosphorus (TP) and TN, and (3) publications within the period from 2010 to the present. The reviewed papers were sourced from the Scopus, ResearchGate, and Google Scholar databases. Figure 3 presents a flow chart illustrating the reviewing methodology adopted in this research.

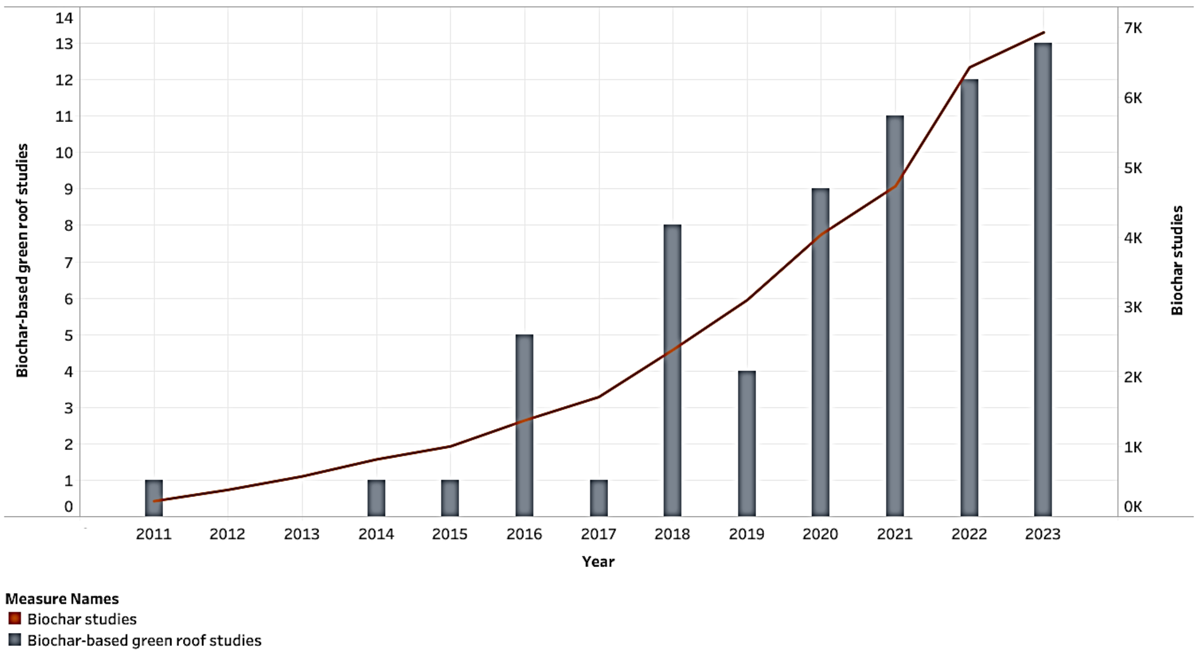

Figure 1. The number of studies on biochar-amended green roofs and biochar recorded in the Scopus database by year of publication from 2011 to 2023.

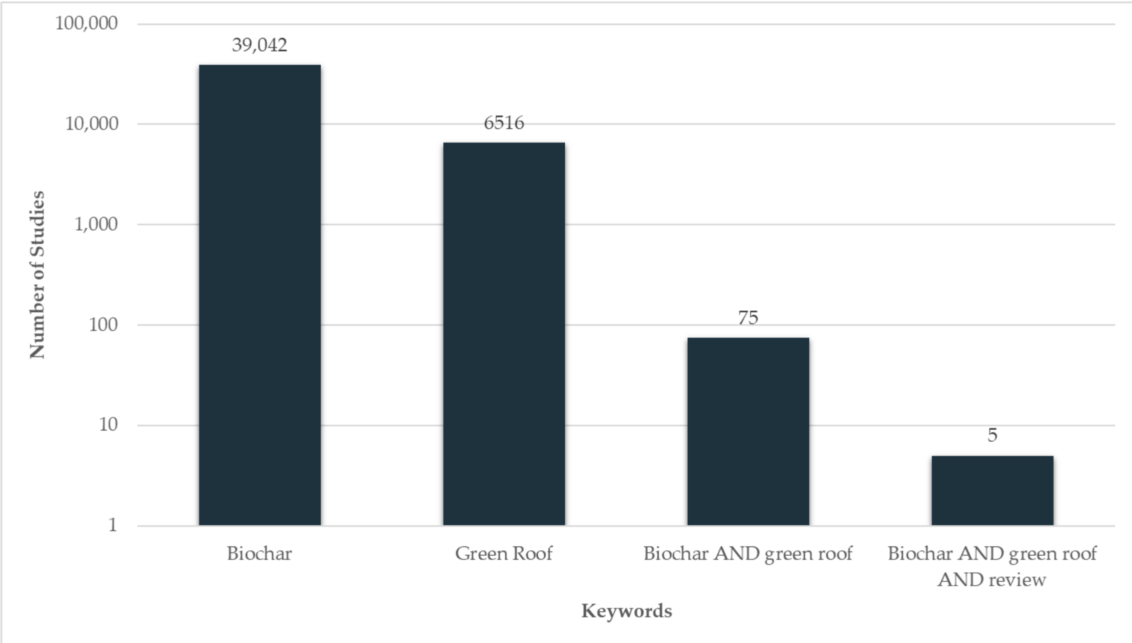

Figure 2. The number of studies on green roofs and biochar using different search keywords in the Scopus database.

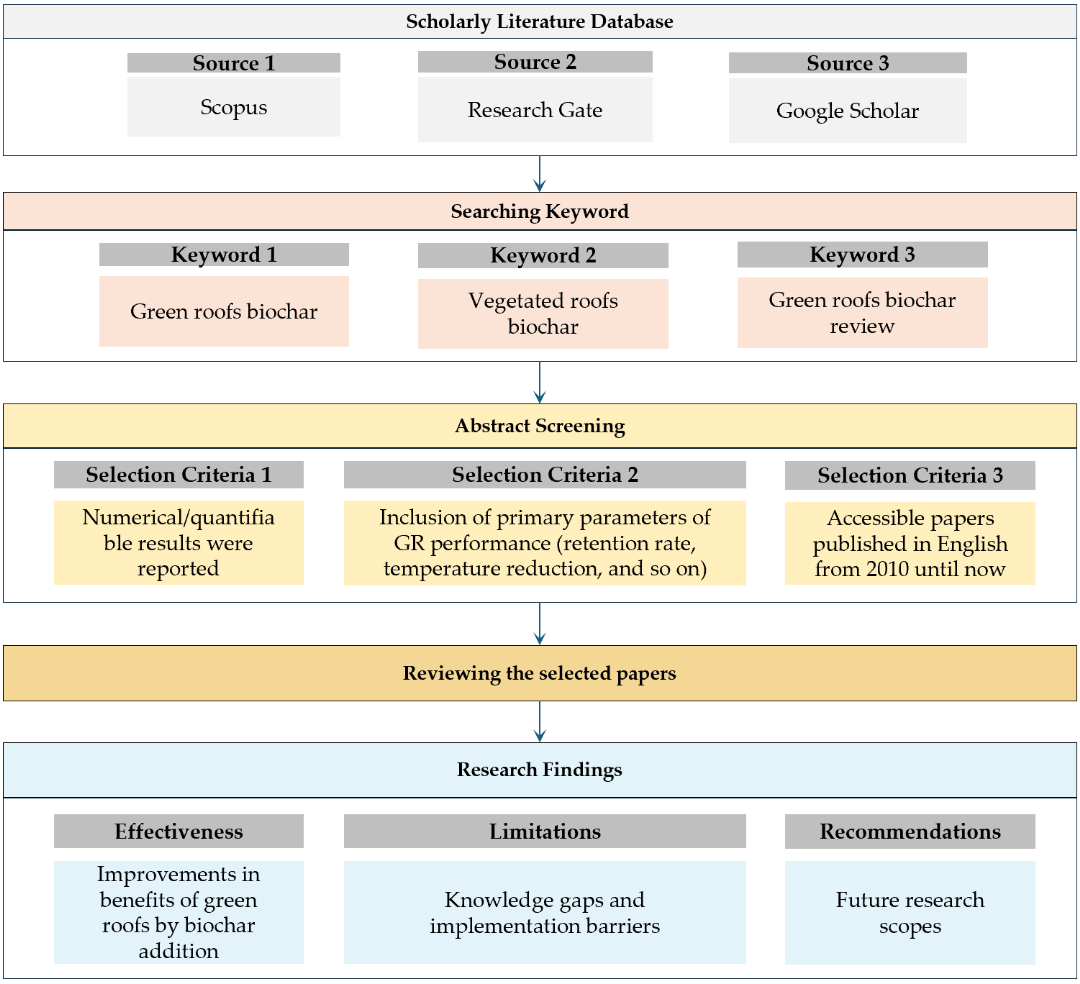

Figure 3. A flow chart depicting the reviewing methodology used in this research.

2. Biochar—Preparation and Unique Physiochemical Characteristics

Biomass is converted into biochar through the carbonization processes consisting of pyrolysis, gasification, and hydrothermal carbonization [31]. Among them, the so-called "pyrolysis", a thermochemical process, is a common method to prepare biochar with temperatures ranging from 300 to 900 °C in an oxygen-deficient environment [36]. The pyrolysis process transforms biomass into a stable form of carbon that is unlikely to escape into the atmosphere [37]. Biochar is largely composed of fixed carbon (85%, organic C of biochar), but it may also contain oxygen, hydrogen, and ash (inorganic component of biochar), depending on the amount of ash present in the original biomass [38]. Pyrolysis is generally divided into three primary categories, namely fast pyrolysis, intermediate pyrolysis, and slow pyrolysis [39]. Compared to other methods, slow pyrolysis has been observed to generate the highest biochar yield [36,39]. Biochar is primarily produced from various organic wastes, including wood chips, wood pellets, tree bark, crop residues, and municipal solid waste [31,40].

The benefits that biochar offers are closely linked to its unique physiochemical characteristics including high porosity, large specific surface area, functional groups, and cation exchange capacity [31]. Among them, the surface area and porosity play an important role in improving water-holding capacity and adsorption capacity [41]. The hydration process during pyrolysis, which involves water loss and removal of volatile compounds from biomass, creates the porous structure of biochar [42]. The surface area of biochar has a strong relationship with its porosity, with micropores having the most significant impact. Feedstocks and pyrolysis conditions determine the physiochemical characteristics of biochar. For example, increasing the pyrolysis temperature produces biochar with a higher micropore volume, larger surface area, and greater carbon content for better adsorption of heavy metals and organic pollutants [36,43]. However, the biochar yield also decreases when increasing temperatures [39,44]. Furthermore, a number of harmful pollutants named "polycyclic aromatic hydrocarbons" (PAHs) are generated during the pyrolysis process. The leaching of these pollutants from biochar–GR systems into the discharge raises concerns regarding human health and the environment [45]. Biochar manufactured at high pyrolysis temperatures of 600–800 °C often has higher PAHs than the acceptable limit. Hence, pyrolysis at 500 °C is preferable with less negative impacts [46,47]. Regarding feedstock, Wang and Wang [31] recommended using feedstocks with low volatile contents to improve the biochar yield. Leng, et al. [48] carried out a comprehensive analysis of biochar feedstock and the pyrolysis temperature to achieve a high biochar porosity and large surface area. They concluded that wood and woody feedstock and an intermediate pyrolysis temperature (400–700 °C) provide optimal conditions for the development of a porous biochar structure [39]. In addition to the primary factors of feedstock and pyrolysis temperature, a thorough understanding of other variables such as reactor type, heating rate, residence time, and biochar modification treatments is necessary to achieve the desired biochar characteristics.

The ability of biochar to retain water is strongly linked to its highly porous structure [49]. The internal porosity of biochar functions as millions of tiny sponges, holding a substantial amount of water. Additionally, the high porosity and aeration resulting from biochar's large surface area (ranging from 800 to 5000 mm^2/g) indirectly enhance microbial diversity and survivability in soil [50]. Biochar can effectively reduce the leaching of organic molecules and nutrients because the functional groups on its surface enhance its cation and anion exchange capacities [51]. The primary surface functional groups of biochar include aromatic and heterocyclic carbon, which play an important role in determining the properties of biochar [52]. Consequently, biochar with a large surface area and high cation exchange capability enhances soil productivity and helps reduce groundwater contamination [53]. Due to the presence of alkali and alkaline-earth metals in biochar, soil pH is also increased, which is advantageous particularly for acidic soils [39]. An increase in soil pH affects the amounts of soluble essential nutrients and chemicals, thereby enabling the growth of plants and microbial communities [54,55]. Biochar itself also has nutrients whose availability depends on the feedstock and pyrolysis temperature, further contributing to the nutrient availability in the soil [50]. Figure 4 provides a summary of the practical applications of biochar in GRs. Figure 5 presents the mechanisms by which biochar alters the structure of GR substrates and improves its water-holding capacity. The aforementioned physiochemical parameters of biochar are crucial for determining its effectiveness in green roofs. Optimal parameters can be achieved by carefully selecting the raw biomass and adjusting the pyrolysis conditions, such as the temperature, residence time, and heating rate.

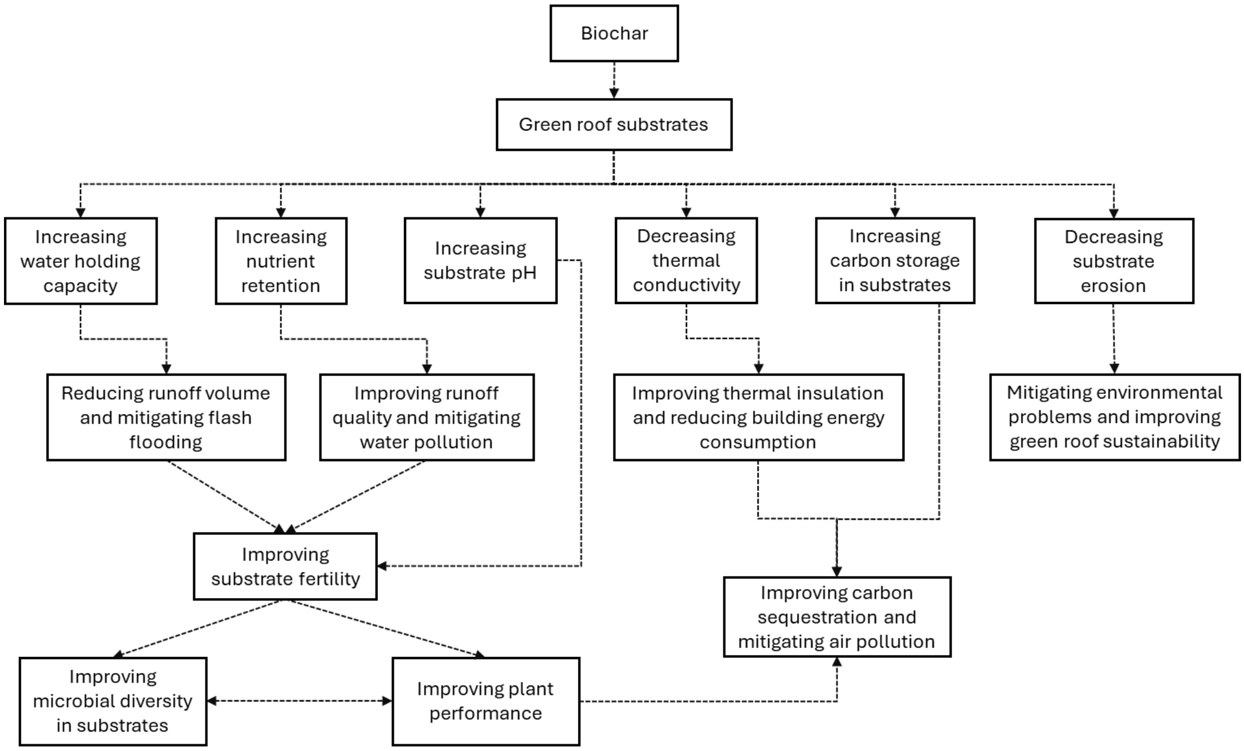

Figure 4. A flow chart illustrating the benefits of biochar in green roofs.

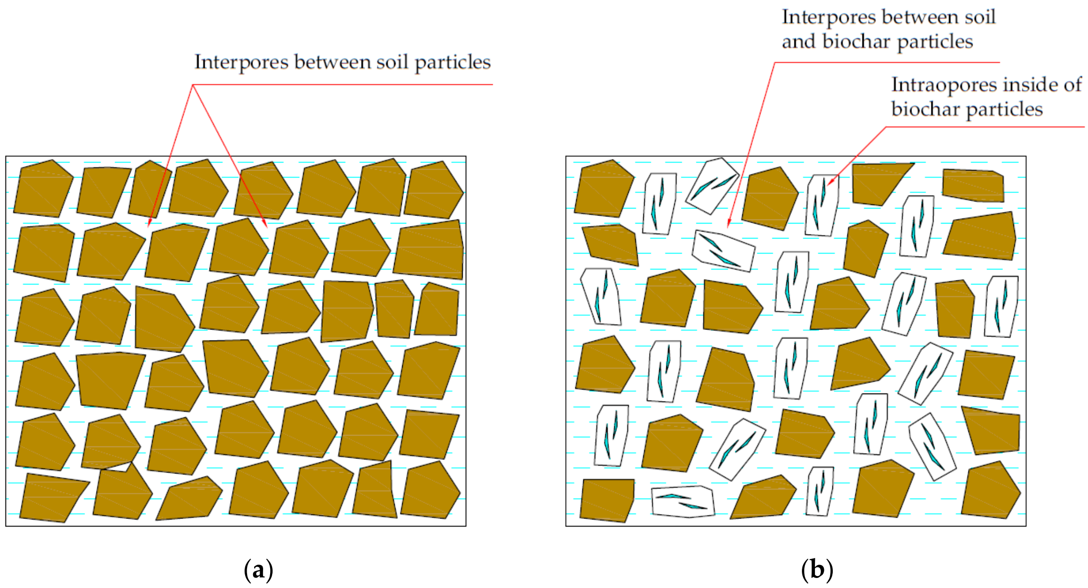

Figure 5. Mechanisms by which biochar increases soil porosity and improves water-holding capacity: (**a**) low-porosity soil structure without biochar, (**b**) high-porosity soil structure due to inter-pores between soil and biochar and intra-pores within biochar particles [56].

Comparisons were made in previous studies between the performance of biochar and other substrate additives. In the study by Kader, et al. [57], biochar surpassed other organic wastes such as sawdust, wood bark, coir, and compost in enhancing plant drought resistance and promoting vegetation growth. Novotný, et al. [58] evaluated the effects of different biochar and organic additives, including dried sewage sludge and compost containing sewage sludge, on runoff quality. Although all substrate additives demonstrated positive impacts, the addition of wood biochar resulted in the most significant benefit. Wang, et al. [59] investigated the performance of three different GR substrates including coconut-shell-based biochar, fiber, and biochar–fiber substrates. Biochar was observed to outperform fiber in different benefit categories such as soil thermal conductivity and water-holding capacity. However, the addition of both biochar and fiber was still suggested to enhance air entry, allowing fast drainage and mitigating crack propagation in substrates. It is also worth noting that the application of other substrate additives also led to improvements when compared to bare substrates. Although biochar offers many of the same advantages as other organic materials, it serves as a more durable substitute that lasts in the soil for many years, thus providing a long-term beneficial impact [60].

Biochar can be applied to the GR as either a top layer, middle layer, or bottom layer of the GR substrate, or it could be thoroughly mixed with the substrate. Figure 6 illustrates the structure of commonly used application methods of biochar in green roofs. Table 1 provides some noteworthy case studies of biochar-amended GRs involving single or multiple key benefits of biochar along with the application methods used in those case studies. This review has identified that thoroughly mixing biochar with other GR substrate components is the most commonly used biochar application method.

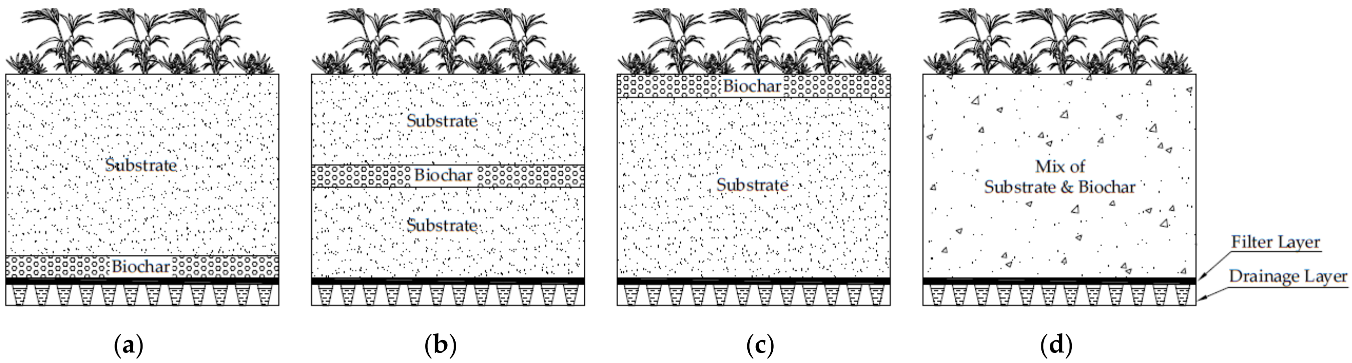

Figure 6. Commonly used biochar application methods in green roofs: (**a**) biochar at the bottom of the substrate, (**b**) biochar in the middle of the substrate, (**c**) biochar at the top of the substrate, and (**d**) biochar thoroughly mixed with the substrate.

Table 1. Case studies illustrating key benefits and application methods of biochar in green roofs.

Case Studies	Key Benefits of Biochar	Biochar Application Methods
[61]	Improved runoff quality, nutrient availability, and microbial community	Middle layer
[62]	Improved runoff retention	Middle layer
[63]	Improved runoff retention and plant performance	Top layer and mixing
[64]	Improved runoff retention and runoff quality	Top layer and bottom layer
[65]	Improved runoff retention	Top layer, mixing, and bottom layer
[66]	Improved soil erosion	Mixing
[67]	Improved carbon sequestration	Mixing
[68]	Improved air quality	Mixing
[69]	Improved temperature reduction	Mixing

3. Benefits of Biochar Amendment in Green Roofs

The benefits of biochar for GRs have not been studied uniformly, as depicted in Figure 7. As can be seen in the figure, runoff retention has received the most research attention. The impacts of biochar on runoff quality, plant performance, and microbial diversity have also been extensively studied. Although thermal reduction is one of the most studied benefits of GRs in general [3], it has not been adequately investigated in biochar-related research. An uneven research focus becomes apparent from the figure, especially when considering benefits such as thermal reduction, carbon sequestration, and soil erosion control. The following sections specifically describe the previous performance of biochar-amended GRs across different benefits of biochar.

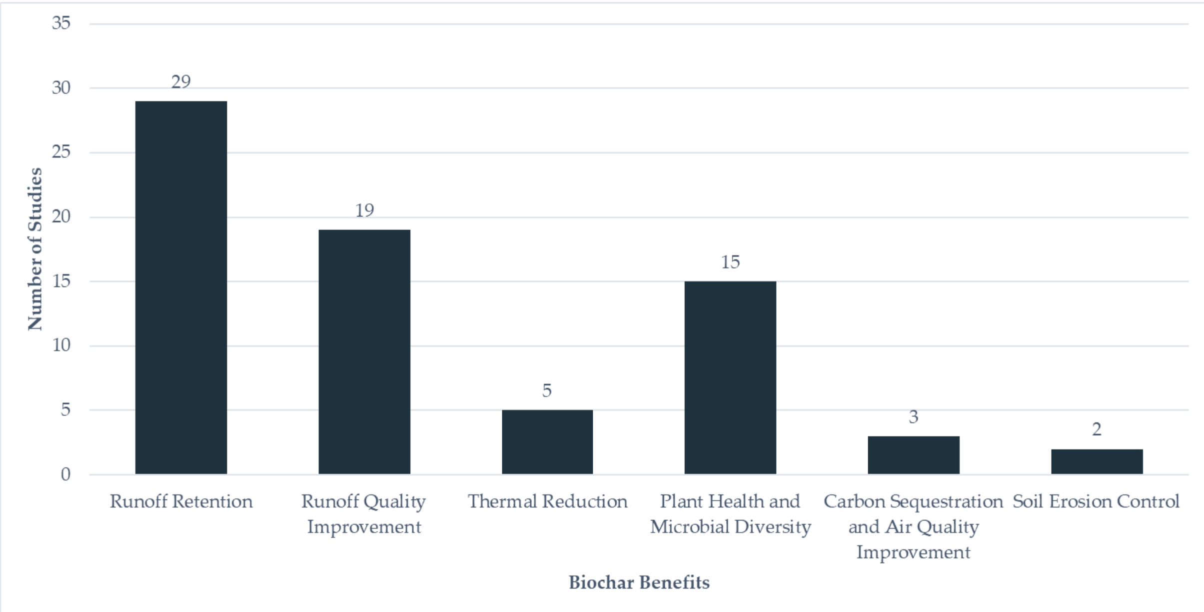

Figure 7. The number of studies examining the benefits of biochar in green roofs.

3.1. *Runoff Retention*

As mentioned earlier, the impact of biochar in increasing runoff retention has been extensively researched. The comparisons between conventional and biochar-based GRs in terms of runoff retention rates are summarized in Table 2. A variety of study approaches were adopted, consisting of soil column, pilot-scale, field-scale, and software modeling. Biochar used in GRs has been manufactured from a variety of feedstocks such as birch, cedar, coconut shells, mixed hardwoods, and urban green wastes. The pyrolysis temperature has ranged from around 400 °C to 750 °C. While the retention rates of GRs after biochar amendment have been reported from both unvegetated and vegetated substrates, the results in Table 2 were only extracted from the latter, to accurately reflect an actual GR system, which must be covered by plants.

Table 2. Water retention capacity of biochar-amended green roofs.

Reference	Approach	Substrate	Biochar Setup	Retention Rate without Biochar (%)	Retention Rate with Biochar (%)
[64]	Field-scale	Recycled, crushed brick, compost, crushed bark, and sphagnum moss	Buried biochar	70 (summer), 50 (autumn)	80 (summer), 64 (rainy autumn)
			Surface biochar		75 (summer), 50 (autumn)

Table 2. *Cont.*

Reference	Approach	Substrate	Biochar Setup	Retention Rate without Biochar (%)	Retention Rate with Biochar (%)
[65]	Pilot-scale	Light expanded clay aggregate, coir chips, and mulch	7.5% mixed—medium biochar	70 (summer), 50 (autumn)	21.95–53.05
			15% mixed—medium biochar		27.44–58.54
			7.5% buried—medium biochar		35.98–59.76
			7.5% mixed—fine biochar		24.39–68.29
			7.5% surface—fine biochar		36.59–67.48
[70]	Pilot-scale	Topsoil	NA	32.1	46.6
[71]	Pilot-scale	Gravel, sand, silt, clay, pumice, Fiber Life compost, and paper fiber	NA	Not saturated: 19.3–32.9	Not saturated: 29.6–32.5
				Saturated: 7.1–8.2	Saturated: 8.5–12.6
[72]	Pilot-scale	Peat, vermiculite, perlite, and sawdust	NA	72.54	72.08
[73]	Soil column	Natural clay soil	NA	45.5	69.3
[74]	Pilot-scale	Peat, vermiculite, perlite, and sawdust	NA	Substrate (5, 10, 15, and 20 mm): 47.1, 52.71, 56.99, and 62.64	Substrate (5, 10, 15, and 20 mm): 47.7, 53.99, 60.42, and 66.5
[75]	Software modeling	Scoria (≤8 mm), scoria (7 mm aggregate), and coir	40% *v*/*v*	Maximum 12% improvement annually	
[76]	Pilot-scale	Crushed, recycled brick, compost, peat, and crushed bark	NA	Maximum 10% improvement	
[77]	Field-scale	NA	2.5, 5, and 10% *w*/*w*	36.6	41.5, 39, and 37.8
[62]	Software modeling	Loam and expanded clay	3 cm and 5 cm depths of biochar	55.05–65.29	66.9 and 69.15
[78]	Pilot-scale	Heat-expanded clay	15% *v*/*v*	36% improvement	
[79]	Pilot-scale	Crushed clay, peat, and green compost	Pelleted wood (10 and 15 cm deep substrates)	25 and 30	33 and 45.5
		Pumice, lapillus, peat, and green compost	Flake wood (10 and 15 cm deep substrates)	38 and 45.5	41.5 and 47

As expected, biochar-amended GRs retained more water when compared to those without biochar. For example, Kuoppamäki, Hagner, Lehvävirta and Setälä [64] found that in summer, biochar applied either at the top (surface biochar) or at the bottom (buried biochar) of the GR substrate improved runoff retention by 5% and 10% (from 70% to 75% and 80%), respectively. The improvement was even more pronounced in autumn with more frequent rainfall, with 14% more retention in the case of buried biochar (from 50% to 64%), whereas surface biochar had no impact. In the study by Nguyen, Chau and Muttil [65], all biochar-amended GR test beds outperformed the conventional one in terms of runoff retention during nine artificial rainfall events. More specifically, test beds with fine biochar particles, either thoroughly mixed into GR substrates or applied on the surface of GRs, exhibited the best performance. Huang, Garg, Mei, Huang, Chandra and Sadasiv [73] used a soil column to evaluate the hydrological performance of GRs modified by biochar. The results showed a considerable increase in runoff retention from 45.5% to 69.3%. In the study of Valagussa, Gatt, Tosca and Martinetti [79], both types of biochar made from pelleted wood and flake wood in both substrate depths of 10 cm and 15 cm enhanced runoff retention. Similarly, biochar of Meng, Zhang, Li and Wang [74] improved runoff retention in different cases of substrate depths (5, 10, 15, and 20 cm). Farrell, Cao, Ang and Rayner [75] concluded that the amendment of 40% (*v*/*v*) biochar to scoria-based GRs could result in an increase in the annual runoff retention, of 12% when modeled with Melbourne's climatic conditions. In a 27-day experiment [80], the cumulative outflow volume from a biochar-amended GR was 26 L (14.1 mm) less than the GR without biochar.

In addition to the studies presented in Table 2, there are other studies examining biochar to enhance the hydrological performance of GRs. Since other hydraulic parameters were assessed, those studies were not included in Table 2. Gan, et al. [81] used soil columns to compare bare soil with biochar-based soil with different amendment ratios (5%, 10%, and 15% *w*/*w*). The ratio of 5% (*w*/*w*) was found to have the highest water storage. Gan, et al. [82] further evaluated the ability of biochar in runoff reduction. The results indicated that soil amended with 10% (*w*/*w*) biochar was the optimal choice for rainwater management, offering the greatest peak outflow reduction and the longest outflow delay. However, 5% (*w*/*w*) biochar outperformed other amendments in terms of runoff retention and peak outflow delay. Wang, Garg, Zhang, Xiao and Mei [59] identified the positive influences of coconut shell biochar on the hydraulic properties of GR substrates in improving both residual and saturated water contents. However, coconut shell fiber was also recommended to be used in conjunction with biochar to reduce the air-entry value for effective stormwater management. Wang, et al. [83] further assessed the runoff retention of biochar-amended soil under both high and low (near-saturated) soil suctions. While a higher retention rate was recorded in soil with biochar due to greater mesopores under high suction, there was no difference between biochar-based soil and bare soil under near-saturated conditions (low suction). Tan and Wang [69] observed the hydrological response of biochar-amended and non-biochar GRs to natural rainfall. The amendment rate of 20% fine biochar particles was superior to others in terms of accumulated runoff reduction. The average peak flow reduction rates were 55.9%, 60.9%, 63.6%, and 65.9% with the amendment rates of 0%, 10% coarse particles, 20% coarse particles, and 20% fine particles, respectively. Additional positive findings related to stormwater management can be found in studies [63,66,84–87].

3.2. Runoff Quality Improvement

The reduction in pollutants in green roof discharge is another significant benefit of biochar that has been extensively studied. While nutrients are vital for plant survival, they can leach from green roof substrates due to rain and irrigation, potentially polluting aquatic environments. Although many runoff quality parameters were evaluated, Table 3 focuses only on the most significant nutrients and heavy metals.

Table 3. Quality of runoff from biochar-amended green roofs.

Reference	Approach	Substrate	Biochar Setup	Pollutant	Concentration without Biochar (mg/L)	Concentration with Biochar (mg/L)	Load without Biochar (mg)	Load with Biochar (mg)
[58]	Pilot-scale	Recycled brick, expanded clay, spongilite, and peat	Wood/sewage sludge/food waste biochar	TN	2.20 ± 1.20	13.8 ± 21.2/ 4.23 ± 3.20/ 7.87 ± 9.03	NA	NA
				TP	0.38 ± 0.35	0.33 ± 0.32/ 1.57 ± 2.23/ 0.42 ± 0.35		
[64]	Field-scale	Recycled, crushed brick, compost, crushed bark, and sphagnum moss	Surface biochar	TP and TN	NA	NA	Sedum: 40 and 580; meadow: 45 and 700 (m^{-2})	Sedum: 35 and 550; meadow: 41 and 560 (m^{-2})
			Buried biochar		NA	NA		Sedum: 29 and 350; meadow: 28 and 400 (m^{-2})
[71]	Pilot-scale	Gravel, sand, silt, clay, pumice, Fiber Life compost, and paper fiber	NA	Organic carbon (sedum and ryegrass)	78.8 and 73.6	25.7 and 21.6	1436–1521 and 1024–1236	425–488 and 395–439
				Inorganic carbon (sedum and ryegrass)	13.3 and 18.6	12.7 and 17.2	233–288 and 257–322	223–242 and 335–345
				TP (sedum and ryegrass)	10.3 and 17.4	8.3 and 8.4	199–216 and 238–352	119–183 and 151–182
				TN (sedum and ryegrass)	NA and 79.2	NA and 10.1	NA	NA
[72]	Pilot-scale	Peat, vermiculite, perlite, and sawdust	NA	TP	0.15	0.21	0.002 ± 0.001 (m^{-2})	0.003 ± 0.001 (m^{-2})
				TN	16.14	9.85	0.205 ± 0.089 (m^{-2})	0.096 ± 0.042 (m^{-2})
				Zn	0.03	0.02	NA	NA
				Fe	0.13	0.1	0.001 ± 0.001 (m^{-2})	0.001 ± 0.001 (m^{-2})

Table 3. *Cont.*

Reference	Approach	Substrate	Biochar Setup	Pollutant	Concentration without Biochar (mg/L)	Concentration with Biochar (mg/L)	Load without Biochar (mg)	Load with Biochar (mg)
[74]	Pilot-scale	Peat, vermiculite, perlite, and sawdust	NA	TP (substrate 5, 10, 15, and 20 cm)	0.28, 0.19, 0.25, and 0.38	0.32, 0.24, 0.35, and 0.43	0.003 ± 0.009, 0.002 ± 0.003, 0.004 ± 0.008, and 0.005 ± 0.008 (m^{-2})	0.005 ± 0.009, 0.004 ± 0.009, 0.007 ± 0.015, and 0.006 ± 0.008 (m^{-2})
				TN (substrate 5, 10, 15, and 20 cm)	22, 28, 29, and 17	10.5, 8, 12, and 12	0.277 ± 0.359, 0.370 ± 0.437, 0.375 ± 0.468, and 0.310 ± 0.433 (m^{-2})	0.114 ± 0.166, 0.087 ± 0.110, 0.169 ± 0.262, and 0.171 ± 0.229 (m^{-2})
				K (substrate 5, 10, 15, and 20 cm)	5, 6.5, 11, and 14	3.75, 4, 9, and 6	0.046 ± 0.045, 0.064 ± 0.079, 0.135 ± 0.143, and 0.177 ± 0.163 (m^{-2})	0.033 ± 0.034, 0.039 ± 0.046, 0.083 ± 0.087, and 0.064 ± 0.066 (m^{-2})
				Ca (substrate 5, 10, 15, and 20 cm)	120, 95, 90, and 60	65, 48, 50, and 45	0.842 ± 0.864, 0.898 ± 1.117, 0.958 ± 0.962, and 0.696 ± 0.600 (m^{-2})	0.479 ± 0.497, 0.432 ± 0.506, 0.448 ± 0.459, and 0.487 ± 0.489 (m^{-2})
				Fe (substrate 5, 10, 15, and 20 cm)	0.07, 0.08, 0.16, and 0.15	0.05, 0.06, 0.11, and 0.13	0.792 ± 0.948, 1.241 ± 2.192, 2.365 ± 2.889, and 2.388 ± 3.135 (m^{-2})	0.715 ± 1.053, 0.915 ± 1.643, 1.644 ± 2.774, and 1.324 ± 2.033 (m^{-2})
				Zn (substrate 5, 10, 15, and 20 cm)	0.05, 0.04, 0.08, and 0.13	0.025, 0.023, 0.05, and 0.03	0.305 ± 0.334, 0.231 ± 0.241, 0.594 ± 0.604, and 0.439 ± 0.497 (m^{-2})	0.145 ± 0.135, 0.101 ± 0.116, 0.231 ± 0.225, and 0.191 ± 0.171 (m-2)
[77]	Field-scale	NA	2.5, 5, and 15%, *w*/*w*	Organic carbon	NA	NA	355 (m^{-2})	310, 400, and 325 (m^{-2})
				Nitrate			1.7 (m^{-2})	2, 1.5, and 3 (m^{-2})
				Phosphate			33 (m^{-2})	25.5, 24, and 20 (m^{-2})
[88]	Pilot-scale	Crushed, recycledbrick, compost, peat, and crushed bark	NA	TP (planted and pre-grown)	NA	NA	130 and 125 ($m^{-2}year^{-1}$)	50 and 55 ($m^{-2}year^{-1}$)
				TN (planted and pre-grown)	NA	NA	3500 and 1200 ($m^{-2}year^{-1}$)	1100 and 600 ($m^{-2}year^{-1}$)

Table 3. *Cont.*

Reference	Approach	Substrate	Biochar Setup	Pollutant	Concentration without Biochar (mg/L)	Concentration with Biochar (mg/L)	Load without Biochar (mg)	Load with Biochar (mg)
[89]	Pilot-scale	Porous aggregates, composted organic matter, and fine sand	Granulated 1–2 mm	P, TN, K, Ca, and Mg (first flush/second flush)	1.1, 23, 200, 170, and 60/0.65, 7.5, 85, 88, and 31	0.9, 27.5, 260, 220, and 76/0.7, 7, 65, 84, and 29	0.0038, 0.085, 0.75, 0.65, and 0.23/0.0015, 0.018, 0.23, 0.22, and 0.075 (m^{-2})	0.0029, 0.085, 0.8, 0.65, and 0.24/0.0013, 0.012, 0.12, 0.15, and 0.05 (m^{-2})
			Granulated 2.8–4 mm			0.8, 27, 240, 190, and 73/0.75, 7.5, 67, 85, and 30		0.0035, 0.1, 0.9, 0.7, and 0.27/0.0014, 0.015, 0.14, 0.17, and 0.06 (m^{-2})
			Unprocessed 1–2 mm			0.85, 25, 280, 185, and 70/0.65, 6, 110, 78, and 30		0.0021, 0.06, 0.7, 0.4, and 0.16/0.0011, 0.009, 0.18, 0.13, and 0.05 (m^{-2})
			Unprocessed 2.8–4 mm			0.7, 16, 160, 140, and 45/0.6, 4, 65, 70, and 25		0.0027, 0.05, 0.7, 0.4, and 0.16/0.0013, 0.008, 0.14, 0.14, and 0.055 (m^{-2})
[90]	Pilot-scale	Pumice or expanded clay, and compost	NA	TP (lowest and highest)	0.05 and 1.47	0.18 and 2.09	NA	NA
[91]	Pilot-scale	NA	NA	TN	3.27	2.16	NA	NA
[92]	Pilot-scale	Topsoil, wood chip, waterworks sludge, and pumice	NA	TN (rain intensity: 5,10, and 15 mm/h)	7.5, 9.5, and 11.2	6.2, 7.5, and 10.8	NA	NA
[93]	Pilot-scale	Light expanded clay aggregate, coir chips, and mulch	7.5% mixed—medium biochar	TN and TP	3.7 to 31 and 0.35 to 0.67	4.8 to 48 and 0.81 to1.29	NA	NA
			15% mixed—medium biochar			7.1 to 47 and 0.56 to 1.66		
			7.5% buried—medium biochar			2.2 to 21 and 0.74 to 1.27		
			7.5% mixed—fine biochar			6.1 to 51 and 0.53 to 0.94		
			7.5% surface—fine biochar			9.5 to 58 and 0.98 to 2.41		

Table 3. *Cont.*

Reference	Approach	Substrate	Biochar Setup	Pollutant	Concentration without Biochar (mg/L)	Concentration with Biochar (mg/L)	Load without Biochar (mg)	Load with Biochar (mg)
[94]	Pilot-scale	Local soil, perlite, and vermiculite	Rice husk/Maize straw (10∼20% *v*/*v*)	TN	103.68	26.21~52.77/10.12~3.97	NA	NA
				TP	0.27	0.22~0.57/0.58~1.07		
				Organic carbon	94.47	101.76~59.41/52.45~26.73		
[95]	Pilot-scale		Sewage sludge biochar (10% and 20% *v*/*v*)	TN (at the beginning/the end)	4.1–11.9/0.9–1.0	27.2–32.8/0.5–0.7 and 13.4–47.3/0.5–0.6	NA	NA
				TP	0.04 to 1.63	0.18 to 2.00 and 0.03–1.71		

As previously discussed, biochar possesses physiochemical properties that help retain a variety of heavy metals and nutrients such as total nitrogen (TN) and total phosphorous (TP), thereby enhancing soil fertility [96]. The primary mechanisms through which biochar captures pollutants are adsorption, cation exchange, and biotransformation [72,90,97]. Furthermore, biochar indirectly improves runoff quality by improving plant performance, which leads to higher water and nutrient uptake by plants [89,92].

Adding biochar to GR substrates in [64] effectively reduced the nutrient loads in GR runoff as compared to non-biochar GRs. Specifically, in sedum GR test modules, biochar evenly spread on the substrate surface reduced the loads of TP and TN from 40 and 580 mg/m^2 to 35 and 550 mg/m^2, respectively. For meadow GRs, TP and TN loads were reduced from 45 and 700 mg/m^2 to 41 and 560 mg/m^2, respectively. The effect was even more considerable in the case of biochar at the bottom of the substrate. Most studied pollutants in [71] comprising TP, TN, and organic carbon had lower loads after the application of biochar, with the exception of inorganic carbon. Meng, Zhang, Li and Wang [74] evaluated the ability of coconut-shell-based biochar in removing nutrients and heavy metals from GR discharge. Results from a monitoring period of more than one year confirmed the positive effects of biochar on runoff quality by reducing loads of TN, potassium (K^+), calcium (Ca^{2+}), iron (Fe), and zinc (Zn). Additionally, biochar was effective in reducing the levels of both TP and TN in GR runoff [88]. More specifically, the average annual loads of TP and TN were reduced from 130 and 3500 mg/m^2 to 50 and 1100 mg/m^2 in on-site planted GR platforms; and from 125 and 1200 mg/m^2 to 55 and 600 mg/m^2 in pre-grown mats, respectively. The impacts of biochar in the study of Liao, Drake and Thomas [89] were more pronounced in the final flush at the end of the 115-day greenhouse experiment. Loads of TN and dissolved P, K, Ca, and Mg (magnesium) in the discharge were diminished by 59%, 20%, 28%, 34%, and 32%, respectively, by using unprocessed biochar. Zhang, et al. [98] assessed the fertilizer retention performance of four GR test plots and confirmed the positive effects of biochar. They concluded that higher biochar amendment rates resulted in lower nitrogen loss rates.

Consistent with the findings on pollutant loads, several studies indicated a reduction in pollutant concentrations following the application of biochar. Xu, et al. [99] concluded that biochar was able to delay the leaching effect of TP and enhance the retention of TN. Piscitelli, et al. [100] concluded that biochar is a promising soil additive to deal with runoff quality degradation, which is a current concern for GRs. Wood biochar and olive husk biochar were both observed to have a high adsorption capacity of different heavy metals, consisting of Cd (Cadmium), Cu (Copper), Cr (Chromium), Ni (Nickel), Pb (Lead), and Zn. The addition of 5.4% v/v biochar in the study by Liao, et al. [101] resulted in decreased nutrient concentrations of TN and dissolved P, K, Ca, and Na in discharge from GR modules with sedum mats. However, the authors observed no impacts of biochar on nutrient loading over three years.

3.3. Thermal Reduction

The thermal properties of GR substrates play a major role in directly determining the thermal insulation capacity, whereas plant growth and performance are the indirect impacts [102]. Lunt, Fuller, Fox, Goodhew and Murphy [102] compared the thermal conductivities of a biochar-based substrate with other substrate mixes. The lowest thermal conductivity value (<0.5 W/m·°C) was recorded in the biochar mix, which could be attributed to its high organic matter content, finer textured substrate structure, and the insulating effect of trapped air within biochar micropores [103–106]. The performance was also not affected by compaction and varying moisture contents. The thermal benefit of biochar was also noticeable in [57]. The thermal conductivity of biochar (0.693 W/m·K) was only higher than that of the wood-bark-based substrate (0.678 W/m·K). Biochar manufactured from coconut shell by slow pyrolysis at 600 °C in [59] increased the soil heat capacity and decreased the thermal conductivity by 31%, thereby enhancing the thermal insulation capacity. Wang, Garg, Zhang, Xiao and Mei [59] also highlighted the dependence of thermal conductivity on the distribution of micropores in biochar-amended soil. In addition, the heat insulation was found to be greater in dry soil than that in wet soil. Wang, Garg, Zhang, Xiao and Mei [59] recommended keeping soil dry rather than wet in summer. The daily minimum and maximum temperatures of GR substrates recorded in [69] also demonstrated the thermal benefit of biochar. The addition of 20% fine biochar particles made the GR substrate significantly cooler than the reference GR substrate. Biochar GRs lessened the temperatures of upper (by 3–5 °C) and lower roof deck surfaces. Petreje, Sněhota, Chorazy, Novotný, Rybová and Hečková [80] also found that the lower maximum temperature at the bottom layer of the biochar-amended GR led to improvements in vegetation cover and evapotranspiration rate. However, the reductions were not substantial. The amount of heat transferred to the indoor environment was decreased by biochar, which could contribute to increasing human thermal comfort (HTC) and building energy performance.

3.4. Plant Health and Microbial Diversity

Vegetation is a crucial component of a GR system; hence, plant survival is essential for maintaining the expected serviceability of GRs. Plant performance is understood to strongly depend on the condition of substrates. Biochar is well known as an effective soil additive to improve soil fertility. The porosity of substrates increased by biochar leads to enhancements in water/nutrient retention, water saving for irrigation, plant drought-stress resistance, and plant root development. Additionally, it is noteworthy that microorganisms or microbes exist in GR substrates. Thus, adding biochar makes GR substrates more porous and hence creates more shelters for microorganisms [83]. Interactions between plants and the microbial community are beneficial to the biomass of plants and microorganisms [107]. This microbiome benefits plants through different mechanisms including improving physical and chemical characteristics of substrates; producing and modifying plant hormones; and producing antibiotics, volatile organic compounds, and lytic enzymes against phytopathogenic microbes [108]. GRs are facing challenges in creating an ideal living place for plants and microbes due to thin substrates, limited irrigation, strong wind, extreme solar heat gain, and isolation from habitats at the ground level [107,109]. Consequently, some preliminary studies [110] have observed a small number of microorganisms in GR substrates, which could lead to a decline in plant performance and limit the ecoservices of GRs. Biochar, being a carbon-rich material, is utilized to generate a favorable environment for microorganisms and plants.

Granulated biochar was studied and compared with traditional biochar in [89] to assess their impacts on plant performance. The results revealed that granulated biochar outperformed traditional biochar by significantly improving plant biomass. Moreover, plant biomass from traditional biochar was even lower than that from non-biochar GRs. Biochar granules were also beneficial in reducing biochar loss caused by water and wind erosion. Biochar also demonstrated effectiveness in supporting the soil bacterial community. Adding biochar to GRs in [109] increased the biomass of soil microbes, eukaryotes, and plants by 75.3%, 199.2%, and 57.5%, respectively. This was due to an increase in soil porosity (by 5.3–9.3%), soil moisture (by 14–37.2%), available nutrients, and cation exchange capacity (by 38.1–75.9%). Varela, et al. [111] also recommended the use of biochar to increase the yield of *Lactuca sativa* L. var. crispa (lettuce). Chen, et al. [112] successfully increased the biomass of microorganisms and plants by 63.9–89.6% and 54.0–54.2%, respectively, using a 10–15% (v/v) sludge biochar application rate. The combined effects of compost and biochar were assessed in the study by Di Bonito, et al. [113]. Increases in the tomato size and biomass of leafy vegetables planted on rooftop gardens were identified. In the study by Kader, Spalevic and Dudic [57], biochar outperformed other organic wastes such as sawdust, wood bark, coir, and compost in terms of plant drought resistance and vegetation growth. In addition to improved (temperature-reducing) evapotranspiration, and enhanced nutrient and water retention, Petreje, Sněhota, Chorazy, Novotný, Rybová and Hečková [80] confirmed that biochar-amended GRs also supported vegetation growth.

Regarding Plant Available Water (PAW) and the Permanent Wilting Point (PWP), the GR substrate amended with 30% (v/v) urban green waste biochar in [114] improved PAW by 16% and delayed PWP by 2 days. Liu, et al. [115] advocated for the utilization of biochar to improve plant performance. Similarly, they found that biochar had a higher PAW and longer PWP, thereby decreasing the irrigation volume and days of plants experiencing water stress. The PWP was delayed by 3 days with the addition rate of 20% (v/v) biochar. The plant coverage area was investigated in the study by Olszewski and Eisenman [78]. They observed an increase of 25 to 33% in the coverage area of peppermint when compared to non-biochar treatments. Additionally, Wang, et al. [116] evaluated plant growth and the microbial community using various criteria, including lthe ight saturation point (LSP), light compensation point (LCP), root exudate bioactivity, and bacterial abundance. They found that a 5% (w/w) biochar amendment significantly enhanced plant growth, while higher amendment rates of biochar constrained vegetation development.

3.5. Air Quality Improvement

Preliminary results have demonstrated that GRs are a promising solution to capture several air pollutants, including CO_2, O_3, NO_2, PM10, and SO_2. CO_2, a greenhouse gas, is the most extensively studied pollutant [117–120]. CO_2 is either captured directly through the photosynthesis process of GR plants or indirectly through the decreased CO_2 emissions due to lower energy consumption. Therefore, the substrate and vegetation play a major role in determining the carbon sequestration capacity of GRs. Chen, Ma, Wang, Xu, Zheng and Zhao [67] noted that a limited number of studies have attempted to quantify the carbon storage in biochar-amended GRs. They identified two primary mechanisms through which biochar enhances carbon sequestration, namely by altering the physical properties of substrates and by promoting plant growth. Specifically, the addition of biochar increased the total carbon (TC) content of substrates, the total organic carbon (TOC) content in plants, and the overall carbon storage of green roofs, thereby enhancing their CO_2 sequestration capacity. Carbon storage of a biochar-amended GR was estimated to be 9.3 kg C/m^2/year, which was higher than 6.47 kg C/m^2/year of a non-biochar GR. Hu and Chen [68] tested biochar in both simulation box (micro-climate) and outdoor experiments. Biochar in all test plots significantly reduced the concentrations of CO_2, CO, SO_2, and NO_2 in the artificial environment, and reduced PM2.5, PM1.0, and PM10 in the natural environment. This capability of biochar was explained by a lower surface temperature and higher plant water availability promoting plant performance [68]. In the study of Zhang, Tang, Bian, Huang, Jin and He [98], all biochar–GR test plots were observed to effectively reduce CO_2 emission in both outdoor and indoor experiments during a 36 h period. The utilization of biochar towards carbon sequestration has also been studied in other research areas. For example, results from a systematic review of 64 studies by Gross, et al. [121] confirmed the significant potential of biochar applied in agricultural soils to sequester CO_2. A global meta-analysis from Xu, et al. [122] illustrated that applying biochar in agriculture had huge benefits relating to crop yield, soil carbon sequestration, and global warming.

3.6. Soil Erosion Control

Alongside agricultural land and other GI practices, GRs are also facing the issue of substrate loss, which is becoming an increasing global concern. Soil erosion causes loss of topsoil, leading to low agricultural productivity and posing an environmental threat through the accumulation of sediments and water contaminants in water bodies [123,124]. The substrate of a green roof differs significantly from that of other green infrastructure measures due to its shallow depth and the challenging growing conditions. The situation is further exacerbated by the high exposure of green roofs to extreme winds, intense rainfall, and limited vegetation cover [15,125]. Soil erosion negatively impacts the vegetation performance, thereby restricting the ecological functions of GRs. The effectiveness of biochar in controlling soil erosion was assessed in [66,126]. Biochar manufactured from invasive weed was tested using flume experiments with a 10 cm soil depth in [66]. Biochar was observed to attenuate soil erosion by 10–69%. The analysis also showed that biochar was the most influential element in soil erosion reduction. Liao, Sifton and Thomas [126] investigated how unprocessed and granulated biochar manufactured from a conifer sawmill performed to control substrate and biochar erosion. Biochar granules contributed to reducing biochar and substrate erosions by 74% and 39%, respectively. In contrast, only 6% of unprocessed biochar remained in the substate after 2 years of the experiment.

4. Barriers Limiting Biochar Amendment in GRs

Tables 2 and 3 highlight significant variations in biochar–GR research. The reviewed studies differ in their methodologies, weather characteristics, substrate composition, biochar characteristics, and other biochar-related parameters such as amendment rates and particle sizes. These differences make it challenging to directly compare results across studies. Nonetheless, a clear trend of positive effects of biochar on green roofs across various benefit categories is evident. As research on biochar in GRs is still in its early stages and lacks comprehensive information, further studies are needed. The following subsections discuss challenges and limitations of biochar-amended GR systems, which restrict the application of biochar in GRs.

4.1. Unpredictability Due to Inconsistent Research Findings

Despite varying substrate mixes, feedstocks, and pyrolysis conditions, most studies in Table 2 demonstrated the positive impacts of biochar on runoff retention in GRs. However, this review identified contradicting findings in few studies. For instance, the study by Qianqian, Liping, Huiwei and Long [72] showed no significant improvement in runoff retention from a biochar-amended GR. The authors reported retention rates of 72.54% and 72.08% from an unmodified GR and a biochar-modified GR, respectively. Results from the study by Saade, et al. [127] illustrated that biochar performed differently with varying biochar types and conditions of vegetation. Biochar improved runoff retention and reduced peak discharge of only test beds (3.24 m^2) with native plants that had a low vegetation cover and density during small rainfall events. Conversely, biochar was observed not to have positive impacts on GR test beds with sedum that had a high vegetation cover and density. In general, most reviewed studies showed a positive influence of biochar on the runoff retention rate of GRs. The improvements could be negligible or significant depending on the feedstock, pyrolysis temperature, substrate compositions, substrate depths, biochar amendment rates, and other biochar variables. Furthermore, concerns about the application of biochar include the reduction in air-filled porosity (AFP), which can lead to waterlogging during high-intensity rainfall events. This, in turn, may adversely impact plant health and the ecosystem services provided by GRs [128]. An effective GR system not only excels in water retention but also has an appropriate water-releasing capability to avoid waterlogging [100].

In contrast to runoff quantity, results from this review indicate a more inconsistent effectiveness of biochar in terms of GR runoff quality, which is in accordance with findings in the study by [129]. The effectiveness of biochar strongly depends on its physiochemical characteristics, which vary according to the type of feedstock, pyrolysis conditions, and types of pollutants [90]. Hence, inconsistent research outcomes were identified in Table 3. Among numerous pollutants, the leaching of TP was prominent in most studies [61,72,74,90,94,95]. For example, Meng, Zhang, Li and Wang [74] reported that loads of TP were higher in runoff from all tested biochar-amended substrates with different depths (5, 10, 15, and 20 cm). In contrast, positive effects were observed for other parameters such as TN. Similar findings relating to loads of TP were also found in other studies [72,94]. Another notable example of biochar degrading runoff quality is the study presented in [90]. Both oat-hull and wood-derived biochar contributed significantly to the TP in the runoff. The event mean concentration (EMC) of TP in runoff from unmodified extensive GRs fluctuated from 0.05 to 1.47 mg/L during the study period of 2 years. Conversely, biochar-amended GRs negatively influenced runoff quality by elevating the

EMC of TP, ranging from 0.18 to 2.09 mg/L. This research outcome highlights the need to evaluate the effects of substrate additives prior to their application. Additionally, Petreje, Sněhota, Chorazy, Novotný, Rybová and Hečková [80] also reported a decline in runoff quality following the addition of biochar, with the increases in the concentration of TN, chemical oxygen demand (COD), and biochemical oxygen demand (BOD).

The impacts of biochar on plant performance have also been uncertain in some studies. Biochar had insignificant influences on the coverage area of native species and stonecrops in the study by Zhu [63]. They were examined in 64 failed extensive GR trays (0.24 m^2) using different biochar treatments (processed and unprocessed biochar, mixing and top-layer application methods). Another study by Besides, Saade, Cazares, Liao, Frizzi, Sidhu, Margolis, Thomas and Drake [127] reported the different effects of biochar on the performance of sedum and native species in GR test beds (1.8 × 1.8 m). While biochar had positive influences on native species, the plant coverage and density of sedum were lower in biochar test beds.

From a broader perspective, research on biochar-amended GRs remains limited, as it is a relatively recent area of study. More importantly, other benefits of biochar in GRs such as temperature reduction, carbon sequestration, and erosion control have received less attention. In this review, only five papers were found that examined the effectiveness of biochar in relation to reductions in temperature and energy use. The mitigation of air pollution is also known as one of the notable benefits provided by GRs. However, only a few studies have been undertaken to investigate the use of biochar to enhance this GR benefit. In addition, this review identified only two biochar–GR papers focusing on soil erosion.

4.2. Limited Understanding of Optimal Biochar-Based Variables

This review paper highlighted the importance of biochar application methods. For example, the application methods of biochar were investigated in [64]. Birchwood biochar was applied at the bottom (buried biochar) and at the top (surface biochar) of the GR substrate. In both sedum and meadow GRs, buried biochar outperformed surface biochar in terms of runoff retention and runoff quality improvement. Although surface biochar in [63] continued having less impact on runoff retention as compared to mixing biochar, it was still recommended due to the lower labor cost. Processed biochar was suggested to be used against unprocessed biochar on the substrate surface to mitigate potential biochar loss. Moreover, biochar was also applied in other ways. The biochar layer was in the middle of the substrate in the studies by [61,62]. However, the mixing method remains the most researched biochar application method [66–69,73,81,83,89].

Processed biochar has recently attracted the attention of researchers [89,126,128,130]. Compared to unprocessed biochar, processed biochar is well documented to have a lesser impact on water and nutrient retention. However, its long-term effects are more pronounced due to higher resistance to biochar and substrate losses [131]. Liao, Drake and Thomas [89] investigated different particle sizes of unprocessed biochar and biochar processed into a granulated form and made similar conclusions. Unprocessed biochar had higher runoff and nutrient retention rates, but biochar granules improved plant performance and had better long-term effects due to less biochar loss. Granulated biochar also performed remarkably well in [126,130] by attenuating biochar and substrate losses and enhancing plant growth.

It is widely accepted that small biochar particles have better retention of water and nutrients due to their higher porosity and larger specific surface area [89]. On the other hand, large (coarse) biochar particles are less subject to water and wind erosion [132]. Some researchers recommended using small biochar particles amended to medium to coarse textured soils to obtain multiple benefits [89,128,133]. Liao, Drake and Thomas [130] suggested the use of granulated biochar with a medium particle size (2–2.8 mm) to enhance plant performance while achieving an acceptable retention capacity. Using very fine biochar results in a higher water retention capacity, whereas the drainage speed is reduced. It helps prevent waterlogging, which can negatively affect plant health. Three particle sizes of biochar including fine (<2 mm), coarse (2 mm), and a mix of fine and coarse were investigated in [128]. Fine biochar particles achieved the highest water retention, but they reduced infiltration and AFP, causing waterlogging in extreme rainfall events. Wang, Garg, Zhang, Xiao and Mei [59] further highlighted the importance of fast drainage of GRs. While the biochar itself slightly improved the air-entry value (AEV) and maximized saturated water content (SWC), the combination of biochar and fiber was more effective. This combination reduced AEV and achieved an acceptable SWC. Enhanced drainage, characterized by a relatively low AEV, helps GRs to maintain adequate water storage for handling frequent rainfall.

A greater amendment rate of biochar was mostly observed to increase the water retention capacity of GRs. For example, the maximum improvement in annual rainfall retention was achieved with the highest biochar amendment rate of 40% (*v*/*v*) in [75]. Significantly higher water retention by increasing the amount of biochar was also achieved in some studies [62,79,98]. Despite its benefits, some studies found that higher amendment rates of biochar did not always lead to increased runoff retention. Goldschmidt [77] observed an increased amount of runoff from GRs with 10% and 15% (*w*/*w*) biochar, as compared to that with 5% (*w*/*w*) biochar. Similarly, the lowest amount of biochar (5% *w*/*w*) in [81,82] achieved the highest runoff reduction. These inconsistent findings highlight the need for further investigation. On the other hand, efforts to utilize biochar in the context of stormwater management need to consider several factors rather than only focusing on runoff retention. For example, though the amount of water retained by 10% and 15% (*w*/*w*) biochar was slightly higher than that by 5% (*w*/*w*) biochar, Gan, Garg, Huang, Wang, Mei and Zhang [81] did not recommend a higher amendment rate of biochar. The addition of 5% (*w*/*w*) biochar was the best stormwater management strategy, greatly alleviating surface runoff and bottom drainage and having the longest runoff outflow delay.

It can be concluded that biochar-related variables have a significant impact on various GR benefits. However, these insights are based on preliminary studies, and further research is recommended to identify optimal biochar–GR systems. The unclear mechanisms through which biochar variables affect GR performance may limit the widespread use of biochar in GRs.

4.3. Environmental Concerns

Biochar has proven effective in agriculture and has recently been introduced in green infrastructure strategies like GRs. Nonetheless, an awareness about the potential of biochar in GRs remains lacking. Additionally, many questions remain unanswered regarding the environmental impacts of biochar-amended GR systems, such as biochar loss and leaching of contaminants [116]. Liao, Sifton and Thomas [126] found that 94% of unprocessed biochar was lost from GRs due to wind and water erosion after only 2 years. Additionally, waste biomass is often used to manufacture biochar, raising concerns about contaminants such as nutrients and heavy metals leaching from biochar-amended GRs [134]. Nevertheless, some studies have concluded that heavy metals in waste-based biochar feedstocks are converted to stable forms and thus the use of biochar has lower environmental risks than the direct use of waste [135,136]. Both positive and negative findings regarding runoff quality from biochar-amended GRs have been reported and discussed earlier in this review. This suggests significant variability in GR performance across different systems and pollutants, underscoring the need for long-term studies to mitigate environmental risks associated with the application of biochar in GRs on a large scale.

This review has also identified a few studies on environmental benefits of biochar in GRs to increase carbon sequestration. Biochar has the potential to combat global warming by capturing several greenhouse gases (GHGs) and enhancing carbon storage. Unlike carbon sequestration, other environmental impacts of biochar in GRs have not been thoroughly explored. Limited information on the Life Cycle Assessment (LCA) of biochar use in GRs was also noted in this review. LCA is a commonly used tool to estimate potential environmental impacts of a product during its life cycle. For example, Azzi, et al. [137] attempted to explore the impacts of biochar on the environment by applying the LCA of an extensive GR and other urban applications of biochar. All biochar applications demonstrated improved environmental performance in terms of carbon sequestration. However, in other impact categories (natural resource use, human toxicity, and ecotoxicity), biochar could be either more or less environmentally friendly, depending on the biochar supply chain and material substitution. Biochar demand was predicted to increase rapidly, which raises environmental concerns regarding its end-of-life impact.

In a broader context, LCA has been carried out for other soil-related applications. Similar findings were found in a comprehensive review on the application of biochar in soil systems by Matuštík, Hnátková and Kočí [134]. Despite high variability in methodologies and contexts across the literature, the positive impacts of biochar in storing stable carbon in soils and reducing GHG emissions from agricultural production are apparent. Those benefits outweigh GHG emission from pyrolysis systems, feedstock processing, and handling. However, our knowledge of the effects on other impact categories relating to human and ecotoxicology remains limited and these require further investigation. Another review, by Kamali, et al. [138], raised environmental concerns about biochar's impacts on human health and ecosystems. The authors also highlighted the effectiveness of biochar in decreasing emissions of GHGs such as carbon dioxide and nitrous oxides. On the other hand, they called for future studies on the long-term effects of biochar in soil structures to ensure its sustainability in soil applications. Thorough investigations into biochar production and applications in the long term are essential.

4.4. Economic Challenges

Costs of biochar are also a major obstacle preventing the utilization of biochar in GRs and other GI measures. Other GR components currently cost significantly less than biochar [128]. Energy required for the high-temperature pyrolysis process is the largest contributor to the cost of biochar [59]. For instance, 75% of the cost of producing biochar from empty fruit bunches was attributed to the use of diesel to heat up the oven at the beginning of the pyrolysis process [139]. Kuppusamy, et al. [140] found that both slow and fast pyrolysis in producing biochar were unprofitable, so the commercialization of biochar was restricted. Moreover, the continuous operation costs of pyrolysis plants are high [141]. Beck, Johnson and Spolek [71] and Li, Garg, Huang, Jiang, Mei, Liu and Wang [84] used only 5% and 7% (w/w) biochar, respectively, considering the limited availability of biochar. Given these challenges, the application of even a small amount of biochar on a large scale would be impractical. The method of biochar application is also an important factor in determining the economic feasibility of biochar. Taking labor costs into consideration, the top-layer application method is more cost effective than other methods [63]. While the mixing method is constrained by high labor costs, the more affordable top-layer method raises environmental concerns due to the higher potential for biochar loss.

A comprehensive review by Kamali, Sweygers, Al-Salem, Appels, Aminabhavi and Dewil [138] concentrated on investigating the economic feasibility of biochar in soil structures. Results indicate that recent studies considered biochar as a cost-effective solution under certain conditions, owing to its potential to increase crop yields and enhance the economic value of carbon sequestration. For example, Galinato, et al. [142] concluded that biochar can only be profitable when its market price is low and the carbon price is high. Similarly, this review did not conduct a life cycle cost analysis of using biochar in GRs. The situation is further complicated for GRs, due to the recent introduction of biochar in GRs and the difficulty in translating many GR benefits into monetary terms, which make an LCA more challenging [1,3]. Consequently, our capacity to accurately calculate the financial benefits of GRs to offset the costs of biochar production and application remains restricted. Future research is needed to address the economic feasibility of biochar in GRs.

4.5. Policy Barriers

In general GR research, the adoption of GRs has also been hindered by the lack of attention from policymakers to the benefits of GRs, especially in developing countries [2].

As a result, the use of biochar in GRs is further constrained, and this is partly responsible for the introduction of this practice only recently. A large amount of sludge and agricultural waste, which are common feedstocks for biochar, has been generated globally. Xu, Yang and Spinosa [44] reported that 6.25 million tons of sludge was produced in China in 2013. Additionally, the United States generates approximately 13.8 million tons of dry sludge annually from wastewater treatment [143]. Thus, converting these wastes into biochar offers significant potential for sustainable urban development. Specifically, the synergy of biochar and green roofs (GRs) can effectively address urban challenges such as air and water pollution, urban flooding, heat island effects, and biodiversity loss [144].

The use of biochar in GRs and other soil structures necessitates collaboration among various organizations and supportive local policies. Figure 8 demonstrates the geographical coverage of studies on biochar-amended GRs that were reviewed in this research. Most research was undertaken in China, which is followed by Canada, Australia, and Italy. This is consistent with findings in the study by Qin, et al. [145]. Local research, using region-specific materials and weather data, is likely to advance the broader adoption of biochar in green roofs (GRs) within those countries. The high number of studies on biochar and GRs in some countries could be attributed to well-developed biochar markets and government support, including funding and policies for biochar research and production. Goldschmidt [77] noted that biochar has not yet become widely commercialized due to its recent introduction. Consequently, there are no established guidelines or standards for its production, which could lead to improper manufacturing and potentially negative impacts on soil microbes and plant growth. Pourhashem, et al. [146] identified three key policy factors essential for the widespread adoption of biochar, namely funding for research and development, financial incentives, and non-financial supportive policy. While financial incentives contribute to reducing biochar costs, non-financial policies enhance social awareness and investment rates and increase market demand for biochar. You, et al. [147] also highlighted the importance of policy in the application of biochar. Policy supports biochar productions systems, thereby enhancing system efficiency and lowering costs of biochar collection, transportation, and pretreatment. Without these laws and regulations, research findings on the benefits of biochar may not be effectively translated into practical applications.

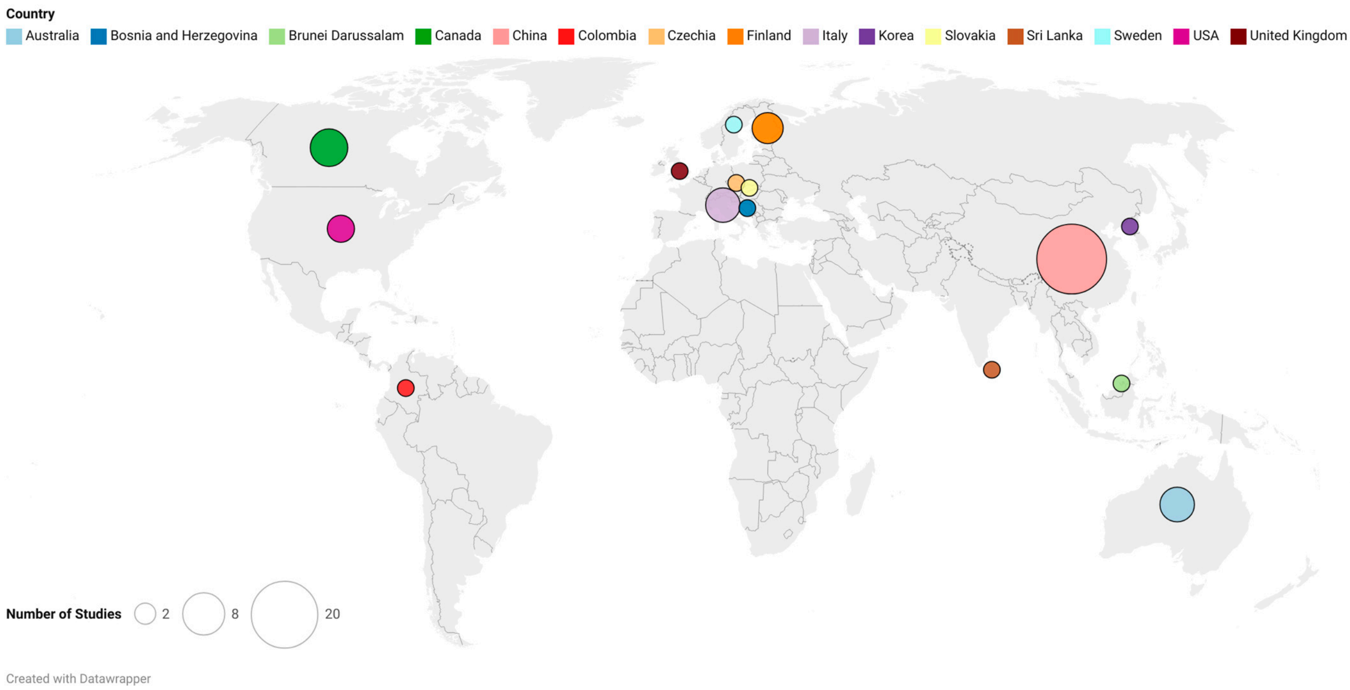

Figure 8. The number of studies on biochar-amended green roofs by country.

5. Future Research Opportunities

5.1. Further Investigations into the Performance of Biochar-Amended Green Roofs

As previously discussed, the performance of biochar in GRs has a strong relationship with biochar-related variables such as particle size, processed forms of biochar, application methods, and amendment rates. Though some valuable findings in relation to biochar variables have been identified, definitive conclusions cannot be drawn due to the limited number of studies on biochar in the context of GRs. This review found a lack of comprehensive studies on biochar application methods. Thus, more research is necessary to determine the optimal application method of biochar in GRs. Furthermore, due to limited research, a thorough understanding of how biochar particle sizes and processed forms affect biochar-amended GRs is still lacking. Additionally, the effects of biochar amendment rates on nutrient retention and plant performance have not been fully covered. Therefore, further studies are needed to address these research gaps.

The benefits of biochar extend beyond stormwater management, runoff quality, and plant performance. It has also shown positive results in thermal insulation capacity, plant growth, microbial diversity, carbon sequestration, and soil erosion control. However, apart from plant growth and microbial diversity, there has been limited research on other biochar benefits. This opens up numerous research opportunities. Future studies should focus on maximizing biochar's potential by addressing multiple benefits simultaneously. An ideal biochar-amended GR should simultaneously improve runoff and nutrient retentions, delay runoff outflow, reduce peak runoff, improve thermal insulation, boost plant performance and microbial diversity, limit biochar and substrate losses, and sequester carbon. To achieve these outcomes, research studies should explore several biochar benefits concurrently.

5.2. Long-Term Observation Studies

This study also highlighted the lack of long-term research needed to fully understand the benefits of biochar amendment in GRs. Most biochar-based GRs reviewed in this study were examined over a short study period. For example, the results in [71,79] were only from two and three simulated rainfall events, respectively. Huang, Garg, Mei, Huang, Chandra and Sadasiv [73] evaluated the hydrological responses of biochar-amended GRs through the use of soil columns using only one simulated rainfall. Eight rainfall events within six months were simulated in [72] to study both the quantity and quality of runoff from biochar-amended GRs. As a result, the long-term performance of biochar-amended green roofs could not be assessed. On the other hand, a limited number of studies with extended monitoring periods were also identified. The performance of GRs amended with biochar during two seasons was observed in [64]. A long monitoring period of roughly a year was adopted in a few studies [74,77,88]. Studies involving multiyear experiments were very limited. For example, a five-year experiment reported in [90] measured phosphorous levels in the discharge from several extensive GRs, with biochar added to one of the GRs during the final two years. Kuoppamäki, Setälä and Hagner [61] tracked the leaching of TP from biochar-amended GR substrates for a period of seven years. Their long-term study revealed a strong correlation between the age of GRs and the effectiveness of biochar. The studies [88,89] found a significant decline in the leaching of nutrients towards the end of the experiments. Similarly, Liao, Sidhu, Sifton, Margolis, Drake and Thomas [101] observed a negative correlation of GR aging with concentrations of TN and dissolved P, K, and Mg over 3 years. Biochar-amended GR substrates of Vavrincová, Pipíška, Urbanová, Frišták, Horník, Machalová and Soja [95] indicated first-flush behavior with higher TN and TP concentrations at the beginning. After 30 months, there were no significant differences between biochar and non-biochar treatments. Therefore, biochar from sewage sludge was concluded to be a sustainable substrate additive for extensive GR substrates. This nutrient-rich biochar gradually released nutrients and did not greatly increase nutrient concentrations in GR runoff when compared to the conventional GRs. The decrease in nutrient concentrations over time could be attributed to well-established plants enhancing nutrient uptake and stabilizing the root substrate. Although the concentrations of TP in runoff from biochar-amended GRs were higher than those from conventional GRs during the experiment, a downward trend of TP leaching over time was identified in [90]. Additionally, Kuoppamäki, Setälä and Hagner [61] studied the leaching of phosphorous (P) and nitrogen (N) and reported similar findings related to biochar and GR aging. They found that biochar consistently reduced P and N leaching until an increase in P levels was noted 6 years after GR installation, which was attributed to fertilization.

Since the pollutant load is calculated by multiplying the runoff volume and pollutant concentration, the long-term effects of biochar on runoff quality become more pronounced due to its substantial impact on reducing runoff volume. An excellent example is the study of Kuoppamäki, Hagner, Lehvävirta and Setälä [64]. In some events, concentrations of TP and TN in runoff from biochar-amended GRs were higher than those from non-biochar GRs. However, results from a nonlinear regression analysis in this study revealed positive impacts of biochar on the cumulative load of TP due to a substantially lower runoff volume. Therefore, regardless of the higher pollutant concentrations and loads reported in some studies, it can be concluded that biochar has long-term potential to mitigate the leaching of pollutants from GRs to the environment. Additionally, Nguyen, Chau and Muttil [93] observed higher concentrations of nutrients in runoff from biochar-amended GR test beds. The authors still concluded that there were positive effects of biochar on GR runoff due to a reduced runoff volume. In addition, Zhu [63] and Saade, Cazares, Liao, Frizzi, Sidhu, Margolis, Thomas and Drake [127] observed insignificant impacts of biochar on plant performance. The results were based on just 16 days between two short-term vegetation surveys and a 5-month observation period. Hence, they recommended extending the monitoring duration in future research.

Some negative findings from short-term studies highlighted the need for conducting multiyear experiments in future research. Although biochar has been widely recognized as a stable and long-lasting soil additive [71], this review strongly recommends conducting long-term studies to evaluate its effects on the performance of GRs.

5.3. Economic and Environmental Analysis

In general, the current GR research lacks a comprehensive understanding of biochar's environmental impacts. Although the LCA method has been extensively used in agricultural soil structures, studies applying LCA to biochar and green roofs are still limited. Reliable LCA tools are essential for assessing the environmental performance of biochar-amended green roofs, and their use is strongly recommended for future studies. In addition, the potential loss of biochar in GRs, especially for unprocessed and fine biochar particles on the surface of GRs, emerges as a significant environmental concern that has not received adequate research attention. Preliminary results indicate that biochar processed into a granulated form is more effective than unprocessed biochar in controlling soil and biochar erosion. Thus, there are opportunities for further research to gather more information on biochar variables and identify optimal biochar–GR configurations with minimal environmental impacts. Consistent with the findings from this review, Kamali, Sweygers, Al-Salem, Appels, Aminabhavi and Dewil [138] emphasized the need to assess the long-term effects of biochar on GR benefits and environmental performance. Reliable research methodologies are crucial for ensuring the sustainability of biochar applications in GRs and other soil structures, which could ultimately enhance public recognition and promote broader use of biochar.

The biochar amendment rate plays a crucial role in determining biochar costs. Therefore, further research is needed to identify the optimal biochar dosage for enhancing GR performance while minimizing costs. Additionally, more studies utilizing life cycle cost analysis are necessary to address the financial feasibility of biochar–GR systems. The use of biochar-amended soil in dual-substrate-layer GRs, as shown in [81], proved more cost effective than single-layer GRs, offering a potential solution to reduce biochar costs. Such studies are highly recommended in the future to transform biochar into an affordable additive for GR substrates.

6. Conclusions

GRs are one of the most widely used water-sensitive urban design (WSUD) strategies aimed at addressing a variety of social and environmental challenges caused by urbanization and climate change. GRs have been studied for decades to optimize their ecosystem services and promote their widespread implementation. Biochar, an innovative carbon-rich material, has been recently introduced into GRs and other GI practices. Biochar has physiochemical characteristics that are beneficial to the performance of GRs including water/nutrient retention, plant performance, microbial diversity, carbon sequestration, thermal reduction, and soil erosion control. Despite significant research efforts to investigate the use of biochar across various fields, the potential of biochar in green roofs has not been thoroughly explored. This paper aimed to review the previous studies analyzing the performance of GRs with the application of biochar. Additionally, this review attempted to provide readers with a broad picture of the efficiency of biochar-based GRs by considering different biochar benefits. Furthermore, this paper also presented knowledge gaps, implementation challenges, and future research opportunities.

The following points are a summary of important findings and recommendations arising from this study:

(a) There is a clear trend indicating the benefits of biochar amendment in GRs. However, significant variation in parameters across biochar–GR studies make direct comparisons challenging. Additionally, the application of biochar in GRs is relatively new and not yet thoroughly studied, highlighting the need for further research to provide comprehensive insights.

(b) Although some studies report contradictory findings, such as higher pollutant concentrations in runoff from biochar-amended GRs, the long-term improvement in runoff quality due to a significant reduction in runoff remains noteworthy.

(c) The research on biochar amendment in GRs has been uneven, with the majority of studies focusing on runoff retention, improved runoff quality, enhanced plant performance, and microbial diversity. Certain other benefits of biochar for GRs, such as thermal reduction, carbon sequestration, and control of soil erosion, have received relatively less attention. Future studies should address this imbalance to provide a more comprehensive understanding of biochar's full range of benefits.

(d) Biochar-related variables such as particle sizes, processed forms, amendment rates, and application methods play an important role in determining the performance of biochar-amended GRs. However, contradictory findings in the literature highlight the need for further research to fully understand the impacts of these variables on the performance of green roofs.

(e) The understanding of the long-term effects of biochar on GRs remains incomplete, likely due to the limited number of studies that conducted analysis with multiyear observations.

(f) While biochar is well recognized to effectively sequester CO_2, the integration of biochar into life cycle assessments (LCAs) is recommended to comprehensively understand its long-term environmental impacts.

(g) It is also recommended to apply LCA to evaluate the cost aspects of biochar in GRs. This can provide deeper insights into the economic feasibility of biochar-amended GRs.

(h) The utilization of biochar in GRs faces several barriers. In addition to inconsistent and limited research information, major challenges include high manufacturing costs, policy-related constraints, and environmental concerns. Addressing these issues is crucial for the widespread adoption of biochar in GRs.

Author Contributions: Conceptualization, C.N.N., A.K., A.C. and N.M.; methodology, C.N.N. and N.M.; software, C.N.N. and N.M.; validation, H.-W.C., A.K., A.C. and N.M.; formal analysis, C.N.N. and N.M.; investigation, C.N.N.; resources, C.N.N. and N.M.; data curation, C.N.N.; writing—original draft preparation, C.N.N.; writing—review and editing, C.N.N., H.-W.C., A.K., A.C. and N.M.; visu-

alization, C.N.N. and N.M.; supervision, N.M. and H.-W.C.; project administration, C.N.N.; funding acquisition, N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Shafique, M.; Kim, R.; Rafiq, M. Green roof benefits, opportunities and challenges–A review. *Renew. Sustain. Energy Rev.* **2018**, *90*, 757–773. [CrossRef]
2. Vijayaraghavan, K. Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renew. Sustain. Energy Rev.* **2016**, *57*, 740–752. [CrossRef]
3. Nguyen, C.N.; Muttil, N.; Tariq, M.A.U.R.; Ng, A.W. Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review. *Water* **2021**, *14*, 68. [CrossRef]
4. Vijayaraghavan, K.; Raja, F.D. Pilot-scale evaluation of green roofs with Sargassum biomass as an additive to improve runoff quality. *Ecol. Eng.* **2015**, *75*, 70–78. [CrossRef]
5. Gong, Y.; Yin, D.; Li, J.; Zhang, X.; Wang, W.; Fang, X.; Shi, H.; Wang, Q. Performance assessment of extensive green roof runoff flow and quality control capacity based on pilot experiments. *Sci. Total Environ.* **2019**, *687*, 505–515. [CrossRef] [PubMed]
6. Beecham, S.; Razzaghmanesh, M. Water quality and quantity investigation of green roofs in a dry climate. *Water Res.* **2015**, *70*, 370–384. [CrossRef] [PubMed]
7. Ferrans, P.; Rey, C.V.; Pérez, G.; Rodríguez, J.P.; Díaz-Granados, M. Effect of green roof configuration and hydrological variables on runoff water quantity and quality. *Water* **2018**, *10*, 960. [CrossRef]
8. Wong, G.K.; Jim, C.Y. Quantitative hydrologic performance of extensive green roof under humid-tropical rainfall regime. *Ecol. Eng.* **2014**, *70*, 366–378. [CrossRef]
9. Johannessen, B.G.; Muthanna, T.M.; Braskerud, B.C. Detention and retention behavior of four extensive green roofs in three nordic climate zones. *Water* **2018**, *10*, 671. [CrossRef]
10. Bevilacqua, P.; Mazzeo, D.; Bruno, R.; Arcuri, N. Surface temperature analysis of an extensive green roof for the mitigation of urban heat island in southern mediterranean climate. *Energy Build.* **2017**, *150*, 318–327. [CrossRef]
11. He, Y.; Yu, H.; Ozaki, A.; Dong, N.; Zheng, S. Long-term thermal performance evaluation of green roof system based on two new indexes: A case study in Shanghai area. *Build. Environ.* **2017**, *120*, 13–28. [CrossRef]
12. He, Y.; Yu, H.; Dong, N.; Ye, H. Thermal and energy performance assessment of extensive green roof in summer: A case study of a lightweight building in Shanghai. *Energy Build.* **2016**, *127*, 762–773. [CrossRef]
13. Ávila-Hernández, A.; Simá, E.; Xamán, J.; Hernández-Pérez, I.; Téllez-Velázquez, E.; Chagolla-Aranda, M. Test box experiment and simulations of a green-roof: Thermal and energy performance of a residential building standard for Mexico. *Energy Build.* **2020**, *209*, 109709. [CrossRef]
14. Manso, M.; Teotónio, I.; Silva, C.M.; Cruz, C.O. Green roof and green wall benefits and costs: A review of the quantitative evidence. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110111. [CrossRef]
15. Cascone, S. Green roof design: State of the art on technology and materials. *Sustainability* **2019**, *11*, 3020. [CrossRef]
16. Nguyen, C.N.; Tariq, M.A.U.R.; Browne, D.; Muttil, N. Performance Evaluation of Large-Scale Green Roofs Based on Qualitative and Quantitative Runoff Modeling Using MUSICX. *Water* **2023**, *15*, 549. [CrossRef]
17. Barnhart, B.; Pettus, P.; Halama, J.; McKane, R.; Mayer, P.; Djang, K.; Brookes, A.; Moskal, L.M. Modeling the hydrologic effects of watershed-scale green roof implementation in the Pacific Northwest, United States. *J. Environ. Manag.* **2021**, *277*, 111418. [CrossRef]
18. Liu, L.; Sun, L.; Niu, J.; Riley, W.J. Modeling green roof potential to mitigate urban flooding in a Chinese city. *Water* **2020**, *12*, 2082. [CrossRef]
19. Talebi, A.; Bagg, S.; Sleep, B.E.; O'Carroll, D.M. Water retention performance of green roof technology: A comparison of canadian climates. *Ecol. Eng.* **2019**, *126*, 1–15. [CrossRef]
20. Jahanfar, A.; Drake, J.; Gharabaghi, B.; Sleep, B. An experimental and modeling study of evapotranspiration from integrated green roof photovoltaic systems. *Ecol. Eng.* **2020**, *152*, 105767. [CrossRef]
21. Arenandan, V.; Wong, J.K.; Ahmed, A.N.; Chow, M.F. Efficiency enhancement in energy production of photovoltaic modules through green roof installation under tropical climates. *Ain Shams Eng. J.* **2022**, *13*, 101741. [CrossRef]
22. Zheng, Y.; Weng, Q. Modeling the effect of green roof systems and photovoltaic panels for building energy savings to mitigate climate change. *Remote Sens.* **2020**, *12*, 2402. [CrossRef]
23. Yeom, D.; La Roche, P. Investigation on the cooling performance of a green roof with a radiant cooling system. *Energy Build.* **2017**, *149*, 26–37. [CrossRef]

24. La Roche, P.; Yeom, D.J.; Ponce, A. Passive cooling with a hybrid green roof for extreme climates. *Energy Build.* **2020**, *224*, 110243. [CrossRef]
25. Nealy, S., Jr. *A Climate Responsive Radiant Green Roof System for Indoor Cooling Purposes*; California State Polytechnic University: Pomona, CA, USA, 2019.
26. Shafique, M.; Lee, D.; Kim, R. A field study to evaluate runoff quantity from blue roof and green blue roof in an urban area. *Int. J. Control. Autom.* **2016**, *9*, 59–68. [CrossRef]
27. Shafique, M.; Kim, R. Application of green blue roof to mitigate heat island phenomena and resilient to climate change in urban areas: A case study from Seoul, Korea. *J. Water Land Dev.* **2017**, *33*, 165–170. [CrossRef]
28. Busker, T.; de Moel, H.; Haer, T.; Schmeits, M.; van den Hurk, B.; Myers, K.; Cirkel, D.G.; Aerts, J. Blue-green roofs with forecast-based operation to reduce the impact of weather extremes. *J. Environ. Manag.* **2022**, *301*, 113750. [CrossRef]
29. Carpenter, C.M.; Todorov, D.; Driscoll, C.T.; Montesdeoca, M. Water quantity and quality response of a green roof to storm events: Experimental and monitoring observations. *Environ. Pollut.* **2016**, *218*, 664–672. [CrossRef]
30. Hussain, R.; Ravi, K.; Garg, A. Influence of biochar on the soil water retention characteristics (SWRC): Potential application in geotechnical engineering structures. *Soil Tillage Res.* **2020**, *204*, 104713. [CrossRef]
31. Wang, J.; Wang, S. Preparation, modification and environmental application of biochar: A review. *J. Clean. Prod.* **2019**, *227*, 1002–1022. [CrossRef]
32. Butu, M.; Rodino, S.; Miu, B.; Fidler, G.; Butu, A. Mine tailings-based technosols for the green infrastructures sector. In Proceedings of the 21st International Multidisciplinary Scientific GeoConference: SGEM 2021, Albena, Bulgaria, 16–22 August 2021; Volume 21, pp. 229–236.
33. Novotný, M.; Marković, M.; Raček, J.; Šipka, M.; Chorazy, T.; Tošić, I.; Hlavínek, P. The use of biochar made from biomass and biosolids as a substrate for green infrastructure: A review. *Sustain. Chem. Pharm.* **2023**, *32*, 100999. [CrossRef]
34. Premarathna, K.; Biswas, J.K.; Kumar, M.; Varjani, S.; Mickan, B.; Show, P.L.; Lau, S.Y.; Novo, L.A.; Vithanage, M. Biofilters and bioretention systems: The role of biochar in the blue-green city concept for stormwater management. *Environ. Sci. Water Res. Technol.* **2023**, *9*, 3103–3119. [CrossRef]
35. Lee, J.; Kwon, E.E. Biochar in Green Roofs. *J. Build. Eng.* **2024**, *89*, 109272. [CrossRef]
36. Cha, J.S.; Park, S.H.; Jung, S.-C.; Ryu, C.; Jeon, J.-K.; Shin, M.-C.; Park, Y.-K. Production and utilization of biochar: A review. *J. Ind. Eng. Chem.* **2016**, *40*, 1–15. [CrossRef]
37. Lee, J.W.; Hawkins, B.; Day, D.M.; Reicosky, D.C. Sustainability: The capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. *Energy Environ. Sci.* **2010**, *3*, 1695–1705. [CrossRef]
38. Basu, P. *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory*; Academic Press: Cambridge, MA, USA, 2018.
39. Narzari, R.; Bordoloi, N.; Chutia, R.S.; Borkotoki, B.; Gogoi, N.; Bora, A.; Kataki, R. Biochar: An overview on its production, properties and potential benefits. *Biol. Biotechnol. Sustain. Dev.* **2015**, *1*, 13–40.
40. Kwapinski, W.; Byrne, C.M.; Kryachko, E.; Wolfram, P.; Adley, C.; Leahy, J.J.; Novotny, E.H.; Hayes, M.H. Biochar from biomass and waste. *Waste Biomass Valorization* **2010**, *1*, 177–189. [CrossRef]
41. Weber, K.; Quicker, P. Properties of biochar. *Fuel* **2018**, *217*, 240–261. [CrossRef]
42. Bagreev, A.; Bandosz, T.J.; Locke, D.C. Pore structure and surface chemistry of adsorbents obtained by pyrolysis of sewage sludge-derived fertilizer. *Carbon* **2001**, *39*, 1971–1979. [CrossRef]
43. Chen, B.; Zhou, D.; Zhu, L. Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environ. Sci. Technol.* **2008**, *42*, 5137–5143. [CrossRef]
44. Xu, G.; Yang, X.; Spinosa, L. Development of sludge-based adsorbents: Preparation, characterization, utilization and its feasibility assessment. *J. Environ. Manag.* **2015**, *151*, 221–232. [CrossRef] [PubMed]
45. Bhakta, A.K.; Snoussi, Y.; Garah, M.E.; Ammar, S.; Chehimi, M.M. Brewer's spent grain biochar: Grinding method matters. *C* **2022**, *8*, 46. [CrossRef]
46. Wang, J.; Odinga, E.S.; Zhang, W.; Zhou, X.; Yang, B.; Waigi, M.G.; Gao, Y. Polyaromatic hydrocarbons in biochars and human health risks of food crops grown in biochar-amended soils: A synthesis study. *Environ. Int.* **2019**, *130*, 104899. [CrossRef]
47. EBC. *European Biochar Certificate–Guidelines for a Sustainable Production of Biochar*; European Biochar Fondation (EBC): Arbaz, Switzerland, 2012.
48. Leng, L.; Xiong, Q.; Yang, L.; Li, H.; Zhou, Y.; Zhang, W.; Jiang, S.; Li, H.; Huang, H. An overview on engineering the surface area and porosity of biochar. *Sci. Total Environ.* **2021**, *763*, 144204. [CrossRef]
49. Liu, Z.; Dugan, B.; Masiello, C.A.; Gonnermann, H.M. Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE* **2017**, *12*, e0179079. [CrossRef] [PubMed]
50. Rasa, K.; Heikkinen, J.; Hannula, M.; Arstila, K.; Kulju, S.; Hyväluoma, J. How and why does willow biochar increase a clay soil water retention capacity? *Biomass Bioenergy* **2018**, *119*, 346–353. [CrossRef]
51. Kocsis, T.; Ringer, M.; Biró, B. Characteristics and applications of biochar in soil–plant systems: A short review of benefits and potential drawbacks. *Appl. Sci.* **2022**, *12*, 4051. [CrossRef]
52. Shaaban, A.; Se, S.-M.; Mitan, N.M.M.; Dimin, M. Characterization of biochar derived from rubber wood sawdust through slow pyrolysis on surface porosities and functional groups. *Procedia Eng.* **2013**, *68*, 365–371. [CrossRef]
53. Li, X.; Shen, Q.; Zhang, D.; Mei, X.; Ran, W.; Xu, Y.; Yu, G. Functional groups determine biochar properties (pH and EC) as studied by two-dimensional 13C NMR correlation spectroscopy. *PLoS ONE* **2013**, *8*, e65949. [CrossRef]

54. Liang, B.; Lehmann, J.; Solomon, D.; Kinyangi, J.; Grossman, J.; O'Neill, B.; Skjemstad, J.O.; Thies, J.; Luizão, F.J.; Petersen, J. Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.* **2006**, *70*, 1719–1730. [CrossRef]
55. Berek, A.K.; Hue, N.; Ahmad, A. *Beneficial Use of Biochar to Correct Soil Acidity*; The Food Provider: Riverside, CA, USA, 2011; pp. 1–3.
56. Smebye, A.; Alling, V.; Vogt, R.D.; Gadmar, T.C.; Mulder, J.; Cornelissen, G.; Hale, S.E. Biochar amendment to soil changes dissolved organic matter content and composition. *Chemosphere* **2016**, *142*, 100–105. [CrossRef] [PubMed]
57. Kader, S.A.; Spalevic, V.; Dudic, B. Feasibility study for estimating optimal substrate parameters for sustainable green roof in Sri Lanka. *Environ. Dev. Sustain.* **2024**, *26*, 2507–2533. [CrossRef] [PubMed]
58. Novotný, M.; Šipka, M.; Miino, M.C.; Raček, J.; Chorazy, T.; Petreje, M.; Tošić, I.; Hlavínek, P.; Marković, M. Influence of different alternative organic substrates as fillings for green roofs on the quality of rainfall runoff. *Sustain. Chem. Pharm.* **2024**, *38*, 101465. [CrossRef]
59. Wang, H.; Garg, A.; Zhang, X.; Xiao, Y.; Mei, G. Utilization of coconut shell residual in green roof: Hydraulic and thermal properties of expansive soil amended with biochar and fibre including theoretical model. *Acta Geophys.* **2020**, *68*, 1803–1819. [CrossRef]
60. Van Nguyen, T.T.; Phan, A.N.; Nguyen, T.-A.; Nguyen, T.K.; Nguyen, S.T.; Pugazhendhi, A.; Phuong, H.H.K. Valorization of agriculture waste biomass as biochar: As first-rate biosorbent for remediation of contaminated soil. *Chemosphere* **2022**, *307*, 135834. [CrossRef]
61. Kuoppamäki, K.; Setälä, H.; Hagner, M. Nutrient dynamics and development of soil fauna in vegetated roofs with the focus on biochar amendment. *Nat.-Based Solut.* **2021**, *1*, 100001. [CrossRef]
62. D'Ambrosio, R.; Mobilia, M.; Khamidullin, I.F.; Longobardi, A.; Elizaryev, A.N. How substrate and drainage layer materials affect the hydrological performance of Green Roofs: CHEMFLO-2000 numerical investigation. In Proceedings of the International Conference on Computational Science and Its Applications, Cagliari, Italy, 10 September 2021; pp. 254–263.
63. Zhu, Y. Can Hydrological Function and Vegetation Cover of Failed Green Roofs Be Restored with Wood-Waste-Derived Biochar? Master's Thesis, University of Toronto, Toronto, ON, Canada, 2020.
64. Kuoppamäki, K.; Hagner, M.; Lehvävirta, S.; Setälä, H. Biochar amendment in the green roof substrate affects runoff quality and quantity. *Ecol. Eng.* **2016**, *88*, 1–9. [CrossRef]
65. Nguyen, C.N.; Chau, H.-W.; Muttil, N. A Field Study to Investigate the Hydrological Characteristics of Newly Established Biochar-Amended Green Roofs. *Water* **2024**, *16*, 482. [CrossRef]
66. Cai, W.; Huang, H.; Chen, P.; Huang, X.; Gaurav, S.; Pan, Z.; Lin, P. Effects of biochar from invasive weed on soil erosion under varying compaction and slope conditions: Comprehensive study using flume experiments. *Biomass Convers. Biorefin.* **2020**, *14*, 1–20. [CrossRef]
67. Chen, H.; Ma, J.; Wang, X.; Xu, P.; Zheng, S.; Zhao, Y. Effects of biochar and sludge on carbon storage of urban green roofs. *Forests* **2018**, *9*, 413. [CrossRef]
68. Hu, Y.; Chen, H. Biochar Amendment in the Green Roof Substrate Improve Air Quality. *E3S Web Conf.* **2022**, *350*, 01005. [CrossRef]
69. Tan, K.; Wang, J. Substrate modified with biochar improves the hydrothermal properties of green roofs. *Environ. Res.* **2023**, *216*, 114405. [CrossRef] [PubMed]
70. Pengiran Damit, A.M.M.b.; Hing Fatt, M.L.; Mohammad Sultan, A.M.S.B.H.; Shams, S. Suitability of substrate and vegetation for tropical green roofs. *J. Appl. Water Eng. Res.* **2023**, *12*, 245–251. [CrossRef]
71. Beck, D.A.; Johnson, G.R.; Spolek, G.A. Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environ. Pollut.* **2011**, *159*, 2111–2118. [CrossRef]
72. Zhang, Q.; Miao, L.; Wang, H.; Wang, L. Analysis of the effect of green roof substrate amended with biochar on water quality and quantity of rainfall runoff. *Environ. Monit. Assess.* **2019**, *191*, 304.
73. Huang, S.; Garg, A.; Mei, G.; Huang, D.; Chandra, R.B.; Sadasiv, S.G. Experimental study on the hydrological performance of green roofs in the application of novel biochar. *Hydrol. Process.* **2020**, *34*, 4512–4525. [CrossRef]
74. Meng, R.; Zhang, Q.; Li, D.; Wang, H. Influence of Substrate Layer Thickness and Biochar on the Green Roof Capacity to Intercept Rainfall and Reduce Pollution in Runoff. *Pol. J. Environ. Stud.* **2021**, *30*, 4085–4103. [CrossRef]
75. Farrell, C.; Cao, C.; Ang, X.; Rayner, J. Use of water-retention additives to improve performance of green roof substrates. In Proceedings of the XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014), Brisbane, Australia, 17 August 2014; Volume 1108, pp. 271–278.
76. Kuoppamäki, K. Vegetated roofs for managing stormwater quantity in cold climate. *Ecol. Eng.* **2021**, *171*, 106388. [CrossRef]
77. Goldschmidt, A.M. Biochar Amendment of Green Roof Substrate: Effect on Vegetation, Nutrient Retention, and Hydrologic Performance. Master's Thesis, University of Cincinnati, Cincinnati, OH, USA, 2018.
78. Olszewski, M.W.; Eisenman, S.W. Influence of biochar amendment on herb growth in a green roof substrate. *Hortic. Environ. Biotechnol.* **2017**, *58*, 406–413. [CrossRef]
79. Valagussa, M.; Gatt, A.; Tosca, A.; Martinetti, L. Physical, chemical and hydraulic characterization of different green roof growing media. In Proceedings of the III International Symposium on Growing Media, Composting and Substrate Analysis, Milan, Italy, 24–28 June 2019; Volume 1305, pp. 391–398.

80. Petreje, M.; Sněhota, M.; Chorazy, T.; Novotný, M.; Rybová, B.; Hečková, P. Performance study of an innovative concept of hybrid constructed wetland-extensive green roof with growing media amended with recycled materials. *J. Environ. Manag.* **2023**, *331*, 117151. [CrossRef]
81. Gan, L.; Garg, A.; Huang, S.; Wang, J.; Mei, G.; Zhang, K. Experimental and numerical investigation on rainwater management of dual substrate layer green roofs using biochar-amended soil. *Biomass Convers. Biorefin.* **2022**, 1–10. [CrossRef]
82. Gan, L.; Garg, A.; Wang, H.; Mei, G.; Liu, J. Influence of biochar amendment on stormwater management in green roofs: Experiment with numerical investigation. *Acta Geophys.* **2021**, *69*, 2417–2426. [CrossRef]
83. Wang, H.; Garg, A.; Huang, S.; Mei, G. Mechanism of compacted biochar-amended expansive clay subjected to drying–wetting cycles: Simultaneous investigation of hydraulic and mechanical properties. *Acta Geophys.* **2020**, *68*, 737–749. [CrossRef]
84. Li, M.; Garg, A.; Huang, S.; Jiang, M.; Mei, G.; Liu, J.; Wang, H. Hydrological properties of biochar-amended expansive soil under dynamic water environment and biochar-amended soil's application in green roofs. *Acta Geophys.* **2024**, *72*, 1055–1065. [CrossRef]
85. Huang, S.; Huang, D.; Garg, A.; Jiang, M.; Mei, G.; Pekkat, S. Stormwater management of biochar-amended green roofs: Peak flow and hydraulic parameters using combined experimental and numerical investigation. *Biomass Convers. Biorefinery* **2020**, *14*, 5835–5846. [CrossRef]
86. Valagussa, M.; Gatt, A.; Tosca, A.; Martinetti, L. Green roof flood mitigation in the Mediterranean region. In Proceedings of the International Symposium on Greener Cities for More Efficient Ecosystem Services in a Climate Changing World, Bologna, Italy, 12–15 September 2017; pp. 287–290.
87. Kuoppamäki, K.; Prass, M.; Hagner, M. Crushed concrete and biochar: A sustainable solution for vegetated roofs. *Urban For. Urban Green.* **2023**, *88*, 128082. [CrossRef]
88. Kuoppamäki, K.; Lehvävirta, S. Mitigating nutrient leaching from green roofs with biochar. *Landsc. Urban Plan.* **2016**, *152*, 39–48. [CrossRef]
89. Liao, W.; Drake, J.; Thomas, S.C. Biochar granulation, particle size, and vegetation effects on leachate water quality from a green roof substrate. *J. Environ. Manag.* **2022**, *318*, 115506. [CrossRef]
90. Cheng, Y.; Vaccari, D.A.; Johannesson, B.G.; Fassman-Beck, E. Multiyear Study on Phosphorus Discharge from Extensive Sedum Green Roofs with Substrate Amendments. *J. Sustain. Water Built Environ.* **2022**, *8*, 04022014. [CrossRef]
91. Peng, H.-Y.; Li, T.; Qi, Y.; He, Y.-P.; Huang, C.-Y.; Zhang, Z.-R. Control measure effects on the effluent quality from extensive green roofs based on stabilized sludge recycling. *Huan Jing Ke Xue* **2019**, *40*, 3612–3617.
92. Qiu, D.; Peng, H.; Li, T.; Qi, Y. Application of stabilized sludge to extensive green roofs in Shanghai: Feasibility and nitrogen leaching control. *Sci. Total Environ.* **2020**, *732*, 138898. [CrossRef] [PubMed]
93. Nguyen, C.N.; Chau, H.-W.; Muttil, N. A Field Study to Assess the Impacts of Biochar Amendment on Runoff Quality from Newly Established Green Roofs. *Hydrology* **2024**, *11*, 112. [CrossRef]
94. Xiong, W.; Li, J.; Wang, H.; Wu, Y.; Li, D.; Xue, J. Biochar Addition and the Runoff Quality of Newly Constructed Green Roofs: A Field Study. *Sustainability* **2023**, *15*, 4081. [CrossRef]
95. Vavrincová, L.; Pipíška, M.; Urbanová, J.; Frišták, V.; Horník, M.; Machalová, L.; Soja, G. Sewage sludge biochar as a sustainable and water-safe substrate additive for extensive green roofs. *Sustain. Chem. Pharm.* **2024**, *39*, 101604. [CrossRef]
96. Qian, K.; Kumar, A.; Zhang, H.; Bellmer, D.; Huhnke, R.J.R.; Reviews, S.E. Recent advances in utilization of biochar. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1055–1064. [CrossRef]
97. Biswal, B.K.; Vijayaraghavan, K.; Tsen-Tieng, D.L.; Balasubramanian, R. Biochar-based bioretention systems for removal of chemical and microbial pollutants from stormwater: A critical review. *J. Hazard. Mater.* **2022**, *422*, 126886. [CrossRef]
98. Zhang, G.; Tang, B.; Bian, H.; Huang, Y.; Jin, H.; He, B.-J. Investigating the Impacts of Biochar Addition to Substrate on Mitigating Carbon Dioxide Emissions in Green Roofs. In Proceedings of the International conference on Climate Change and Environmental Sustainability, Chongqing, China, 7 October 2022; pp. 131–140.
99. Xu, C.; Liu, Z.; Cai, G.; Zhan, J. Nutrient leaching in extensive green roof substrate layers with different configurations. *Environ. Sci. Pollut. Res.* **2022**, *29*, 34278–34287. [CrossRef]
100. Piscitelli, L.; Rivier, P.-A.; Mondelli, D.; Miano, T.; Joner, E.J. Assessment of addition of biochar to filtering mixtures for potential water pollutant removal. *Environ. Sci. Pollut. Res.* **2018**, *25*, 2167–2174. [CrossRef]
101. Liao, W.; Sidhu, V.; Sifton, M.A.; Margolis, L.; Drake, J.A.; Thomas, S.C. Biochar and vegetation effects on discharge water quality from organic-substrate green roofs. *Sci. Total Environ.* **2024**, *922*, 171302. [CrossRef]
102. Lunt, P.H.; Fuller, K.; Fox, M.; Goodhew, S.; Murphy, T.R. Comparing the thermal conductivity of three artificial soils under differing moisture and density conditions for use in green infrastructure. *Soil Use Manag.* **2022**, *39*, 260–269. [CrossRef]
103. Abu-Hamdeh, N.H. Thermal properties of soils as affected by density and water content. *Biosyst. Eng.* **2003**, *86*, 97–102. [CrossRef]
104. Abu-Hamdeh, N.H.; Reeder, R.C. Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. *Soil Sci. Soc. Am. J.* **2000**, *64*, 1285–1290. [CrossRef]
105. Zhu, D.; Ciais, P.; Krinner, G.; Maignan, F.; Jornet Puig, A.; Hugelius, G. Controls of soil organic matter on soil thermal dynamics in the northern high latitudes. *Nat. Commun.* **2019**, *10*, 3172. [CrossRef]
106. Atinafu, D.G.; Yun, B.Y.; Wi, S.; Kang, Y.; Kim, S. A comparative analysis of biochar, activated carbon, expanded graphite, and multi-walled carbon nanotubes with respect to PCM loading and energy-storage capacities. *Environ. Res.* **2021**, *195*, 110853. [CrossRef] [PubMed]

107. Fulthorpe, R.; MacIvor, J.S.; Jia, P.; Yasui, S.-L.E. The green roof microbiome: Improving plant survival for ecosystem service delivery. *Front. Ecol. Evol.* **2018**, *6*, 5. [CrossRef]
108. Santoyo, G.; Urtis-Flores, C.A.; Loeza-Lara, P.D.; Orozco-Mosqueda, M.d.C.; Glick, B.R. Rhizosphere colonization determinants by plant growth-promoting rhizobacteria (PGPR). *Biology* **2021**, *10*, 475. [CrossRef]
109. Chen, H.; Du, X.; Lai, M.; Nazhafati, M.; Li, C.; Qi, W. Biochar improves sustainability of green roofs via regulate of soil microbial communities. *Agriculture* **2021**, *11*, 620. [CrossRef]
110. Molineux, C.J.; Connop, S.P.; Gange, A.C. Manipulating soil microbial communities in extensive green roof substrates. *Sci. Total Environ.* **2014**, *493*, 632–638. [CrossRef] [PubMed]
111. Varela, A.; Sandoval-Albán, A.; Muñoz, M.; Gómez, A.G.; Bogoya, J.M.; Combariza, G. Evaluation of green roof structures and substrates for *Lactuca sativa* L. *in tropical conditions. Urban For. Urban Green.* **2021**, *60*, 127063. [CrossRef]
112. Chen, H.; Ma, J.; Wei, J.; Gong, X.; Yu, X.; Guo, H.; Zhao, Y. Biochar increases plant growth and alters microbial communities via regulating the moisture and temperature of green roof substrates. *Sci. Total Environ.* **2018**, *635*, 333–342. [CrossRef]
113. Di Bonito, R.; Biagiotti, D.; Giagnacovo, G.; Viola, C.; Campiotti, C. Sustainable and energy saving urban horticulture on rooftop gardens in Mediterranean climatic conditions. In Proceedings of the International Symposium on Greener Cities for More Efficient Ecosystem Services in a Climate Changing World, Bologna, Italy, 12–15 September 2017; pp. 383–388.
114. Cao, C.T.; Farrell, C.; Kristiansen, P.E.; Rayner, J.P. Biochar makes green roof substrates lighter and improves water supply to plants. *Ecol. Eng.* **2014**, *71*, 368–374. [CrossRef]
115. Liu, J.; Garg, A.; Wang, H.; Huang, S.; Mei, G. Moisture management in biochar-amended green roofs planted with Ophiopogon japonicus under different irrigation schemes: An integrated experimental and modeling approach. *Acta Geophys.* **2022**, *70*, 373–384. [CrossRef]
116. Wang, H.; Zhang, K.; Gan, L.; Liu, J.; Mei, G. Expansive soil-biochar-root-water-bacteria interaction: Investigation on crack development, water management and plant growth in green infrastructure. *Int. J. Damage Mech.* **2021**, *30*, 595–617. [CrossRef]
117. Karteris, M.; Theodoridou, I.; Mallinis, G.; Tsiros, E.; Karteris, A. Towards a green sustainable strategy for Mediterranean cities: Assessing the benefits of large-scale green roofs implementation in Thessaloniki, Northern Greece, using environmental modelling, GIS and very high spatial resolution remote sensing data. *Renew. Sustain. Energy Rev.* **2016**, *58*, 510–525. [CrossRef]
118. Li, J.-f.; Wai, O.W.; Li, Y.S.; Zhan, J.-M.; Ho, Y.A.; Li, J.; Lam, E. Effect of green roof on ambient CO_2 concentration. *Build. Environ.* **2010**, *45*, 2644–2651. [CrossRef]
119. Yang, J.; Yu, Q.; Gong, P. Quantifying air pollution removal by green roofs in Chicago. *Atmos. Environ.* **2008**, *42*, 7266–7273. [CrossRef]
120. Baraldi, R.; Neri, L.; Costa, F.; Facini, O.; Rapparini, F.; Carriero, G. Ecophysiological and micromorphological characterization of green roof vegetation for urban mitigation. *Urban For. Urban Green.* **2019**, *37*, 24–32. [CrossRef]
121. Gross, A.; Bromm, T.; Glaser, B. Soil organic carbon sequestration after biochar application: A global meta-analysis. *Agronomy* **2021**, *11*, 2474. [CrossRef]
122. Xu, H.; Cai, A.; Wu, D.; Liang, G.; Xiao, J.; Xu, M.; Colinet, G.; Zhang, W. Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C: N ratio and soil pH: A global meta-analysis. *Soil Tillage Res.* **2021**, *213*, 105125. [CrossRef]
123. Ghofrani, Z.; Sposito, V.; Faggian, R. A comprehensive review of blue-green infrastructure concepts. *Int. J. Environ. Sustain.* **2017**, *6*, 15–36. [CrossRef]
124. Zhao, G.; Mu, X.; Wen, Z.; Wang, F.; Gao, P. Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China. *Land Degrad. Dev.* **2013**, *24*, 499–510. [CrossRef]
125. Liquete, C.; Kleeschulte, S.; Dige, G.; Maes, J.; Grizzetti, B.; Olah, B.; Zulian, G. Mapping green infrastructure based on ecosystem services and ecological networks: A Pan-European case study. *Environ. Sci. Policy* **2015**, *54*, 268–280. [CrossRef]
126. Liao, W.; Sifton, M.A.; Thomas, S.C. Biochar granulation reduces substrate erosion on green roofs. *Biochar* **2022**, *4*, 61. [CrossRef]
127. Saade, J.; Cazares, S.P.; Liao, W.; Frizzi, G.; Sidhu, V.; Margolis, L.; Thomas, S.; Drake, J. Influence of Biochar Amendment on Runoff Retention and Vegetation Cover for Extensive Green Roofs. In Proceedings of the Canadian Society of Civil Engineering Annual Conference, Whistler, BC, Canada, 25–28 May 2022; pp. 1117–1132.
128. Werdin, J.; Conn, R.; Fletcher, T.D.; Rayner, J.P.; Williams, N.S.; Farrell, C. Biochar particle size and amendment rate are more important for water retention and weight of green roof substrates than differences in feedstock type. *Ecol. Eng.* **2021**, *171*, 106391. [CrossRef]
129. Yan, J.; Yang, P.; Wang, B.; Wu, S.; Zhao, M.; Zheng, X.; Wang, Z.; Zhang, Y.; Fan, C. Green Roof Systems for Rainwater and Sewage Treatment. *Water* **2024**, *16*, 2090. [CrossRef]
130. Liao, W.; Drake, J.; Thomas, S.C. Biochar granulation enhances plant performance on a green roof substrate. *Sci. Total Environ.* **2022**, *813*, 152638. [CrossRef]
131. Thomas, S.C. Post-processing of biochars to enhance plant growth responses: A review and meta-analysis. *Biochar* **2021**, *3*, 437–455. [CrossRef] [PubMed]
132. Seitz, S.; Teuber, S.; Geißler, C.; Goebes, P.; Scholten, T. How Do Newly-Amended Biochar Particles Affect Erodibility and Soil Water Movement?—A Small-Scale Experimental Approach. *Soil Syst.* **2020**, *4*, 60. [CrossRef]
133. Omondi, M.O.; Xia, X.; Nahayo, A.; Liu, X.; Korai, P.K.; Pan, G. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma* **2016**, *274*, 28–34. [CrossRef]

134. Matuštík, J.; Hnátková, T.; Kočí, V. Life cycle assessment of biochar-to-soil systems: A review. *J. Clean. Prod.* **2020**, *259*, 120998. [CrossRef]
135. Cao, Y.; Pawłowski, A. Life cycle assessment of two emerging sewage sludge-to-energy systems: Evaluating energy and greenhouse gas emissions implications. *Bioresour. Technol.* **2013**, *127*, 81–91. [CrossRef]
136. Barry, D.; Barbiero, C.; Briens, C.; Berruti, F. Pyrolysis as an economical and ecological treatment option for municipal sewage sludge. *Biomass Bioenergy* **2019**, *122*, 472–480. [CrossRef]
137. Azzi, E.S.; Karltun, E.; Sundberg, C. Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. *Biochar* **2022**, *4*, 18. [CrossRef]
138. Kamali, M.; Sweygers, N.; Al-Salem, S.; Appels, L.; Aminabhavi, T.M.; Dewil, R. Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chem. Eng. J.* **2022**, *428*, 131189. [CrossRef]
139. Harsono, S.S.; Grundman, P.; Lau, L.H.; Hansen, A.; Salleh, M.A.M.; Meyer-Aurich, A.; Idris, A.; Ghazi, T.I.M. Energy balances, greenhouse gas emissions and economics of biochar production from palm oil empty fruit bunches. *Resour. Conserv. Recycl.* **2013**, *77*, 108–115. [CrossRef]
140. Kuppusamy, S.; Thavamani, P.; Megharaj, M.; Venkateswarlu, K.; Naidu, R. Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions. *Environ. Int.* **2016**, *87*, 1–12. [CrossRef] [PubMed]
141. Pratt, K.; Moran, D. Evaluating the cost-effectiveness of global biochar mitigation potential. *Biomass Bioenergy* **2010**, *34*, 1149–1158. [CrossRef]
142. Galinato, S.P.; Yoder, J.K.; Granatstein, D. The economic value of biochar in crop production and carbon sequestration. *Energy Policy* **2011**, *39*, 6344–6350. [CrossRef]
143. Seiple, T.E.; Coleman, A.M.; Skaggs, R.L. Municipal wastewater sludge as a sustainable bioresource in the United States. *J. Environ. Manag.* **2017**, *197*, 673–680. [CrossRef]
144. Kumar, A.; Bhattacharya, T. Biochar: A sustainable solution. *Environ. Dev. Sustain.* **2021**, *23*, 6642–6680. [CrossRef]
145. Qin, F.; Li, J.; Zhang, C.; Zeng, G.; Huang, D.; Tan, X.; Qin, D.; Tan, H. Biochar in the 21st century: A data-driven visualization of collaboration, frontier identification, and future trend. *Sci. Total Environ.* **2022**, *818*, 151774. [CrossRef] [PubMed]
146. Pourhashem, G.; Hung, S.Y.; Medlock, K.B.; Masiello, C.A. Policy support for biochar: Review and recommendations. *GCB Bioenergy* **2019**, *11*, 364–380. [CrossRef]
147. You, S.; Li, W.; Zhang, W.; Lim, H.; Kua, H.W.; Park, Y.-K.; Igalavithana, A.D.; Ok, Y.S. Energy, economic, and environmental impacts of sustainable biochar systems in rural China. *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 1063–1091. [CrossRef]