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Addition of Biochar to Green Roof Substrate to Enhance Plant Performance: A Long-Term Field Study

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Abstract: Green roofs (GRs) have been widely adopted as an effective Green Infrastructure (GI) practice in cities worldwide, offering ecosystem services such as stormwater management and reduction of the urban heat island effect. However, their widespread implementation is still limited by a lack of local research and uncertain research findings. As a result, the potential benefits of GRs often cannot justify their high investment costs. Previous studies have sought to enhance the effectiveness of GRs by evaluating new GR systems, such as integrating GRs with green walls, blue roofs, photovoltaic (PV) panels, radiant cooling systems, as well as the use of innovative materials in GR substrates. Biochar, a carbon-rich substrate additive, has been recently investigated. The addition of biochar improves water/nutrient retention of GRs, thereby increasing substrate fertility and promoting plant performance. Although studies have examined the effects of biochar on GR plant growth, long-term observational studies focusing on the impacts of various biochar-related parameters remain necessary. Therefore, this research aims to assess the performance of GR plants with different biochar parameters, namely, amendment rates, application methods, and particle sizes. A one-year-long observational data of plant height, coverage area, and dry weight from six GR test beds was collected and analyzed. Results demonstrate the positive impacts of biochar on plant growth in different biochar-GR setups and types of plant species (wallaby grass, common everlasting, and billy buttons). The GR with medium biochar particles at the amendment rate of 15% v/v had the best plant performance. This contributes to increasing the feasibility of GRs by maximizing GR benefits to buildings where they are installed while reducing GR costs of irrigation and maintenance. The conclusions were further supported by observed data indicating reduced substrate temperature, which in turn reduces building energy consumption. Since vegetation is crucial in determining the effectiveness of a GR system, this study will offer valuable insights to GR designers and urban planners for developing optimal biochar-amended GR systems. Such systems provide numerous benefits over traditional GRs, including enhanced plant growth, reduced building energy costs, a shorter payback period, and reduced structural requirements.

Keywords: biochar; green roof; rooftop garden; green infrastructure; vegetation growth; plant performance; innovative building design; sustainable construction

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1. Introduction

Green roofs (GRs) are one of the promising Green Infrastructure (GI) practices that can simultaneously address multiple social and environmental issues. GRs have huge potential to transform urban areas into green spaces sustainably and provide several ecosystem services. More specifically, a GR system with plenty of layers (vegetation, substrate/growing medium, filter layer, drainage layer, and so on) can hold a significant amount of rainwater to mitigate urban flooding, improve stormwater quality, enhance Human Thermal Comfort (HTC) and save energy, increase noise insulation, purify air, restore biodiversity, and economic and social benefits. Though GRs have been significantly researched over the past decades [1–3], the implementation of GRs has been limited due to numerous constraints. One of the primary reasons is that the performance of GRs has not been consistently reported and properly understood. It is worth noting that findings about GR are highly variable according to weather conditions, substrate composition, substrate thickness, age of GR, maintenance, and fertilizer application [4–6]. For example, a comprehensive review paper by Bevilacqua [7] found that a generic conclusion could not be made about the performance of GRs in terms of building energy savings. GR performed differently in different climate characteristics and GR designs, such as plants and substrate thickness. Similar findings about the contradictory impacts of GRs on building energy consumption were reported by Alim, et al. [8]. Another challenge is the high capital costs of GRs, which is a growing concern for building owners and GR investors. The payback period for a GR system is challenging to determine because some benefits, such as building aesthetics, recreational spaces, health benefits, and biodiversity, are difficult to quantify in monetary terms [1,5,6]. Moreover, some GR systems have been reported to be economically infeasible. For example, a 50-year Life Cycle Cost Analysis (LCCA) by Yao, et al. [9] found that GRs have negative net savings as compared to conventional white roofs. This challenge is contributed to by inadequate local research information since the LCCA was mostly from the USA, where the GR market is less mature and has higher costs of GR materials and maintenance [8]. In addition to economic aspects, Zhang and He [10] highlighted that concerns about structural safety impact the implementation of GRs among various stakeholders, including designers, contractors, builders, building operators, and owners. Since many potential areas for constructing GRs are old buildings with weak structural capabilities, the feasibility of widely implementing GRs is further limited. Although the costs of GRs remain high when compared to that of traditional roofs, the benefits of GRs need to be more pronounced and compelling for authorities to implement regulations that encourage their widespread adoption.

In addition to using simulation tools to better understand the benefits of GRs [11–14], innovative technologies such as integrated GR systems and new GR materials have been employed to enhance the multiple advantages of GRs. For instance, the integration of GRs with photovoltaic (PV) systems has led to positive results. GRs cooled indoor air temperatures while also boosting electricity production due to the cooler temperature of photovoltaic (PV) panels [15–17]. GRs were also more effective when they were integrated with radiant and evaporative components (water pipes and sprinklers) of a radiant cooling system [18–20]. Additionally, GRs have been also combined with green walls to further improve HTC, which is followed by a decrease in building energy consumption [21,22]. Moreover, a so-called "Blue-green roof" system by adding another water storage layer to a GR system has been found effective in greatly alleviating runoff volume [23–25]. In addition, new GR materials have also been applied to achieve more effective GR functions. For example, Carpenter, et al. [26] obtained a remarkable average retention rate of 96.8%, which was higher than the frequently reported values due to the use of an effective drainage layer. Biochar, a carbon-rich substrate additive, has been investigated in different fields, including agriculture and geotechnical structures, due to its advantageous physiochemical properties. Biochar is a product of the pyrolysis process, transforming biomass into a stable form of carbon that cannot escape to the atmosphere for a long period of time. Biochar possesses a highly porous structure and large specific surface area, so it is able to retain more water and nutrients and improve soil fertility and plant growth [27,28]. As a result, the serviceability of GRs could be maintained during their expected lifetime with less effort and reduced costs for operation and maintenance. Furthermore, biochar-amended GRs are lighter relative to a traditional GR with the same substrate thickness due to the reduced dry and saturated bulk density of substrates [29]. This implies the installation of a thicker substrate layer without adding extra structural loading.

The effectiveness of adding biochar into GR substrates has recently captured the interest of researchers. While biochar in agriculture has been significantly investigated and implemented [30,31], biochar in GR systems is still in the early stages due to a recent introduction. Besides obstacles associated with high manufacturing costs resulting in limited availability [32,33], the application of biochar in GRs has also been constrained by insufficient and inconsistent research information. More particularly, the capability of biochar in improving water retention has been mostly agreed [34–41], whereas biochar performed differently in terms of water quality. For example, loads of Total Phosphorus (TP) and Total Nitrogen (TN) in the discharge of GRs modified by biochar were lower than those of non-biochar GRs [34,42,43]. By contrast, biochar failed to reduce loads of TP in runoff in previous studies [44–46]. In addition to the uncertain performance of biochar-amended GRs, the lack of multiyear observation studies results in an incomplete understanding of the long-term effects of biochar in GR systems [47–49]. Consequently, the compatibility of biochar with a specific GR substrate mixture is recommended to be assessed in pilot-scale GRs in a multiyear observation prior to a large-scale implementation [43,50].

Vegetation plays a major role in determining the effectiveness of a GR system. However, the plants on a GR are often subjected to harsh growing conditions, including extreme weather like intense solar radiation and strong winds, as well as low moisture and nutrient availability in the thin substrates typical of extensive GR systems [51]. If GR plants are in poor condition, their ability to reduce stormwater volume and building energy consumption may be diminished. Bevilacqua [7] stated that the cooling potential of GRs was highly connected to plant diversity and coverage. As a result, researchers have recently focused on studying the benefits of biochar in enhancing substrate moisture content, improving substrate fertility, and boosting plant performance. For example, Liao, Drake and Thomas [51] examined different particle sizes of granulated and traditional biochar. A 115-day experiment under greenhouse conditions observing plants in GR growth containers (71 cm) found that granulated biochar prevailed over traditional biochar in terms of plant growth, and intermediate granulated biochar particles had the most significant impact. Under rooftop conditions, the performance of plants in five identical GR plots (0.3 m × 1 m) during a year was observed in the study of Chen, et al. [52]. The impacts of different biochar amendment rates (5%, 10%, 15%, and 20% v/v) on GR plants were evaluated. They found that the biomass of GR plants was higher in biochar-amended GRs than that in non-biochar GRs. They also concluded that the amount of biochar in GR substrates had a noticeable impact. Additionally, Saade, et al. [53] investigated the effectiveness of adding 5.4% v/v biochar to 1.8 m × 1.8 m extensive GR test beds in increasing plant coverage area and density. Biochar only positively affected native species, whereas the growth of sedum was lower in biochar test beds. However, no significant differences were found between the test beds during around 5 months of observation; thus, the authors highlighted the requirement for further monitoring.

While the impacts of biochar on GR plants have been previously investigated, the understanding of the long-term performance of GR plants in different biochar-GR setups remains restricted. Therefore, this research aims to assess the long-term impacts of biochar on different types of GR plants. Given that biochar offers multiple benefits to increase the feasibility of widespread application of GRs on rooftops of either existing or new buildings, this paper focuses on evaluating the effectiveness of biochar in improving plant performance. The aim is to maintain GR serviceability, maximize the benefits to the buildings where they are installed, and reduce operational and maintenance costs, ultimately encouraging the broader adoption of GRs. This research is a continuation of work presented in the studies by Nguyen, Chau and Muttil [41] and Nguyen, et al. [54], which focused on runoff retention and runoff quality, respectively. Additionally, this research also seeks to understand the impact of various biochar-related parameters, which include biochar amendment rates, particle sizes, and application methods, on plant performance. Research outcomes are expected to obtain necessary information about the biochar benefit to plant growth under an Australian climate; consequently, a GR system can effectively provide ecosystem services during its lifetime. The obtained data also contributes to enhancing awareness about the influential parameters of biochar, thereby identifying the optimal biochar-GR systems. In-depth knowledge from GR research using innovative materials/technologies to improve GR performance and alleviate the GR costs for irrigation and maintenance is important to attract the attention of the community, building owners, and authorities, thereby promoting the widespread application of GRs.

2. Method and Materials

The methodological framework used in this study consists of three steps and is presented in Figure 1. The first step consists of the design and construction of the six GR test beds. Step 2 consists of the selection of biochar and biochar-related parameters. Based on a detailed literature review of biochar-GR research and the identified knowledge gap, it was decided to investigate the impacts of three biochar-related parameters, namely biochar amendment rate, particle size, and application methods. Within the second step, different plant species suitable for extensive GRs were considered, and 3 species were chosen to investigate the benefits of biochar amendment to plant performance. Step three consists of data collection and undertaking measurement of selected parameters. Further details regarding these three steps can be found in the following sub-sections within this section.

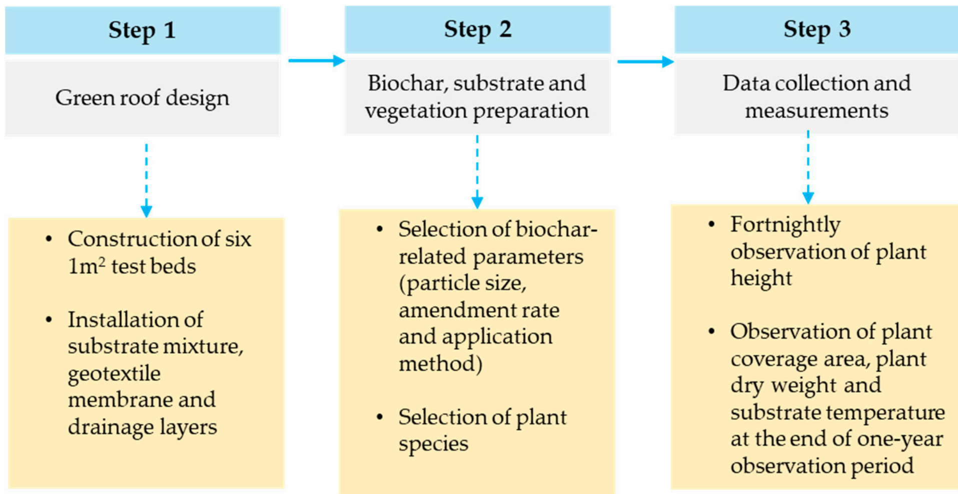
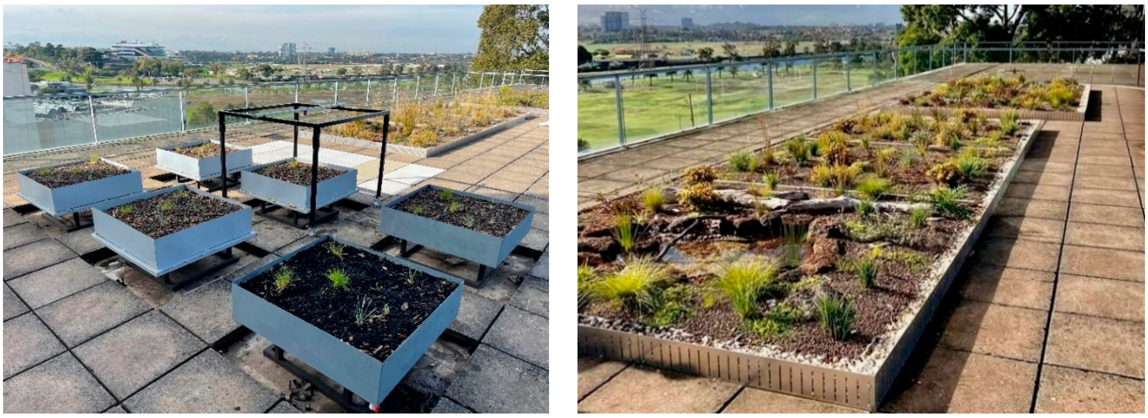


Figure 1. A flow chart depicting the methodological framework used in this study.

2.1. Green Roof Design

The observations were carried out on the rooftop of Building M at the Footscray Park campus of Victoria University (VU), Victoria, Australia. The study area is under the influence of the temperate oceanic climate (Köppen climate classification Cfb), which is characterized by warm summers and mild winters. In 2020, 50 m^2 of GR was installed on the rooftop of Building M as part of a project generating green spaces for the campus area (Figure 2a). However, this 50 m^2 GR was not suitable for the investigation of the benefits of biochar to plant growth, and hence, six 1 m^2 GR test beds were installed on the same rooftop (Figure 2b). Six 1 m × 1 m galvanized steel trays elevated 0.3 m from the roof tiles followed a typical extensive GR design with a 150-mm substrate thickness, non-woven geotextile membrane as a filter layer, and a 50-cm drainage layer by Atlantis 20 mm Flo-cell and VersiDrain® 30. In terms of GR types, built-in-place GRs, and modular GRs are two commonly used extensive GR systems [55]. Modular GR trays have advantages, including being lightweight, flexible and affordable design, easy installation and expansion, and low maintenance [56,57]. However, the experimental setup in this study aimed to utilize 1 m^2 trays to mimic the conventional built-in-place extensive GRs that provide long-lasting durability and long-term benefits, especially in areas prone to extreme weather conditions.

Figure 3 presents a cross-section of the GR system used in this study, featuring the application of 7.5% v/v medium biochar particles at the bottom of the substrate. The following sections provide details on the GR substrate mixture, biochar characteristics, experimental setup involving GR and biochar, and the selected plants used in this research.



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

Figure 2. The green roofs on the rooftop of Building M at the Footscray Park campus of Victoria University (**a**) The 50 m^2 GR system and (**b**) The six GR test beds.

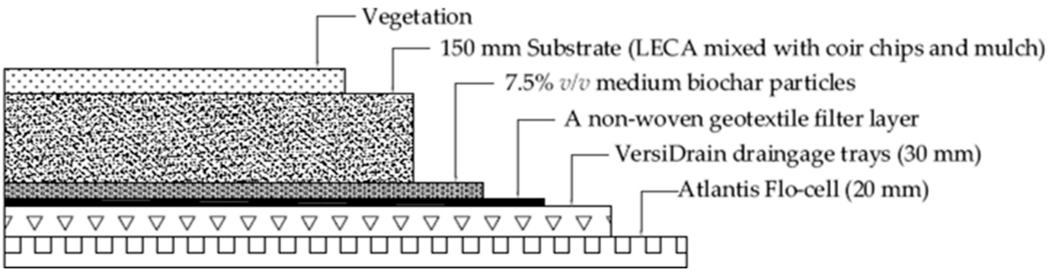


Figure 3. The cross-section of a green roof test bed with 7.5% v/v medium biochar particles applied at the bottom of the substrate.

2.2. Biochar, Substrate, and Vegetation Preparation

Pre-grown plants of three common wallaby grasses (*Rytidosperma caespitosum*), two common everlasting wildflowers (*Chrysocephalum apiculatum*), and two Billy Buttons wildflowers (*Pycnosorus globosus*) were transferred to each test bed on 5 May 2023. These plants are drought-tolerant and are well-suited for the thin, extensive GR substrate used in this study and can withstand infrequent irrigation, irregular maintenance, and low substrate nutrients. Moreover, since they are native plants, they are expected to adapt to the local climate and soil conditions more easily and provide broader coverage. The size of each plant species was similar at the time they were planted in the test beds. The distribution of the plants in each of the six test beds is shown in Figure 4. Subsequent to this, the observation period started. The chosen 150-mm GR substrate is a mixture of light-expanded clay aggregate (LECA), hardwood mulch, and coir chips (80%, 15%, and 5% v/v, respectively). LECA is commonly known as a lightweight material that can absorb 18% of water by weight. The same substrate was used for all GR test beds. However, the differences between the treatments were the application methods and particle sizes of biochar. Biochar applied in this study used woody materials (eucalyptus) as feedstock with the pyrolysis target temperature of 500–550 °C. The examined biochar particle size ranges were 1–3 mm and less than 1 mm (hereinafter referred to as medium and fine particles, respectively). Biochar was added in different ways, including thoroughly mixing the biochar into the substrate (mixing method), applying biochar to the top surface (top-dressed method), and applying biochar at the bottom of the substrate (bottom-applied method). Table 1 provides the specifications of the GR-biochar experimental setup used in this study.

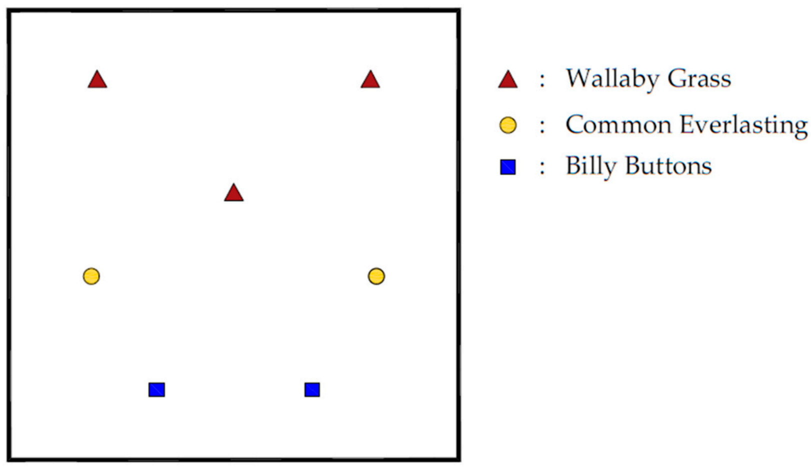


Figure 4. The distribution of plants in each test bed.

Table 1. Specifications of biochar-amended green roof test beds studied in this research.

GR Test Bed	Biochar Amendment Rate (% *v*/*v*)	Biochar Application Method	Biochar Particle Size
GR-0	0	NA	NA
GR-7.5M-M	7.5	Mixing Method	Medium
GR-7.5B-M	7.5	Bottom-applied Method	Medium
GR-15M-M	15	Mixing Method	Medium
GR-7.5M-F	7.5	Mixing Method	Fine
GR-7.5T-F	7.5	Top-dressed Method	Fine

Most of the test beds applied biochar at a dose of 7.5% v/v, which has been successfully used in previous studies, and high costs and low availability of biochar. For instance, 5–7% v/v was recommended by Li, et al. [58] to avoid plant mortality and obtain a good water retention capacity. Similarly, Wang, et al. [59] found that GR substrates amended by 5% v/v biochar effectively improved plant growth, whereas 15% v/v biochar could prevent root expansion. Additionally, Beck, Johnson and Spolek [43] suggested the biochar amendment rate of 7% v/v in GRs due to the low availability of biochar. However, given that biochar would perform differently according to types of substrate types and vegetation, this study still investigated the impact of a higher dose of biochar on plant performance with one test bed applying 15% v/v biochar. It is also noteworthy that the amount of biochar in GR substrates has a significant impact on plant growth in previous research [51,52,60,61]. Regarding the application methods, biochar has been mostly applied by mixing, whereas a few papers applied biochar as a top or middle layer of substrates [34–36,62–67]. Thus, the understanding of the performance of biochar at the bottom of GR substrates is missing, especially in vegetation-relating research. As compared to the top-dressed method, Kuoppamäki, Hagner, Lehvävirta and Setälä [34] found positive effects of bottom-applied biochar on GR runoff quantity and quality, which could accordingly affect plant performance. Therefore, one of the test beds applied biochar as a bottom layer of the substrate. Regarding particle sizes, fine to medium biochar particles are suggested to be used in coarse-textured substrates to not only achieve high water retention capacity but also maintain fast drainage and avoid GR waterlogging [32,66,68,69]. Oppositely, large particles were found less effective in retaining water/nutrients as compared to small particles with higher porosity and specific surface area [66]. Consequently, this research compared one test bed with fine biochar particles with one test bed with medium particles using the same mixing method to study the impact of biochar particle sizes on GR plant performance. Despite the loss potential of fine biochar particles on the GR top surface caused by wind and water erosion [65,70], this study amended fine biochar particles to one of the test beds by the top-dressed method. In cases of aged GRs when biochar cannot be applied by other methods without affecting established plants, fine biochar particles penetrate GR substrates through rainfall or irrigation more easily than larger particles do. Thus, this application method is particularly advantageous for enhancing plant performance in failed GRs.

2.3. Data Collection and Measurements

The observation period started as soon as similar pre-grown plants of each species were moved to the studied GRs on 5 May 2023. The performance of plants in each GR was properly compared under the same experimental conditions, such as rooftop weather conditions and irrigation scheduling. Plant heights were recorded fortnightly. Four average plant heights for each plant species were reported. Hence, information on plant development in four different observation periods was provided. More specifically, plants were subject to cold, cold and dry, warm and wet, and hot and dry seasons. Weather characteristics in the study area during the observation period are illustrated in Figure 5. It is noted that the growths of GR plants struggled due to unfavorable rooftop weather conditions and nutrient-deficient substrates. Hence, they slowly developed in the first few months, and a similar amount of nitrogen-rich fertilizer was added to each test bed on 3 October 2023. At the end of the observation period on 16 May 2024, a photo showing the plant coverage area of each test bed was taken. Plant samples, including their roots, were then carefully removed from the substrates. Substrate and biochar particles were removed from the plant roots using tweezers. The plant samples were further cleaned by using a 100-mesh sieve. Afterward, they were gently washed before they were dried in a forced-air oven at 60 °C for 48 h. Eventually, the dried samples were weighed to measure the plant dry weights. Similar methodologies were adopted in previous studies [51,52].

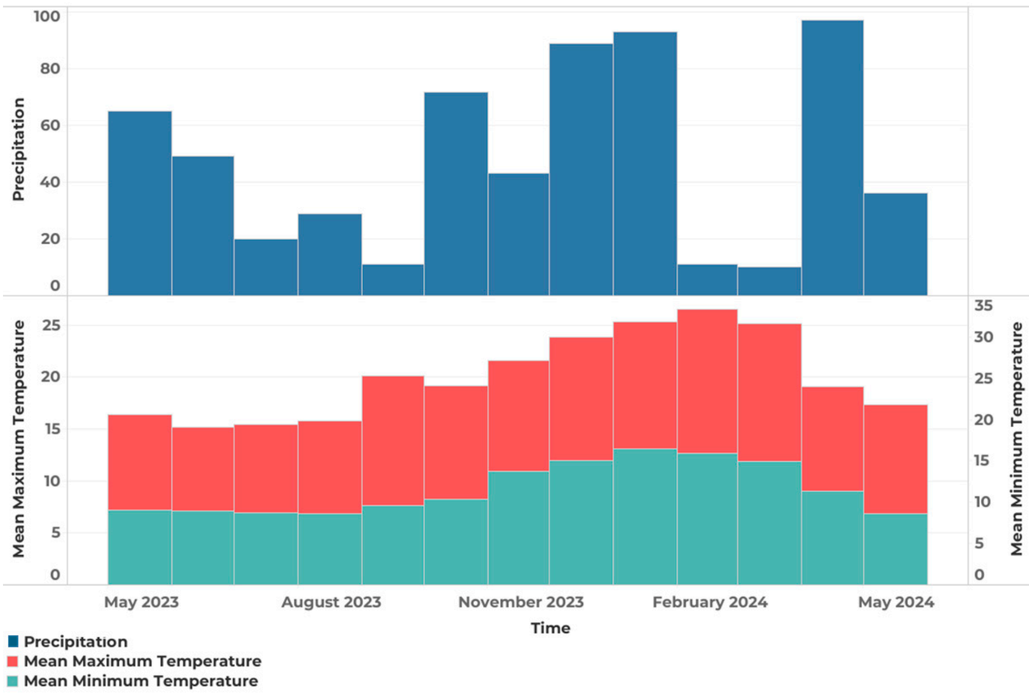


Figure 5. Weather characteristics at the study area during the observation period from May 2023 to May 2024.

The addition of biochar to GR substrates results in an increase in substrate porosity. A higher porous GR substrate due to biochar makes GRs cooler since biochar increases Water Holding Capacity (WHC) and transpiration rate in substrates, which is more pronounced on hot days [60]. Therefore, biochar effectively promotes plant performance due to increased Plant Available Water (PAW) and Permanent Wilting Point (PWP). In this study, thermal sensors were installed in the center of each test bed to measure substrate temperatures at a depth of 10 cm. Thermal data at 5 min intervals were continuously recorded from

27–29 May 2024 and 31 May–2 June 2024 to assess the impact of biochar-related parameters on GR substrate temperature under hot and cold weather conditions. The obtained thermal data is expected to explain the effectiveness of biochar in improving plant growth by regulating substrate temperature and moisture. On the other hand, nutrient availability in GR substrate is also an important factor for healthy plant growth. Runoff quantity and quality data are essential to support findings related to plant performance in biochar and non-biochar GRs. These data were obtained from two previous studies carried out at the same experimental site [41,54].

3. Results

3.1. Plant Height

The height of each plant was recorded fortnightly, and average heights from the four observation periods were reported in this research. These observations aim to represent different development periods of the plant species during one year of observations. There was no significant difference between the GRs in terms of the height of each plant species in the first few months. Plant heights developed slowly in the early stages as they adapted to the harsh roof environment. The second observation period took place from 1 August 2023 to 15 November 2023, during which the plants experienced faster growth after the addition of nitrogen-rich fertilizer to each test bed on 3 October 2023. The third observation period occurred from 16 November 2023 till 15 February 2024, when the plants grew towards their maximum heights under warm and wet weather conditions (December 2023 and January 2024). The final measurements of plant heights were carried out during a hot and dry period (February and March 2024).

The first observation period recorded a maximum wallaby grass height of 52 cm in GR-7.5M-M. The positive impacts of biochar on the wallaby grass height could be seen even during the very beginning of the monitoring period. However, the differences between biochar and non-biochar GRs were insignificant (Figure 6). A similar trend was found for most test beds during the next observation period when this plant species grew taller and then dried out. The decrease in plant heights was observed at the end of the observation period. Biochar-related parameters generally did not have a significant impact, except in the case of GRs with fine biochar particles at the top of the substrate (GR-7.5T-F), which failed to increase the height of this plant species. In general, wallaby grass in biochar-amended GRs performed better than in traditional GRs in terms of plant height, and the most noticeable effects were recorded in the final observation.

For the common everlasting wildflowers, all plants kept growing taller, even after the hot and dry period, and reached up to 33 cm in GR-15M-M. When compared to the control GR, the benefit of biochar in promoting the vertical development of common everlasting plants was not easily identifiable in some biochar test beds (Figure 7). The differences between those test beds were not significant, and no consistent trends were observed. The exceptions were GR-15M-M and GR 7.5M-F, which had the greatest impacts on biochar in the last two observation periods.

Figure 8 illustrates the growths of billy button plants, which in this study were notably weak in the first two observation periods. Furthermore, one of the billy button plants in the traditional GR test bed died during the last observation period, and the performance of billy button plants in the test bed with mixed fine biochar particles was remarkably poor. It could be due to the poor rooftop environmental conditions (drought stress, extreme winds, and so on). In contrast, they started developing quickly, with a maximum height of 56 cm in GR-7.5M-M observed during the last two observation periods. The differences between the test beds were negligible during the first and second observation periods. However, the positive impacts of biochar on the height of billy button plants became pronounced after the first two observation periods with the exception of GR-7.5M-F. Overall, medium biochar particles mixed at the application rates of 7.5% and 15% v/v had the highest performance.

Figure 6. Average height of three wallaby grasses with standard error in the six green roof test beds during the monitoring period.

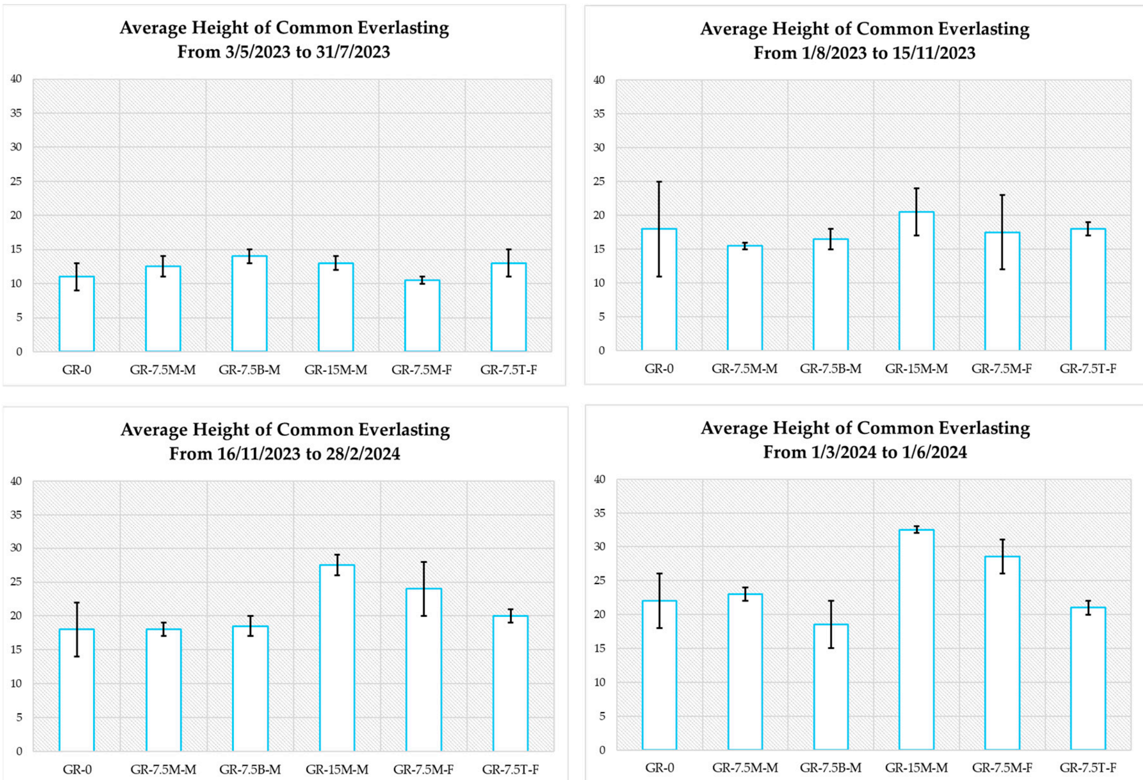


Figure 7. Average height of two common everlasting plants with standard error in the six green roof test beds during the monitoring period.

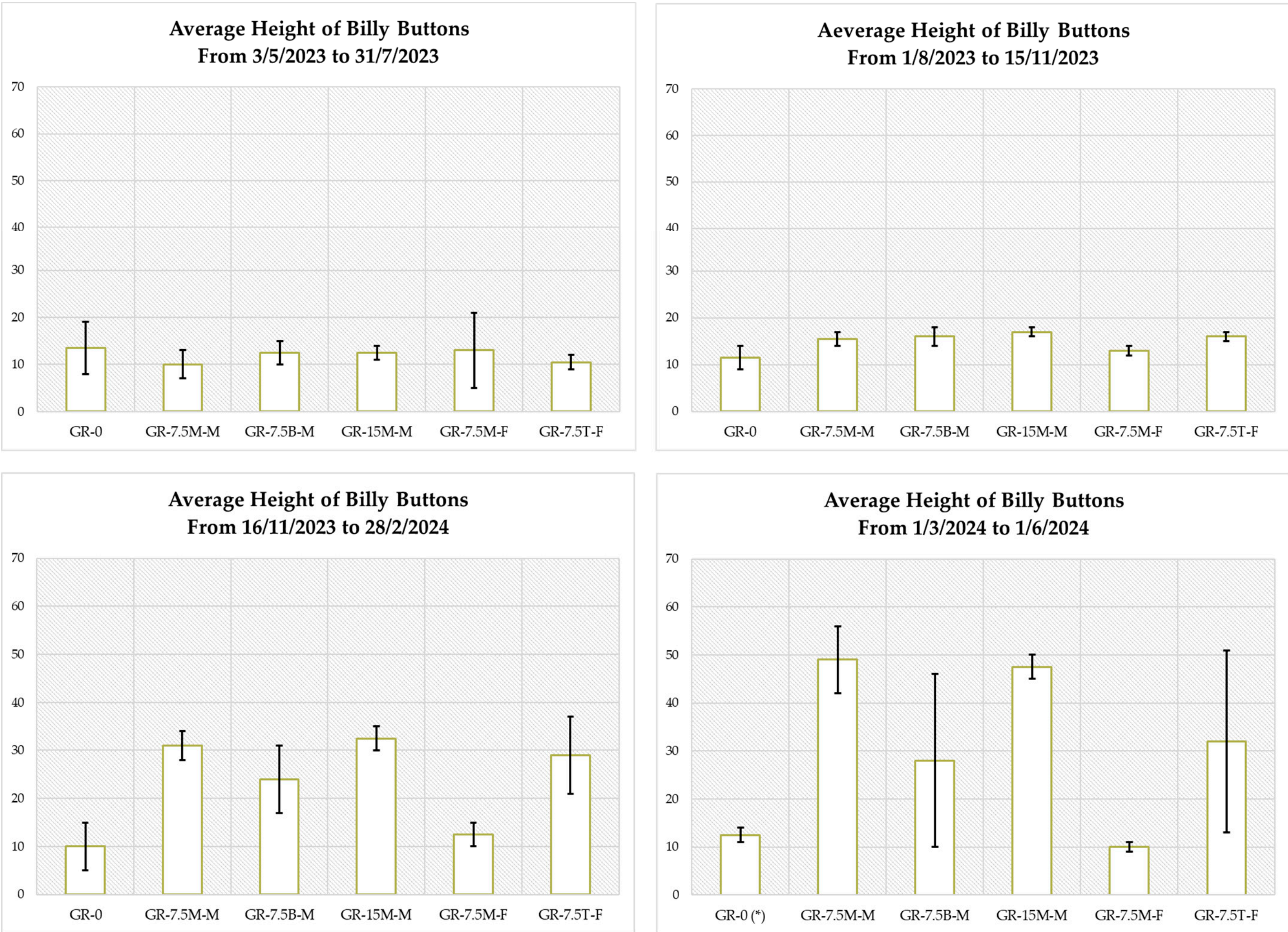


Figure 8. Average height of two billy button plants with standard error in the six green roof test beds during the monitoring period. (*) one plant died, the average height was measured from one plant only.

3.2. Dry Weight and Plant Coverage Area

Since plant height cannot fully reveal the performance of the vegetation, another plant heath indicator, namely "dry weight" was taken into consideration. Plant dry weight was measured at the end of the study period, and the corresponding data are presented in Figure 9. The results demonstrate the variation of dry weights of studied plants according to plant species. Similar to height, the dry weight of wallaby grass in GR-7.5T-F was lower than that in GR-0. The impacts of biochar on other GR test beds were found to be positive, and the maximum dry weights of this plant species were from GR-15M-M. Moreover, the highest dry weights of common everlasting and billy button plants were also observed in GR-15M-M. Despite lower heights of the common everlasting plants in GR-7.5B-M and GR-7.5T-F than those in GR-0, dry weights from these two GRs with biochar were higher. A contrasting situation was observed in billy button plants in GR 7.5M-M, where plants were tall but had a low dry weight. In contrast to wallaby grass, the impacts of biochar on dry weights of both common everlasting and billy button plants were positive in all biochar-amended GRs. Taking the total dry weight into account, the test bed modified by mixing medium biochar particles at a dose of 15% v/v had the best performance. There were no significant differences between other biochar test beds.

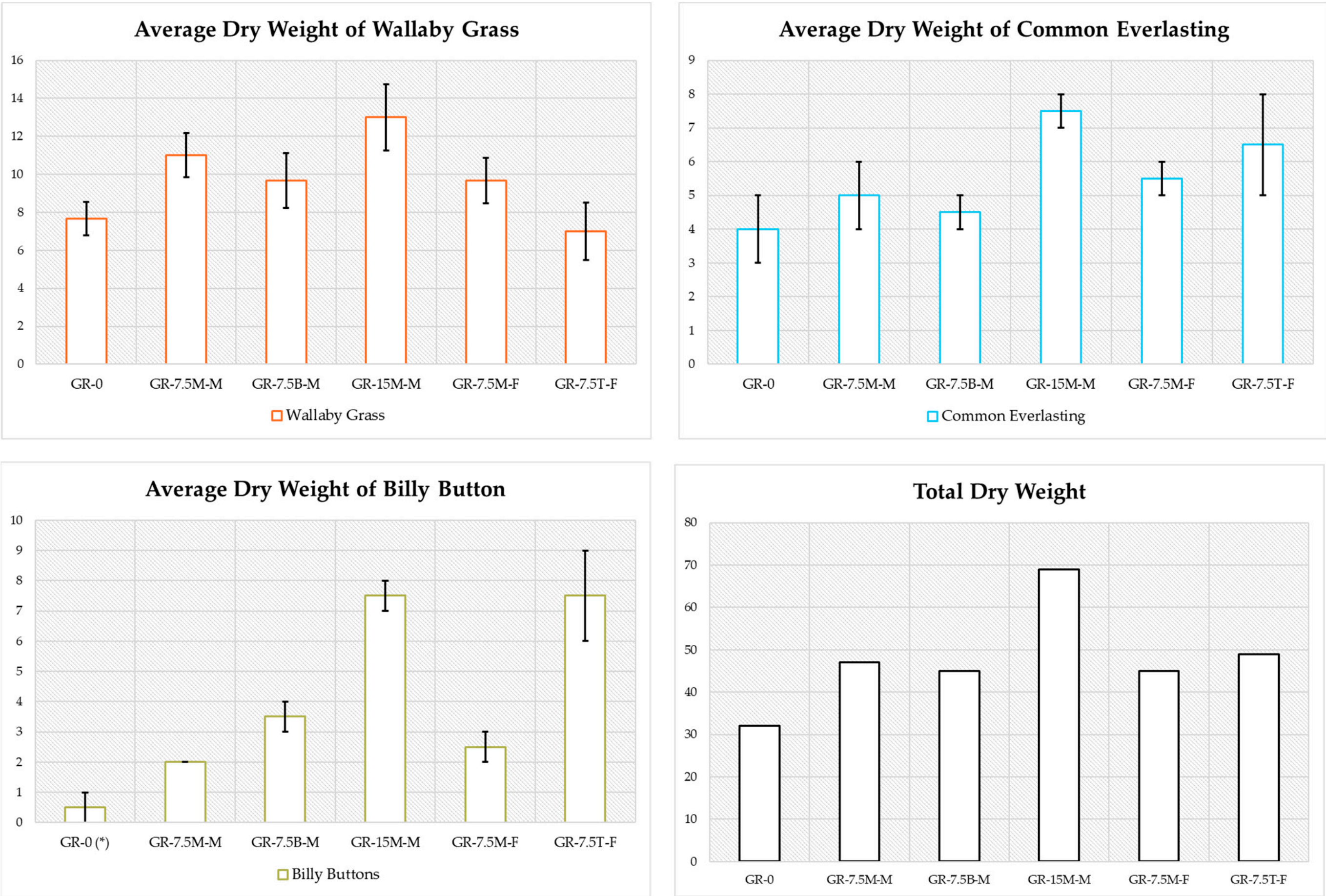


Figure 9. Average dry weight of plants with standard error in six green roof test beds at the end of the monitoring period. (*) one plant died, the average dry weight was measured from one plant only.

Most plants in this research tended to develop vertically instead of growing laterally; a further investigation into vegetation conditions through the plant coverage area was only reported at the end of the monitoring period (Figure 10). The plant coverage area in the unmodified GR was apparently lower than that in biochar-modified GRs. In accordance with plant height and dry weight, biochar in GR-15M-M had the greatest effects on the plant coverage area. Since most plants had a columnar growing shape, the differences between other biochar-amended GRs were barely noticeable.

3.3. Substrate Temperature

Figures 11 and 12 illustrate temperature data at 5-min intervals collected from a thermal sensor installed at a 10 cm substrate depth in the center of each test bed Figure 11. demonstrates the substrate temperature in three consecutive hot days from 27 May to 29 May 2024, whereas data in Figure 12 was continuously recorded during three relatively cold days from 29 May to 2 June 2024. Regardless of the ambient rooftop temperature in hot and cold periods, a similar thermal pattern was identified in all test beds. Specifically, the temperature of biochar-amended substrates of GR-7.5M-M, GR-15M-M, and GR-7.5M-F was noticeably lower than that of GR-0 with no biochar. A slight improvement in substrate temperature was observed when biochar was applied at the bottom of the substrate of GR-7.5B-M. In contrast, biochar increased substrate temperature when it was applied using the top-dressed method (GR-7.5T-F) during the day. However, GR-7.5T-F released absorbed heat more quickly than GR-0 and cooled down faster at night. Although the substrate temperatures followed the same pattern during hot and cold days, the effects of biochar in reducing substrate temperature were more pronounced at higher ambient temperatures.

Compared to GR-0, the maximum reduction in substrate temperature during the hottest times of the hot days was 4 °C and 3.5 °C for GR-7.5M-M and GR-15M-M, respectively. They were reduced to 2 °C during the cold days.

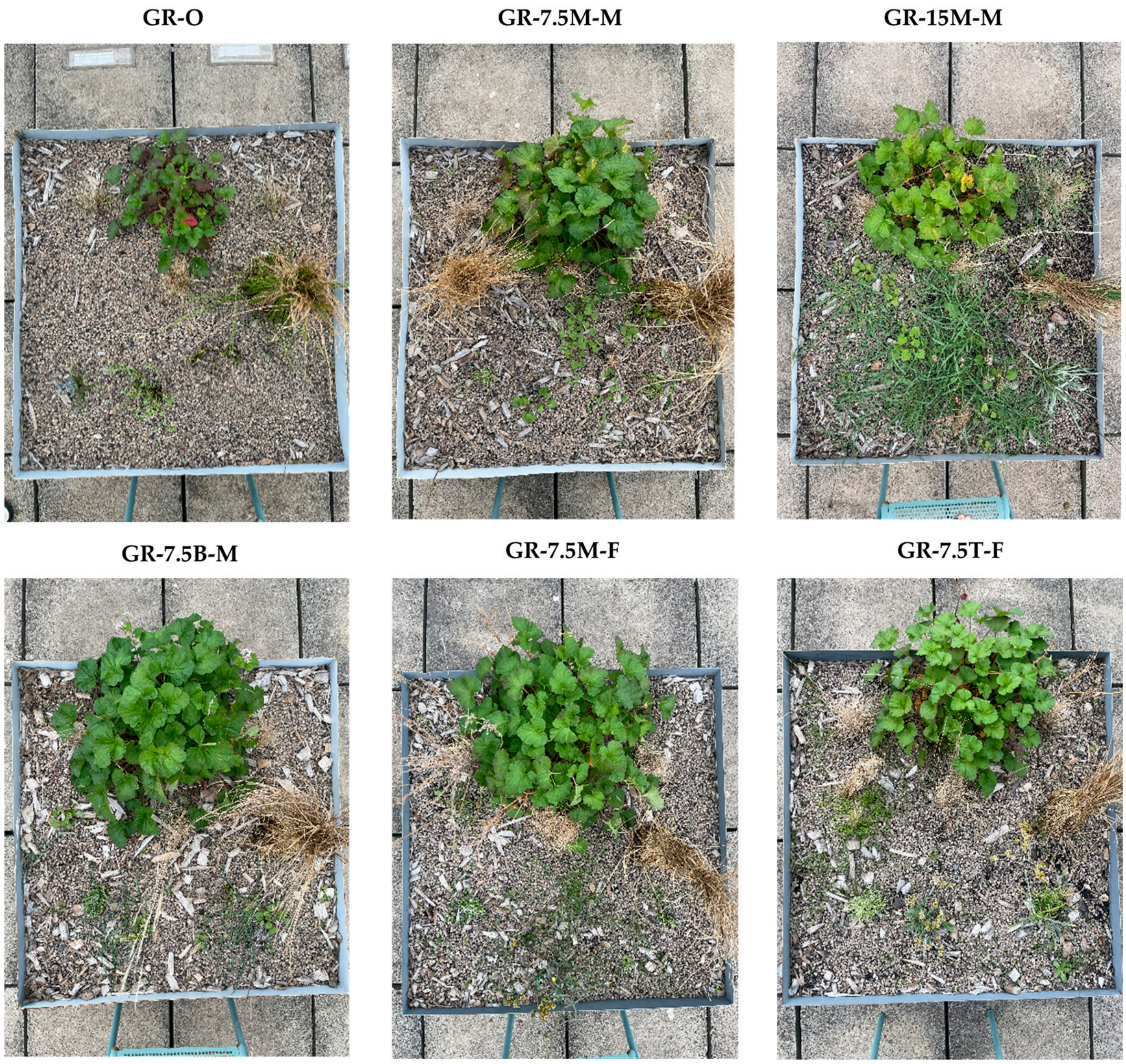


Figure 10. Plant coverage area in the six green roof test beds at the end of the monitoring period.

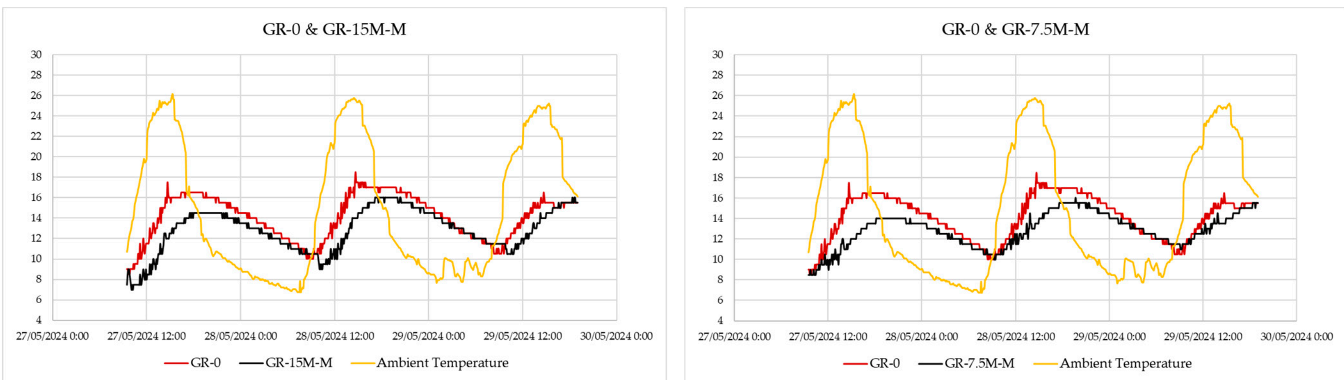


Figure 11. *Cont*.

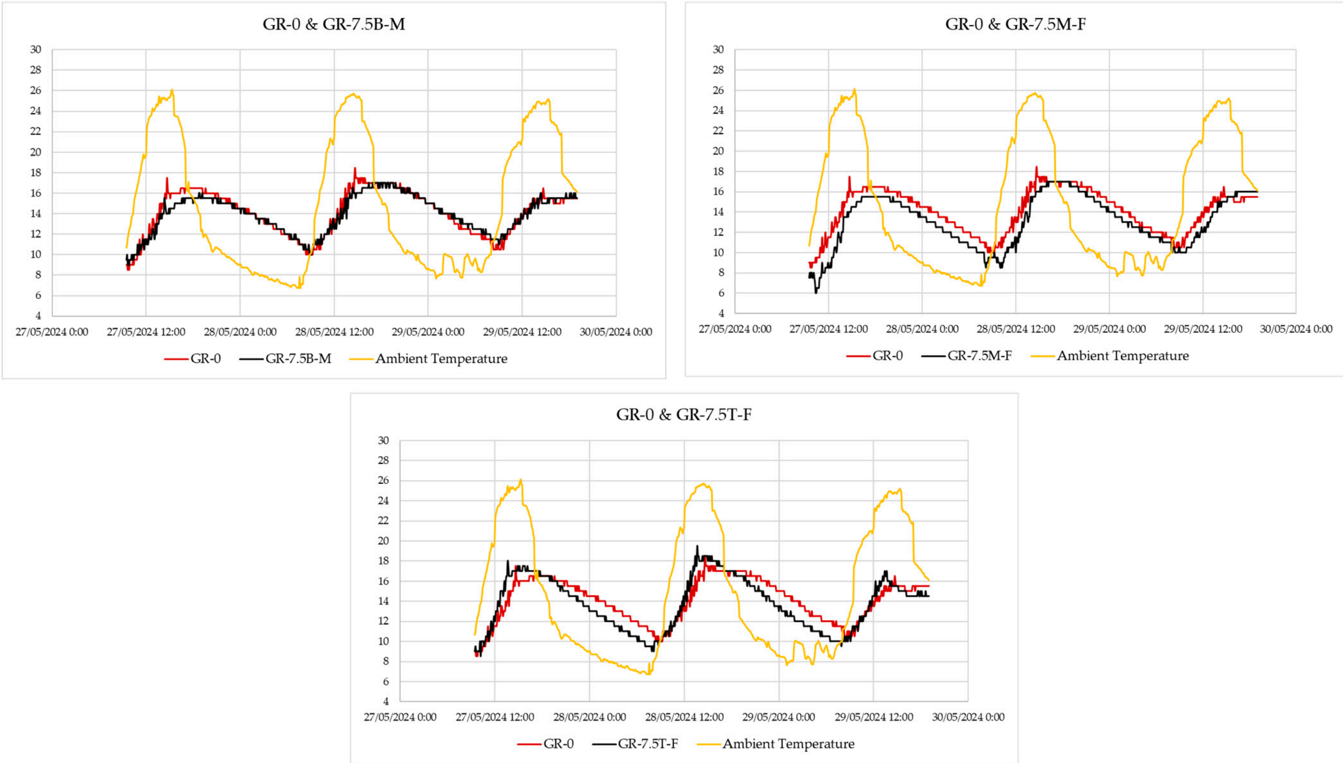


Figure 11. Temperature at 10 cm substrate depth in the six green roof test beds from 9:30 to 19:00 over three consecutive hot days (from 27 May 2024 to 29 May 2024).

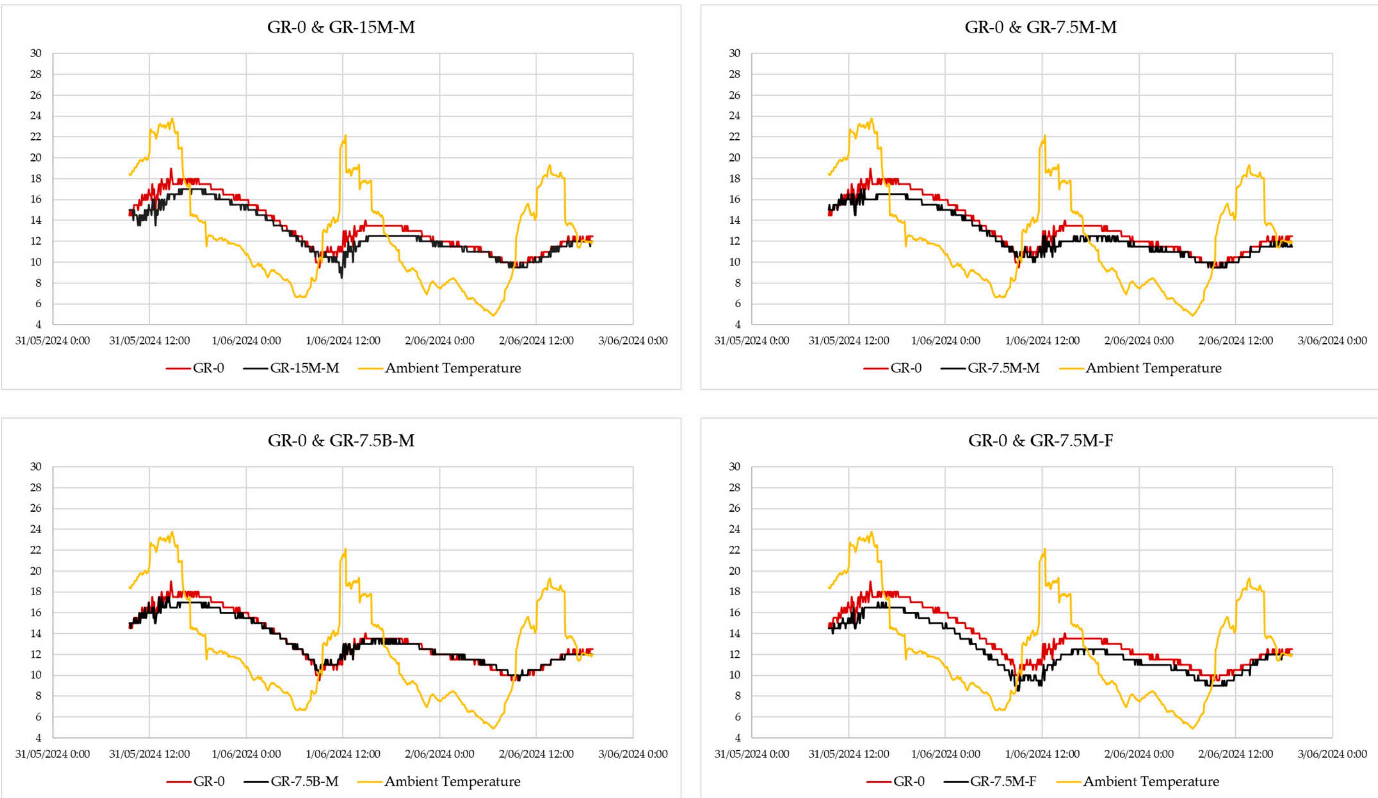


Figure 12. *Cont.*

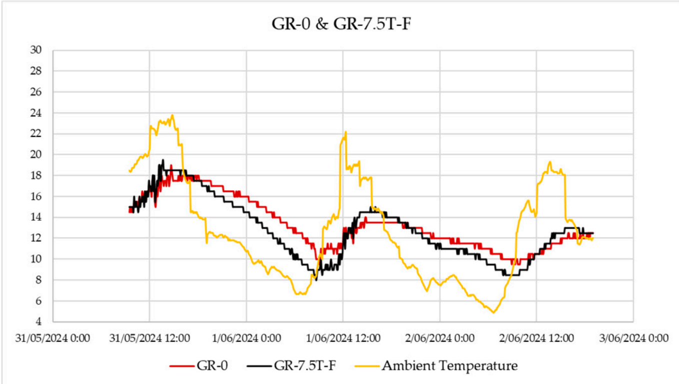


Figure 12. Temperature at 10 cm substrate depth in the six green roof test beds from 9:30 to 19:00 over three consecutive cold days (from 31 May 2024 to 2 June 2024).

4. Discussion

4.1. Impacts of Biochar on Green Roof Plant Performance

Six 1 m^2 GR test beds were constructed on the building rooftop to investigate the impacts of biochar on plant performance. As previously mentioned, this research sought to investigate the plant responses in test beds designed to replicate the conventional built-in-place GR systems, which are known for their longevity and adaptability across various environments, in contrast to modular GRs. A similar experimental setup has been observed in other studies examining the impact of biochar on vegetation cover, such as the research conducted by Saade, Cazares, Liao, Frizzi, Sidhu, Margolis, Thomas and Drake [53]. They observed plant coverage area and density of sedum and native species in four 1.8 × 1.8 m built-in-place GR test beds. However, the application of such built-in-place test beds limits the ability to replicate and randomize biochar-GR treatments, which constrains the assessment of the significance of differences between the treatments, as in the present study. Therefore, future research on the impact of biochar on GR plants should also consider the use of modular GR trays or small-growth containers. They are more appropriate to make replications with randomization of GR-biochar treatments. Such experiments using modular GR trays can be found in the studies by Cao, Farrell, Kristiansen and Rayner [29], which included 10 replications per treatment and 100 experimental plots (9 cm × 9 cm), and by Goldschmidt [39], which featured five replications per treatment and 45 plastic trays (60 cm × 29 cm).

The impact of biochar on plant performance became more evident by the end of the one-year study period. This suggests that biochar has significant long-term effects on plant performance. Similar observations have been reported in past studies. For instance, Vavrincová, et al. [71] began to notice significant differences in plant coverage area between biochar-amended and non-biochar GRs starting from the second year. In contrast, Olszewski and Eisenman [61] reported insignificant impacts of biochar by considering plant density and coverage area during a short monitoring period of 5 months. Future studies are recommended to carry out multiyear observations to fully understand the effectiveness of biochar on plant growth.

Overall, although most plants survived throughout the study period, they did not achieve the growth levels observed when they were planted in optimal ground-based growing environments. Billy buttons were observed to have the poorest performance, especially in GR-0 and GR-7.5M-F. They hardly developed either vertically or horizontally. One plant died in GR-0 during the final observation period. This could be attributed to their exposure to extreme solar heat, strong winds, limited nutrient availability, and possible incompatibility between plants and LECA-based substrates used in this research. Since vegetation plays a major role in maintaining the expected GR services, it is necessary to identify optimal plants for specific GR substrates by conducting pilot-scale experiments under different climatic conditions [50,72]. Although some plants from each species nearly reached their maximum heights, they could not grow to their full mature width. It is worth noting that most of the studied plants tended to grow upright instead of developing laterally. As a result, the dry weights of some tall plants were lower than those of short plants, and vice versa. Consistent with previous findings, the impacts of biochar on plant performance in this study are highly dependent on plant species. The only exception is the addition of 15% medium biochar particles by the mixing method (GR-15M-M). Throughout the monitoring period, this green roof setup (GR-15M-M) consistently exhibited the best performance in terms of both height and dry weight across different plant species. While other biochar test beds did not always increase plant heights during certain observation periods, biochar consistently enhanced plant performance in terms of dry weights across all biochar-amended green roofs in this study. Therefore, plant dry weight could be a more accurate indicator of plant growth since it provides meaningful and precise information about long-term plant performance encompassing leaves, flowers, stems, and roots.

This research observed higher plant growth with the increase in the biochar amendment rate from 7.5% to 15%, a trend that has also been documented in previous studies. For instance, Chen, Du, Lai, Nazhafati, Li and Qi [52] and Chen, Ma, Wei, Gong, Yu, Guo and Zhao [60] studied sludge biochar at different application rates of 5%, 10%, 15%, and 20% v/v. They found the highest plant dry weight with 15% v/v biochar (15.92 g plant^{-1}), whereas 11.5 g plant^{-1} was from 5% v/v biochar. They also recommended 10–15% v/v biochar as the optimum rate for plant performance since the application of 20% v/v biochar resulted in a reduced plant dry weight. Olszewski and Eisenman [61] reported similar findings, noting the maximum dry weight of peppermint was at the 15% v/v biochar addition rate. In contrast, biochar at 5% and 10% v/v had no impact on basil plants.

The present study also made conclusions regarding other biochar-related parameters. The influence of biochar application methods on plant performance was evident when comparing GR-7.5M-M with GR-7.5B-M, and GR-7.5M-F with GR-7.5T-F. The mixing method tended to have greater effects, whereas the effects of the bottom-applied or top-dressed method were weaker since they did not directly promote plant growth by regulating temperature, moisture, and nutrients around the plant roots. This is further discussed in the following sub-section. However, the difference between GR-7.5M-F and GR-7.5T-F was negligible. Therefore, fine biochar particles applied using the top-dressed method are strongly recommended to either restore failed GRs or to enhance established GRs when the mixing or bottom-applied methods cannot be implemented. Similar studies are required due to the insufficient understanding of the relationship between biochar application methods and plant growth. Despite mixed results among plant species in GR-7.5M-M and GR-7.5M-F using the same biochar application rate and method, medium particles (1–3 mm) showed a slight improvement over fine particles (less than 1 mm). This finding is consistent with the study by Tang, et al. [73]. The authors of that study suggested the use of small to intermediate biochar (0.5–2.0 mm) for the optimal performance of velvetleaf and cowpea. Intermediate particle sizes (2–2.8 mm) of two different biochars were also optimal for plant growth in the study of Liao, Drake and Thomas [51]; however, the improvements were minimal. They also observed the negative impacts of conventional biochar on the performance of *Agastache foeniculum* relative to non-biochar treatments. Several meta-analyses also supported findings about the greater effects of biochar with particle sizes in the range of 0.5 to 2 mm [74–76]. The positive impacts of biochar on plant growth at intermediate particle sizes are the combined effect of aeration, drainage, and WHC of GR substrates [51].

This research observed different impacts of biochar on each plant species. Biochar significantly enhanced the plant performance of common everlasting and billy buttons, whereas the effects on wallaby grass were minimal. They also varied among the test beds. While the impacts of biochar on billy buttons were the most apparent in GR-15M-M and GR-7.5T-F, their performance in other biochar test beds was poor. Contradictory results for certain plant species and types of biochar have been documented in past studies [29,51,61], indicating substantial variability in how biochar affects the performance of different plant species. Therefore, further investigations on biochar and plant growth are still required. Long-term field experiments with native plants are strongly recommended to gain a thorough understanding of how plants perform under challenging rooftop growing conditions over time. Long-term observations of pilot-scale field experiments are necessary to ensure the successful implementation of large-scale GRs with optimal plant species.

4.2. Influential Factors: Substrate Temperature and Nutrient Availability

Data on substrate temperature at 10 cm depth was obtained in this research to investigate the reasons behind the differences in plant performance between biochar and non-biochar GRs. The different biochar setups used in this study were effective in reducing GR substrate temperature during both hot and cold periods. However, the effects were more remarkable during the highest ambient temperature. Additionally, biochar-related parameters also significantly impacted the temperature of GR substrates, and they were associated with plant performance. The smallest reduction in substrate temperature was observed in GR-7.5M-M and GR-15M-M, with GR-7.5M-F following closely behind. This may have contributed to the improved plant performance by increasing substrate moisture in these test beds. A similar finding was reported by Chen, Ma, Wei, Gong, Yu, Guo and Zhao [60]. They compared the GR temperature at 15-cm substrate depth among 0%, 5%, 15%, and 20% v/v sludge biochar and found 10–15% v/v as the optimal biochar application rate for temperature reduction. The regression analysis showed a negative correlation between substrate moisture and substrate temperature in hot summer (up to 45 °C). The addition of biochar resulted in higher substrate moisture content, thereby reducing substrate temperature. In winter, GR substrate moisture remained higher under biochar treatments, even though biochar-amended substrates became warmer when compared to non-biochar substrates. In addition to substrate temperature/moisture, biochar benefits to other plant growth-relating parameters such as Plant Available Water (PAW) and Permanent Wilting Point (PWP) have also been well documented. For example, 30% v/v green waste biochar in the study by Cao, Farrell, Kristiansen and Rayner [29] increased PAW by 16% and delayed PWP by 2 days. Liu, et al. [77] observed that 20% v/v biochar delayed PWP by 3 days and decreased irrigation water volume and number of plant water-stress days.

Nevertheless, some test beds did not follow the abovementioned thermal pattern. The substrate temperature of GR-7.5B-M was nearly the same as that of GR-0, which illustrates that the bottom-applied method of biochar did not significantly alter the substrate temperature measured at 10 cm depth as compared to the mixing method. Furthermore, biochar, which was applied using the top-dressed method, even increased the temperature at 10 cm substrate depth. Although fine biochar particles in GR-7.5T-F could gradually move down into the LECA-based substrates over time, they did not seem to reach during the data collection period yet. In general, biochar applied using the bottom/top-dressed method did not alter the substrate pore structure at 10 cm depth where temperature data was measured. Future studies are recommended to collect temperature data at different substrate depths to completely understand the correlation between substrate temperature/moisture and plant performance.

The better plant growth observed in some GRs, where biochar had no notable impact on substrate temperature or moisture, may be attributed to nutrient availability in the substrates. Data on runoff quantity and quality from the GR test beds studied in this research were collected and reported in the studies of Nguyen, Chau and Muttil [41] and Nguyen, Chau and Muttil [54], respectively. The performance of plants could be reasonably explained by data collected from runoff quantity/quality experiments since they occurred within the observation period of this research. Results revealed that biochar substantially enhanced the water retention capacity of all biochar-amended GRs. The application of 7.5% v/v fine biochar particles by either the mixing or top-dressed method (GR-7.5M-F and GR-7.5T-F) had the highest performance, followed by GR-7.5B-M. On the other hand, mixed results regarding runoff quality were obtained. Water quality indicators including pH, EC, and Total Phosphorus (TP) and Total Nitrogen (TN) concentrations, were analyzed.

Results illustrated that different biochar setups failed to reduce nutrient concentrations when compared to the non-biochar treatment. Nonetheless, the significant potential of biochar for improving runoff quality was evident when evaluating nutrient loads estimated by multiplying nutrient concentrations by runoff volume. As a result, nutrient loss from biochar-amended GR substrates into runoff was reduced, thereby helping to maintain a nutrient-rich growing environment for plants. Higher nutrient availability in GR-7.5T-F and GR-7.5B-M could explain the higher plant performance regardless of higher substrate temperature and lower substrate moisture as compared to GR-0. In a study with a similar outcome, Liao, Drake and Thomas [66] evaluated the impact of vegetation on green roof runoff quality and concluded that plant performance in biochar GRs was improved due to reduced nutrient leaching. Another study by Liao, et al. [78] also found that biochar increased the coverage area of sedum by decreasing concentrations of essential nutrients such as TN, dissolved P, K, Ca, and Na in runoff. Several studies were found to support the observation that the addition of biochar increases nutrient retention capacity. For example, biochar by either the top-dressed or bottom-applied methods in the study of Kuoppamäki, Hagner, Lehvävirta and Setälä [34] reduced loads of TP and TN in the GR discharge. Additionally, the leaching of various water pollutants, including TN, TP, and heavy metals, from biochar-amended GRs was mitigated [4,39,42–45,79]. The long-term effects of biochar on nutrient retention and plant performance could be also obtained through less GR discharge volume. In the study of Kuoppamäki, Hagner, Lehvävirta and Setälä [34], results from field experiments illustrate an increase of up to 10% in the water retention capacity of biochar-amended GRs relative to traditional GRs in the summer. Findings from a numerical model named "CHEMFLO-2000" also supported the effectiveness of biochar [35]. The simulation results showed that GRs with 3 cm and 5 cm depth of biochar increased runoff retention from 55.05–65.29% to 66.9 and 69.15%, respectively. Another experiment using soil test columns by Huang, Garg, Mei, Huang, Chandra and Sadasiv [36] also found an improved runoff retention from 45.5% to 69.3%. Furthermore, improvements in hydraulic properties of GR substrates, such as the soil-water characteristic curves and saturated water content, due to the addition of biochar were also reported [58,80].

4.3. Biochar Benefits to Plant Performance in the Context of Buildings

This paper focused on evaluating GR plant performance under the impact of biochar addition within the context of building and construction, including aspects like building energy saving and structural loading. The selection of parameters, uncluding substrate temperature and runoff quantity/quality was based on their direct impacts on GR plant performance. The importance of these parameters in explainig substrate moisture content and nutrient availability for enhanced plant growth was also highlighted and taken into consideration in previous studies on GR vegetation performance [51,60,66]. Therefore, data on substrate temperature was collected in this research to identify underlying mechanisms of enhanced plant growth by biochar addition. However, since the cooling effects of GRs influence building heating and cooling demands, it is recommended that future studies include a comprehensive investigation of the thermal performance of biochar-amended GRs. Reduction in building temperature and energy consumption is one of the most notable benefits of GRs, which has attracted significant attention from researchers [1]. For example, Cascone [81] evaluated the energy efficiency of an innovative and sustainable GR with a recycled drainage layer, locally sourced materials, and high organic content in substrates. After analyzing the thermo-physical parameters of GRs and the building (surface temperature, heat flow, volumetric content) during the summer period in Mediterranean climate, the studied GR alleviated the heat transfer to the building and the internal surface temperature by 2 °C relative to the reference concrete roof. Aboelata adopted a numerical approach using ENVI-met and a DesignBuilder model was adopted by [82]. The simulation results indicated that intensive GRs reduced the energy consumption of buildings by 4%, 2.4%, and 1.4% for heights of 12 m, 18 m, and 30 m, respectively, on a typical summer day in Cairo. Despite the energy savings, Aboelata [82] recommended the use of extensive GRs owing to less construction and maintenance costs. The benefits of biochar for water retention and plant performance also positively impact building energy efficiency. Nonetheless, the thermal performance of biochar-amended GRs has been insufficiently researched. The cooling effects of biochar on GRs were found to be positive in the study by Tan and Wang [83]. Their 20% v/v fine biochar particles decreased the external roof surface temperature by 3–5 °C and lessened the heat absorbed by GRs by at least 0.06 MJ/m^2 daily. A biochar-coconut coir compost substrate used by Lunt, et al. [84] had the lowest thermal conductivity regardless of moisture content as compared to the other two artificial soil-based substrates. The thermal conductivity of biochar-amended soil was compared with that of bare soil in the study by Wang, Garg, Zhang, Xiao and Mei [32]. At different testing powers (50, 100, and 200 mW), biochar was observed to decrease soil thermal conductivity and increase thermal insulation.

The construction of GRs on building rooftops has also been hindered due to issues concerning structural safety. This poses a major challenge for the widespread implementation of GRs, since existing buildings, especially old ones, were not designed to support the additional structural load of a GR system [10]. Thus, structural assessments are necessary before installing green roofs, which increases the capital costs associated with them [85]. Additionally, concerns about potential structural damage from GRs limit the choice of plants and substrate thickness, thereby restricting the potential benefits of GRs. Increasing substrate depth often results in enhancing plant growth and GR performance, such as higher heat insulation and water retention capacity, but puts extra weight loading on building structures [86–88]. Furthermore, greater substrate depth accommodates a wider variety of suitable plants, including those that produce vegetables, potentially increasing profits and reducing the payback period. Biochar is a lightweight substrate additive that can modify substrate structures through its micropores and macropores, affecting the overall weight of a green roof system [51]. For example, Cao, Farrell, Kristiansen and Rayner [29] found that biochar reduced both dry and saturated bulk density of GR substrates. Consequently, for the same weight, a scoria-based substrate with 40% v/v biochar was 1.5 cm/m^2 thicker as compared to the substrate with scoria only. Future studies are encouraged to include research on biochar and its impact on green roof structural loading. To address challenges in the widespread implementation of GRs, they need to become more structurally and economically feasible, requiring little to no additional expenditure for structural reinforcements and generating higher monetary value through cooling effects and extended roof membrane lifespan.

5. Conclusions

Vegetation is an important part of a GR system, and it plays a major role in maintaining GR performance during its lifetime. However, GR plants are subject to unfavorable growing conditions on rooftops, such as extreme solar heat and strong wind. While drought-tolerant plants are often chosen in GRs, there exist concerns regarding plant performance. Therefore, attempts have been made to modify GR substrates for a better growing environment. Biochar has been recently introduced in GRs and also in agriculture to enhance plant performance by regulating substrate water/nutrient retention. While the impacts of biochar on GR plants have been previously investigated, the understanding of the long-term performance of GR plants in relation to biochar-related parameters is still limited. Therefore, this research investigates the performance of plants in six different 1 m^2 biochar-amended GR test beds with varying biochar-related parameters (amendment rates, particle sizes, and application methods). Key findings obtained from this study are summarized as follows:

(a) In this study, the addition of biochar resulted in the improvement of plant performance in all biochar-amended GRs.
(b) The test bed modified by 15% v/v medium biochar particles had the best plant performance in terms of plant height, plant dry weight, and plant coverage area.
(c) A 15% v/v amendment is recommended as the optimal biochar amendment rate for plant growth. The mixing method of biochar amendment tended to have better effects

on plant growth as compared to the top-dressed and bottom-applied methods. The use of intermediate biochar particles is suggested for optimal plant performance.

(d) Plant performance is strongly linked to substrate temperature, moisture content, and nutrient availability. The observed data indicated reduced substrate temperature, likely due to the higher moisture content in biochar-amended substrates. Besides, data on runoff quantity and quality from the same test beds within the observation period of plant growth (from a previous study) demonstrated higher nutrient availability due to the addition of biochar.

(e) In accordance with previous studies, the effects of biochar on plant performance varied among plant species and GR substrates. Therefore, future local studies with long-term observations are necessary to identify optimal GR systems tailored to specific climate conditions.

(f) In addition to improving plant performance, biochar amendment also offers solutions to improve building energy savings, reduce structural loading, and shorten the payback period. However, due to inadequate evaluation of these benefits, further studies are recommended.

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