Developing innovative green roof strategies for improving runoff retention and water quality

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Abstract

A significant consequence of rapid urbanization is the conversion of green spaces into impervious surfaces, such as concrete pavements and roads. This has led to an increase in flash flooding, more intense Urban Heat Island (UHI) effects, and higher levels of water and air pollution. In response, numerous innovative solutions have been explored and implemented. Among these, green roofs (GRs) stand out for their potential to address a range of environmental and social challenges.

Despite several efforts in GR research over the past few decades, the widespread implementation of GRs remains limited due to an incomplete understanding of their performance and influencing factors, insufficient local research, lack of supportive legislation, and uncertain economic benefits. This PhD thesis aims to deepen the understanding of GR performance within the Australian climate, with a particular focus on runoff quantity and quality. The findings in this study are intended to support the widespread adoption of GRs by highlighting their substantial benefits to both the community and decision-makers.

This thesis is organized into three main sections. The first section provides foundational knowledge for the subsequent chapters, derived from two comprehensive review papers. The first review paper identifies research gaps in general GR studies, while the second focuses on biochar and its application in GR research. The second section involves the development of a stormwater model to assess the hydrological performance of GRs on a catchment scale. The third section evaluates the effects of biochar on GRs through field experiments that analyze runoff quantity, runoff quality, and plant performance.

Based on the findings from this PhD study, the following conclusions can be drawn:

Section 1

The first review identifies knowledge gaps and generate future research directions. These gaps include identifying factors that affect GR performance, developing innovative GR materials and technologies, assessing GR performance on a larger scale, and obtaining local research data.

The second review pointed out an overall trend of positive impacts of biochar on GR performance. However, the understanding of the effects of biochar on GRs is still in the preliminary stages. Future studies with long-term observations are required, particularly on

the environmental impacts of biochar, its economic feasibility, and optimal biochar-related parameters.

Section 2

A stormwater model based on eWater's MUSICX software was developed to simulate the hydrological performance of GRs applied on each building at Victoria University's Footscray Park campus. The results showed that large-scale GRs positively impacted annual runoff volume and loads of Total Phosphorus (TP), Total Nitrogen (TN), and Total Suspended Solids (TSS). However, a treatment train including GRs and other treatment devices was required to achieve local stormwater objectives.

Section 3

Field experiments were carried out to examine the effects of biochar on GR runoff retention. Data was collected from the six newly established $1m^2$ biochar-amended GR test beds under different artificial rainfall intensities. The results illustrated that biochar successfully enhanced GR benefits by reducing runoff volume and delaying runoff outflows. The optimal biochar-GR setup was the GR modified by 7.5% *v/v* medium biochar particles applied at the bottom of the GR substrate.

The impacts of biochar on the quality of GR runoff were also assessed using the same GR test beds. GR runoff was analyzed for pH, Electrical Conductivity (EC), and concentrations of Total Phosphorus (TP) and Total Nitrogen (TN). Mixed results were observed among different biochar-GR setups and water quality parameters. However, biochar retained significant potential to improve runoff quality by significantly increasing water retention.

One-year observational data on plant performance was obtained from the same GR test beds. Biochar was found to improve performance of wallaby grass, common everlasting, and billy buttons. The most pronounced impact of biochar was observed in the GR substrate mixed with 15% *v/v* medium biochar particles. The enhanced plant performance plays a major role in maintaining GR performance during its life cycle while improving the economic value of GRs.

Declaration

““I, Cuong Ngoc Nguyen, declare that the PhD thesis entitled “Developing innovative green roof strategies for improving runoff retention and water quality” is no more than 80,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work”.

“I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University’s Higher Degree by Research Policy and Procedures.

Signature: [redacted]

Date: 22/08/2024

Acknowledgement

I would like to express my sincere gratitude to those who have contributed to the successful completion of this PhD thesis. First and foremost, I am deeply indebted to my principal supervisor, Dr Nitin Muttil, for his invaluable guidance and support throughout this research endeavor. His extensive knowledge of stormwater and green infrastructure has been instrumental in shaping the direction and focus of this thesis. Dr Muttil's insightful feedback and encouragement have been essential to the successful attainment of the research objectives. I would also like to express my appreciation to my associate supervisor, Dr Hing-Wah Chau for his ongoing support and valuable contributions to this research. His expertise and advice were crucial to the successful completion of the thesis.

In addition to my supervisors, I would like to acknowledge the significant contributions of Dr. Dale Browne and Michael Hannah to this research. As experts in water-related fields, including green roofs and other Water Sensitive Urban Design (WSUD) practices, and with their proven experience in stormwater modelling, their expertise was indispensable. Their collaboration in developing the MUSIC-based model for simulating large-scale green roofs was important in the successful completion of this PhD thesis.

I also would like to extend my gratitude to the Institute of Sustainable Industries and Liveable Cities (ISILC) of Victoria University for the provision of my tuition fees sponsorship. Additionally, the successful completion of this research was made possible through the financial support of local suppliers, KHD-Landscape Engineering Solutions and Green Man Char, who provided Versidrain drainage trays and biochar, respectively, for use as green roof materials.

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Details of included papers: Thesis by publication

Chapter No.	Publication Title	Publication Status (e.g. published, accepted for publication, to be revised and resubmitted, currently under review, unsubmitted but proposed to be submitted)	Publication Details (e.g. date published, verification of Scopus quartile ranking of the publication, indicator of quality etc.)
1	Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review.	Published.	December 2021. Water MDPI. Scimago Journal Rank: Q1. Impact Factor: 3.4 (2022).
2	Biochar amendment in green roof substrate: A comprehensive review on benefits, performance, and challenges.	Published.	August 2024. Applied Sciences MDPI. Scimago Journal Rank: Q2. Impact Factor: 2.5 (2024).
3	Performance Evaluation of Large-scale Green Roofs based on Qualitative and Quantitative Runoff Modelling.	Published.	January 2023. Water MDPI. Scimago Journal Rank: Q1. Impact Factor: 3.4 (2022).
4	A Field Study to Investigate the Hydrological Characteristics of Newly Established Biochar-Amended Green Roofs.	Published.	February 2024. Water MDPI. Scimago Journal Rank: Q1. Impact Factor: 3.4 (2022).
5	A Field Study to Assess the Impacts of Biochar Amendment on Runoff Quality	Published.	August 2024. Hydrology MDPI. Scimago Journal Rank: Q2. Impact Factor: 3.1 (2024).

	from Newly Established Green Roofs.		
6	Addition of biochar to enhance plant performance in green roofs: A long-term field study.	Published.	September 2024. Buildings MDPI. Scimago Journal Rank: Q2. Impact Factor: 3.1 (2024).

Declaration by Cuong Ngoc Nguyen

Signature: [redacted] **Date:** 22/08/2024

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Chapter 1

Introduction

1.1. Background

Intensive urban growth throughout the world has resulted in several issues negatively affecting and the environment and the quality of human life. The rapid urbanization has led to a significant increase in impervious surfaces in urban areas, which has exacerbated the impacts of climate change. For example, more severe urban heat island (UHI) effects are observed in highly built-up areas with concrete/asphalt roads and buildings. Such hard surfaces absorb a higher amount of solar heat during the day and radiate it back to the atmosphere at night [1]. Lack of pervious surfaces also prevents rainwater from naturally infiltrating into the ground, which results in increased runoff volume, decreased groundwater recharge, and degraded runoff quality [2]. Consequently, stormwater infrastructure systems are under greater stress due to the increased intensity and frequency of flooding. Moreover, social and environmental issues caused by urbanization also include increased air and noise pollution, loss in biodiversity, energy shortages, and negative impacts on human health and well-being.

To address the aforementioned urban challenges, a diverse array of solutions has been investigated in recent decades. Among these, green roofs (GRs), a prominent component of green infrastructure (GI) and water-sensitive urban design (WSUD), have garnered significant attention from researchers, policymakers, and the community. The substantial expanse of underutilized flat roofs presents a promising opportunity for widespread GR implementation, facilitating a sustainable transition from impervious surfaces to green spaces. A typical GR comprises multiple layers, including vegetation, substrate, filter, drainage, and waterproof membranes [3]. This configuration enables GRs to deliver a range of ecosystem services, such as thermal regulation, stormwater management, air purification, noise reduction, and socio-economic benefits [4]. GRs are primarily categorized as extensive (EGRs) or intensive (IGRs), differentiated by substrate depth. While IGRs feature substrates exceeding 20 cm, EGRs typically have substrates less than 15 cm [5]. This distinction influences the performance of each system. IGRs, with their deeper substrates, support a wider range of vegetation and exhibit superior performance in terms of rainwater retention, thermal insulation, and air quality improvement through the inclusion of trees and shrubs. Conversely, EGRs, limited by shallower substrates, are restricted to drought-tolerant plants such as succulents and sedums, resulting in lower overall performance. Despite these limitations, EGRs have achieved greater popularity due to their lower cost, reduced structural demands, and less maintenance [6].

Extensive research has been conducted on green roofs (GRs) in the recent decades [7, 8]. However, the practical application of this technology remains hindered due to various factors. One such challenge is the lack of consistent research on the benefits of GRs, which has created ambiguity regarding their overall effectiveness [9]. While stormwater retention is a widely acknowledged advantage, consensus on GRs' ability to improve runoff quality is lacking. GR runoff quality is significantly influenced by substrate composition, substrate thickness, GR age, maintenance, and fertilizer application [6, 8, 10]. Although nutrients are essential for plant growth, their leaching into runoff through rainfall and irrigation poses environmental risks. For instance, pilot-scale GRs in the study of Vijayaraghavan and Raja [11] demonstrated a capacity to retain heavy metals, while those of Beecham and Razzaghmanesh [12] exhibited limited pollutant reduction. Similarly, the efficacy of GRs in reducing total phosphorus (TP) and total nitrogen (TN) has shown variability [13,14]. Beyond runoff quality, the efficacy of GRs in reducing temperature and energy consumption varies across climatic regions. Wong and Jim [15] reported a modest 11.9% rainwater retention rate for GRs in a humid subtropical climate with intense rainfall events exceeding 300 mm. Johannessen et al. [16] observed a similarly low runoff retention rate of 11% for a GR in Bergen, characterized by annual rainfall of approximately 3110 mm. Conversely, runoff retention rates for GRs have been frequently reported within a range of 55% to 88% [6]. Regarding temperature and energy saving, in hot climates, GRs have demonstrated significant reductions in roof surface and indoor air temperatures, leading to energy savings [17-19]. In contrast, Ávila-Hernández et al. [20] found limited cooling benefits from GRs in certain Mexican cities with higher heating demands. Consequently, localized research is crucial for optimizing GR performance using regionally appropriate materials and considering specific climatic conditions. Furthermore, the performance of GRs at the catchment scale remains a critical research gap. A dearth of studies investigating the large-scale impacts of GRs through computer modeling has impeded their widespread implementation. Moreover, other potential GR benefits, including those related to air quality, noise reduction, biodiversity, and socioeconomic factors, have been inadequately explored

[6,8,9]. Consequently, the limited understanding of GR ecosystem services hinders efforts to engage urban planners in promoting GR adoption.

In response to these challenges, numerous strategies have been explored to enhance the benefits derived from GRs. These approaches encompass the integration of GRs with other systems and the incorporation of innovative materials and technologies. For instance, blue roofs have been combined with GRs in Korea to augment water retention capacity [21-23]. Furthermore, the synergistic effects of installing solar panels adjacent to GRs have been investigated to increase electricity production and improve cooling effects of GRs [24-26]. Additionally, previous studies have documented further reductions in indoor air temperature through the combination of GRs and green walls [27-29]. Given that GR performance is influenced by their constituent components, the application of innovative materials has also been a focus of research. Biochar, a carbon-rich material, has emerged as a promising addition to GR systems. Its physicochemical properties, including high porosity, large specific surface area, functional groups, and cation exchange capacity, contribute to enhanced runoff retention, water quality, plant growth, and microbial diversity [30,31]. To provide a comprehensive overview of GR performance, research opportunities, and challenges, two in-depth review papers are presented in Chapter 2 of this PhD thesis. These reviews guided the formulation of research objectives and methodologies for the subsequent chapters.

1.2. Aims of the Study

The overall research aim of this study is to facilitate the widespread implementation of green roofs (GRs) by deepening the understanding of their benefits, which is further enhanced through the application of innovative strategies. To achieve this goal, the research was structured into three primary components. The initial phase involved conducting two comprehensive literature reviews to synthesize existing knowledge on GRs and the emerging application of biochar as an amendment to GR substrate. A critical research gap identified in the first phase was the limited understanding of GR performance at the catchment scale. This gap was addressed in the second phase through the development of a stormwater modeling tool. The final phase comprised of field-based experiments to evaluate the effectiveness of biochar-amended GRs. To accomplish these research objectives, the following specific aims were established:

- Conduct a comprehensive literature review to identify trends, knowledge gaps, and methodological approaches in GR research.
- Conduct another literature review to examine the impacts of biochar on GR performance and inform the design of field experiments.
- Develop a simulation model using MUSICX from eWater to assess the hydrological performance of a catchment-scale GR in terms of runoff quantity and quality.
- Establish field-based test beds to evaluate the stormwater management performance of biochar-amended GRs, focusing on stormwater retention and runoff outflow delay.
- Assess the water quality of runoff from biochar-amended GRs through the measurement of pH, electrical conductivity (EC), total phosphorus (TP), and total nitrogen (TN).
- Evaluate the impact of biochar on plant performance in GR test beds by monitoring plant dry weight, height, and coverage area over a one-year period.

The methodological framework used in this study is illustrated in Figure 1. The outlined aims are interconnected to fulfil the overall research goal of this study.

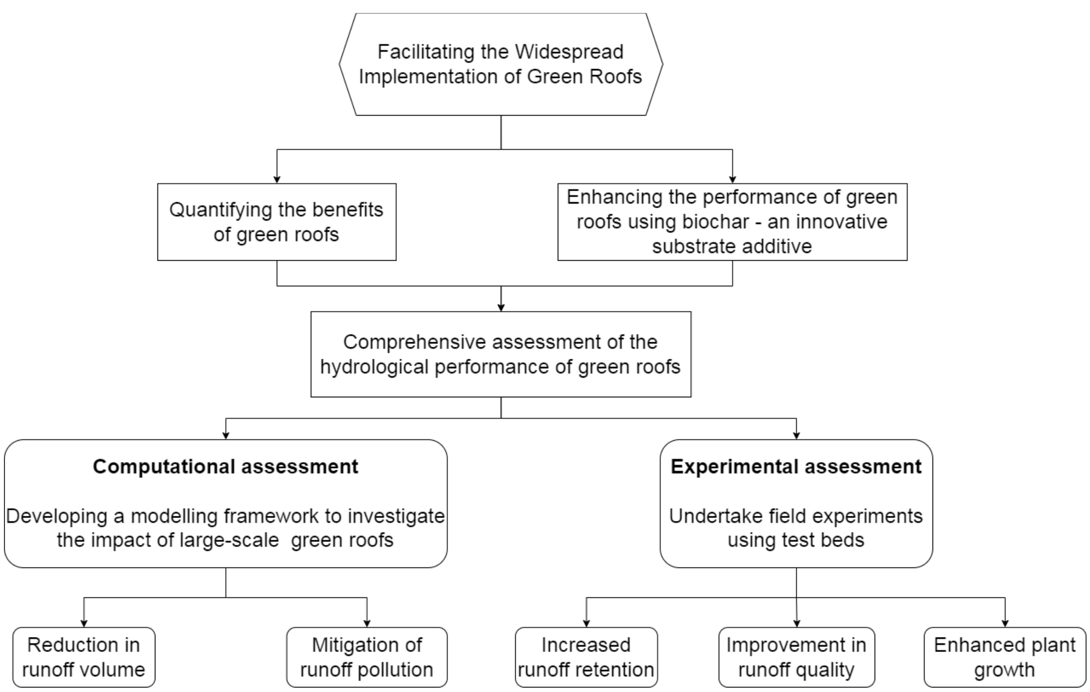

Figure 1. The interconnections among the outlined aims of this research.

1.3. Study Area

The study area for all research conducted in this thesis is the Footscray Park campus of Victoria University (VU), located in the western suburbs of Melbourne, Australia. Situated within a temperate oceanic climate (Köppen climate classification Cfb), the region experiences warm summers and mild winters with approximately 650 mm of annual precipitation. At the end of 2020, a 50 m² green roof (GR) divided into five distinct growing spaces was constructed on Building M of the VU Footscray Park campus. This GR installation is part of a broader initiative to transform the university campus into a green, sustainable, and climate-responsive environment. Figure 2 presents this 50 m² GR two months post-installation. The GR with the different growing spaces were used to assess impacts of variations in GR size, organic content, and vegetation type, as detailed in Figure 3.

Figure 2. Five green roof plots on Building M of the Footscray Park campus of Victoria University, Melbourne, Australia.

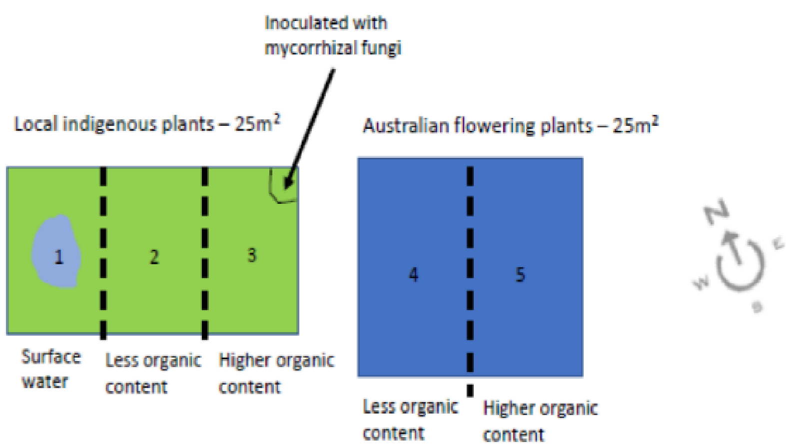

Figure 3. Specifications of five green roof plots on Building M of Footscray Park campus of Victoria University, Melbourne, Australia.

Chapter 3 presents the development of a stormwater model utilizing weather data collected from a nearby weather station. This model was employed to simulate the hydrological performance of a green roof (GR) system replicating the 50 m² GR installed on Building M at VU. The developed model was to simulate the hydrological performance of a GR system replicating the 50 m^2 VU's GR on Building M. The simulated GR featured a 15 mm substrate composed of a mixture of Light Expanded Clay Aggregate (LCCA), coir chips, and mulch. Additional simulation parameters included the impervious surface area and vacant flat roof areas of the VU campus.

Due to unfavourable conditions on the rooftop of Building M for collection of runoff data from the 50 m² GR, six experimental green roof (GR) test beds were established (Figure 4). These test beds consisted of 1m x 1m galvanized steel trays elevated 0.3 m above the roof tiles using a metal frame. This configuration facilitated the placement of a small water container beneath each test bed for runoff data collection. Exposed to identical atmospheric conditions, these test beds were employed to investigate the stormwater management performance of biochar-amended GRs in Chapter 4 and plant growth in Chapter 5.

Figure 4. The establishment of six green roof test beds on Building M of Footscray Park campus of Victoria University, Melbourne, Australia.

1.4. Significance of the Research

Despite the substantial potential of green roofs (GRs), their widespread implementation remains hindered by several factors. A significant limitation is the dearth of locally-based research, which restricts the understanding of GR performance when using indigenous plants and materials under specific climatic conditions. This PhD thesis sought to address this knowledge gap by providing valuable insights into the behavior of Australian-based GRs incorporating indigenous plants and local materials. Additionally, a modeling tool was developed to simulate the performance of large-scale GRs using historical weather data and local stormwater guidelines. With a focus on stormwater management, the study comprehensively investigates the capacity of GRs to mitigate urban flooding and water pollution. Given the increasing intensity and frequency of climate change impacts globally and in Australia, GRs and other water-sensitive urban design (WSUD) practices offer a sustainable approach to addressing a range of social and environmental challenges.

Another obstacle to widespread GR adoption is the insufficient public awareness of their benefits. Consequently, the dissemination of positive research findings from this study could significantly contribute to generating interest and support for GRs among the community and policymakers. While GR benefits have been documented in the literature, their potential has not been effectively communicated to policymakers, resulting in a lack of supportive regulations to facilitate broader GR implementation. In addition to inconsistent research outcomes, the high costs associated with GR installation, operation, and maintenance, coupled with uncertain long-term returns on investment, have hindered decision-making processes related to GR adoption. Therefore, this research and future studies are essential for identifying influential parameters and optimizing GR systems for specific locations.

Moreover, this thesis also aimed to fill the research gap in biochar-amended GR systems. Biochar has been researched and applied considerably in agricultural fields, but it is still at the preliminary stage of GR research. Therefore, the effectiveness of biochar in improving stormwater retention capacity, runoff quality, and vegetation growth of GRs was investigated in Chapter 4 and Chapter 5 of this thesis. Moreover, different biochar-relating parameters such as particle sizes, application methods, and amendment rates were assessed to suggest optimal biochar-GR setups for future applications.

Additionally, this PhD thesis contributes to knowledge advancement by identifying research gaps, addressing specific challenges, and generating future research opportunities. The comprehensive review papers presented herein provide a robust foundation for subsequent GR studies by offering up-to-date insights into GR performance, research methodologies, and innovative materials and technologies. Given the limited understanding of large-scale GR impacts, this research presents a simplified modeling approach applicable to both Australian and global contexts. The proposed modeling framework can be adapted by researchers and practitioners to investigate the performance of large-scale GRs in diverse catchment settings, with opportunities to refine the model for enhanced simulation accuracy. Furthermore, this thesis addressed a research gap in biochar-amended GR systems. While biochar has been extensively studied in agricultural applications, its role in GR systems remains in its infancy. Consequently, this research investigated the effectiveness of biochar in enhancing stormwater retention capacity, runoff quality, and vegetation growth within GR systems, as detailed in Chapters 4 and 5. The study also explored various biochar-related parameters, including particle size, application method, and amendment rate, to inform optimal biochar-GR configurations for future implementations.

1.5. Outline of the Thesis

Figure 5 illustrates the thesis structure, outlining the interconnection between the six chapters and their corresponding publications. A detailed description of each chapter is as follows:

Chapter 1 provides an overview of the GR concept, describes the primary research objectives, underscores the research significance, and outlines the thesis structure. It further identifies critical knowledge gaps, outlines the adopted research methodologies, and justifies the necessity of the research.

Chapter 2 presents a comprehensive overview of GRs through two in-depth literature reviews. The first review evaluates the performance of existing GR systems to identify potential research avenues and methodologies for subsequent chapters. Building upon the identification of innovative GR materials in the first review, the second focuses on investigating the efficacy of biochar as a substrate additive for GRs. This chapter serves as a foundational resource for the selection of biochar and the establishment of biochar-amended GR test beds in Chapters 4 and 5.

The first review paper presented in Chapter 2 highlighted the limited understanding of green roof (GR) impacts at the catchment scale. Chapter 3 addresses this deficiency by developing a computer-based simulation model. A MUSIC-based model was constructed to simulate the hydrological performance of a hypothetical scenario where GRs are installed on all flat-roofed buildings at Victoria University's Footscray Park Campus, Melbourne, Australia. he model was rigorously calibrated using local MUSIC calibration guidelines, 50-year precipitation data, and empirical hydraulic properties derived from previous studies of similar GR systems. Furthermore, a modeling framework incorporating two modeling approaches was established to facilitate the assessment of large-scale GRs in other locations or the refinement of model accuracy by subsequent researchers.

Chapter 4 investigates the benefits of biochar in enhancing GR stormwater management performance. To achieve this, multiple GR test beds incorporating various biochar configurations were established on the rooftop of Building M at Victoria University's Footscray Park Campus, Melbourne, Australia. Rainfall simulation experiments were conducted on these test beds. The first study within this chapter analyzed runoff retention and outflow delay data, while the second focused on assessing the impact of biochar on runoff quality through measurements of pH, electrical conductivity (EC), total phosphorus (TP), and total nitrogen (TN).

Chapter 5 assesses the impact of biochar on GR plant performance. Biochar has been extensively documented as a soil amendment capable of enhancing water and nutrient retention, thereby increasing substrate fertility and promoting plant growth. At the same experimental site as Chapter 4, vegetation within different biochar-amended GRs was monitored over a one-year period. Plant height measurements were recorded at regular intervals to assess vertical growth, while plant dry weight was determined at the end of the observation period.

Chapter 6 provides a comprehensive summary of the research findings presented in this thesis. Additionally, the chapter offers detailed recommendations for future research directions to address identified knowledge gaps. This research endeavors to stimulate public and governmental support for widespread GR implementation. Achieving this goal necessitates a comprehensive understanding of GR benefits that can effectively outweigh their associated challenges, such as high initial costs, intensive maintenance requirements, and increased structural loads. The interconnection of the thesis chapters, as illustrated in Figure 5, clearly demonstrates how research gaps were identified and subsequently addressed through a combination of field experimentation and computer modeling, ultimately leading to the attainment of research objectives.

Chapter 1: Introduction.
This chapter commences with an overview of green roofs, followed by a summary of the research presented within this thesis, including research objectives, significance, and structural outline.

Chapter 2: Literature reviews of green roof ecosystem services and biochar amendment to green roof substrates.
This chapter presents two comprehensive literature reviews that serve as a foundational knowledge base for subsequent chapters. These reviews collectively provide a robust foundation of knowledge regarding potential research avenues and methodologies.
Contains the papers entitled:
(1): Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review.
(2): Biochar amendment in green roof substrate: A comprehensive review on benefits, performance, and challenges.

Chapter 3: Development of a model simulating the hydrological performance of large-scale green roofs.
This chapter presents a simplified modeling approach to assess the hydrological impacts of catchment-scale green roofs in terms of runoff quantity and quality. The study area encompasses the entirety of Victoria University's Footscray Park campus. Model inputs include historical weather data, vacant flat roof areas, and impervious/pervious surface area distributions within the campus.
Contains the paper entitled:
(1): Performance Evaluation of Large-Scale Green Roofs Based on Qualitative and Quantitative Runoff Modeling Using MUSICX

Chapter 4: Investigate the performance of newly established biochar-amended green roofs in terms of stormwater management (runoff quantity and quality).
This chapter presents field experiments conducted on biochar-amended green roof test beds. Data collected includes stormwater retention, runoff outflow delay, and runoff quality parameters such as pH, electrical conductivity (EC), total phosphorus (TP), and total nitrogen (TN) concentration.
Contains the papers entitled:
(1): Performance Evaluation of Large-Scale Green Roofs Based on Qualitative and Quantitative Runoff Modeling Using MUSICX.
(2): A field study to assess the impacts of biochar amendment on runoff quality from newly established green roofs

Chapter 5: Observing the vegetation performance of biochar-amended green roof test beds.
This chapter examines the influence of biochar on green roof vegetation performance. Plant height across different green roof test beds was monitored through regular measurements of plant height and vegetation cover. At the end of the monitoring period, the plant dry weight was assessed.
Contains the papers entitled:
(1): Addition of biochar to enhance plant performance in green roofs: A long-term field study.

Chapter 6: Conclusion.
This chapter presents a consolidated summary of the research findings derived from this PhD thesis. Additionally, detailed recommendations for future research directions are provided to address identified knowledge gaps.

Figure 5. Flow chart illustrating the interconnection between chapters presented in this thesis.

Chapter 2

Literature reviews of green roof ecosystem services and biochar amendment to green roof substrate

2.1. Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review

2.1.1. Introduction

Chapter 2 comprises of two comprehensive literature reviews aimed at establishing a robust foundation of knowledge and research methodologies for subsequent chapters. A green roof system, characterized by multiple structural layers, offers a range of ecosystem services, including stormwater management, air quality improvement, noise reduction, mitigation of the urban heat island (UHI) effect, ecosystem restoration, and economic and social benefits. Despite decades of research and widespread recognition as a promising green infrastructure, the widespread implementation of green roofs remains hindered by several obstacles. The first review focused on the green roof concept, delving into system structures, benefits, research trends, knowledge gaps, opportunities, and associated challenges. A rigorous abstract screening process was employed to select over 100 papers published between 2010 and the time of this research. Paper selection was further refined based on the review's scope, which centered on quantifying green roof performance. Findings from this review revealed inconsistent reporting of green roof performance and a research focus on specific benefits, such as temperature reduction and stormwater retention. Additionally, the geographic limitations of green roof research were evident. To address these shortcomings, the review identified opportunities to enhance green roof effectiveness, thereby stimulating future research endeavors. Key findings informing subsequent chapters include the necessity of computer modeling tools to assess large-scale green roof performance (Chapter 3) and the need for innovative materials and technologies to optimize green roof benefits (addressed in the second review – Chapter 2 and subsequent Chapters 4 and 5).

This chapter contains the following journal paper, which is the first of the two review papers included in this chapter:

- Nguyen, C.N.; Muttil, N.; Tariq, M.A.U.R.; Ng, A.W.M. Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review. *Water* **2022**, *14*, 68. https://doi.org/10.3390/w14010068.

2.1.2. Declaration of co-authorship and co-contribution: papers incorporated in thesis by publication

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DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review

Surname: Nguyen First name: Cuong

Institute: Institute for Sustainable Industries and Liveat Candidate's Contribution (%): 75%

Status:

Accepted and in press: ☐ Date:

Published: ☑ Date: 31/12/2021

2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

Signature	Date
[redacted]	18/05/2024

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;

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3. There are no other authors of the publication according to these criteria;

4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

5. The original data will be held for at least five years from the date indicated below and is stored at the following **location(s)**:

Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Cuong Ngoc Nguyen	75	Conceptual ideas, research, data analysis, writing	[redacted]	18/05/2024
Nitin Muttil	15	Critical comments and discussion on conceptual ideas & research methodologies		22/08/2024
Muhammad Atiq Ur Rehman Tariq	5	Feedback and discussion on research and writing		20/8/2024
Anne W. M. Ng	5	Feedback and discussion on research and writing		18/8/2024

Updated: September 2019

water MDPI

2.1.3. Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review

Review

Quantifying the Benefits and Ecosystem Services Provided by Green Roofs—A Review

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Abstract: Water-sensitive urban design (WSUD) has been widely used in cities to mitigate the negative consequences of urbanization and climate change. One of the WSUD strategies that is becoming popular is green roofs (GR) which offer a wide range of ecosystem services. Research on this WSUD strategy has been continuously increasing in terms of both quantity and quality. This paper presents a comprehensive review quantifying the benefits of GRs in papers published since 2010. More precisely, this review aims to provide up-to-date information about each GR benefit and how they have improved over the last decade. In agreement with previous reviews, extensive GRs were considerably researched, as compared to very limited studies on intensive and semi-intensive GRs. Each GR ecosystem service was specifically quantified, and an imbalance of GR research focus was identified, wherein urban heat- and runoff-related benefits were outstandingly popular when compared to other benefits. The results also highlight the recent introduction of hybrid GRs, which demonstrated improvements in GR performance. Furthermore, limitations of GRs, obstacles to their uptake, and inconsistent research findings were also identified in this review. Accordingly, opportunities for future research were pointed out in this review. This paper also recommends future studies to improve upon well-known GR benefits by exploring and applying more innovative GR construction techniques and materials. At the same time, further studies need to be undertaken on inadequately studied GR benefits, such as reduced noise and air pollution. In spite of the existence of reliable modelling tools, their application to study the effects of large-scale implementations of GRs has been restricted. Insufficient information from such research is likely to restrict large-scale implementations of GRs. As a result, further studies are required to transform the GR concept into one of the widely accepted and implemented WSUD strategies.

Keywords: WSUD; green roofs; ecosystem services; quantify benefits; large-scale implementation

1. Introduction

Water-sensitive urban design (WSUD) strategies have been widely used in cities to mitigate the negative consequences of rapid urbanization and climate change. Whilst WSUD is a popular term in Australia and a few other countries, blue-green infrastructure (BGI) is also a commonly used term. Green roofs (GR) have been regarded as a promising BGI strategy to deal with these globally growing concerns of urbanization and climate change. This BGI strategy, sometimes called a living roof or vegetated roof, offers a wide range of environmental, social, and economic benefits compared to conventional roofs (CRs) [1]. The stormwater management and the mitigation of heat-related issues are the two primary GR benefits that have attracted the attention of researchers the most. Additionally, GR is capable of reducing energy consumption, improving air and runoff quality, and alleviating noise pollution [2]. The vegetated roof also enhances the aesthetic aspects of a building and urban ecology by converting impervious roof surfaces to green spaces [3].

The configurations of a GR vary according to its geographical location, requirements, and the purposes for which it is built. Generally, a typical GR consists of the following layers (from the bottom to the top): waterproofing membrane, drainage layer, filter layer, substrate (growing medium), and vegetation layer. The insulation layer is optional and added when GRs are implemented on existing roofs (i.e., retrofitting a green roof). In the event that long-rooted plants are applied, anti-root layers are compulsory to protect both the GR system and its underneath structure [1]. In terms of GR types, GRs are categorized into intensive GRs (IGRs) and extensive GRs (EGRs). The main difference between these two groups is the substrate depth. While the IGR substrate is more than 20 cm thick, the EGR growing medium is thinner, with less than 15 cm [4]. Consequently, IGRs are suitable for the vast majority of plants, whereas EGRs are only able to support the survival of drought-resilient plants, such as succulents. By contrast, EGRs are much more prevalent than IGRs for several reasons, including lesser efforts for maintenance, lighter weights, and lower construction costs [5,6]. A semi-intensive GR (SIGR) is a type of GR with an intermediate substrate depth between those of EGRs and IGRs. A moderate substrate thickness allows a SIGR to accommodate small shrubs [7].

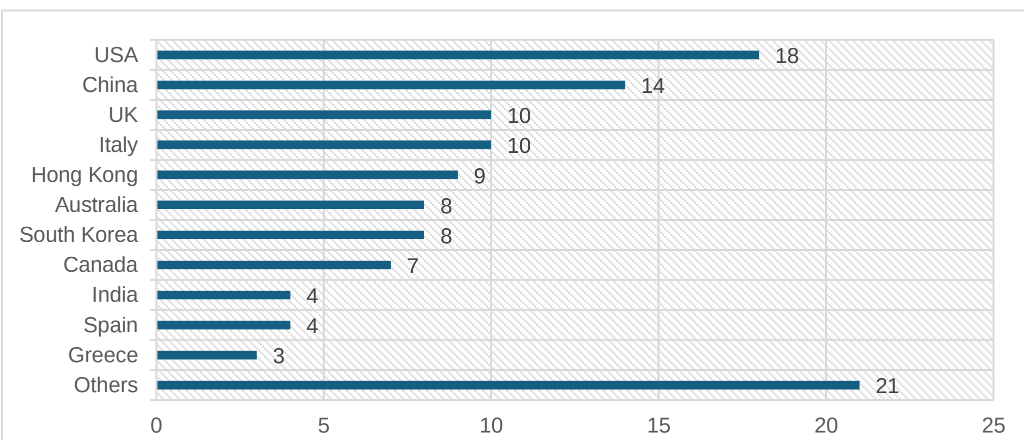

Figure 1. Distribution of reviewed papers by their country of implementation.

Though the success of GR projects at a pilot- (or small-) scale as well as at a large-scale have been reported globally, there is still a long way to go towards global acceptance and implementation of this innovative type of roof. This could be a result of the unbalanced focus on GRs between developed countries and the rest of the world. The reviewed papers are distributed across various countries, as presented in Figure 1. Figure 1 points out that most of the 102 papers reviewed in this study are from the USA, Europe, and other developed countries. The last decade saw the implementation of GRs in other countries such as Australia, China, Hong Kong, and Italy. The USA is still leading in terms of GR research, which was also reported by other studies, such as Blank, *et al.* [8]. A more recent study by Zheng, *et al.* [9] has also provided a similar finding. They studied 75 papers analyzing runoff retention in GRs and found that minimal efforts have been made to study and implement GRs in some regions of the world, including Africa, Central America, and Central Asia. This lack of GR-related research and knowledge in developing or under-developed countries leads to stakeholders, such as building owners, developers, and builders, being unaware of the benefits and optimal components of GRs appropriate for their study locations and roof sites [1,2].

As far as the scale of GR implementation is concerned, they have been implemented at various spatial scales. In this study, they are grouped into three categories: pilot-scale (or small-scale), full-scale, and large-scale. Pilot-scale GRs occupy a small portion of the roof area and/or they are commonly installed on raised test beds or modules, whereas full-scale GRs are those covering the entire roof area with some non-vegetated paths for rooftop access, maintenance, and use of equipment [10]. Finally, the term "large-scale" refers to studies considering the application of GRs at scales that exceed the single-building scale, such as the city-wide scale, municipal scale, or catchment scale. Figure 2 indicates the domination of pilot-scale and full-scale GR studies, whereas only 10 studies (i.e., 10% of the reviewed studies) investigated the potential of implementing GRs at a large scale. The large-scale implementation of GRs is constrained by several factors. For instance, the installation and maintenance costs for a GR remain high, which requires further studies to explore GR components that are not just economical but are also environmentally friendly. Another barrier could be the knowledge gap in quantifying the benefits of the large-scale implementation of GRs. There are 12 studies which did not conduct a field experiment and/or did not investigate large-scale GRs through simulation models. They were, hence, categorized as "others". Though the prospects of GRs at large scales are reasonably foreseeable, the insufficient information from limited research is likely to prevent authorities from issuing policies that encourage the large-scale implementation of GRs (such as financial incentives and utility bill reduction) [2].

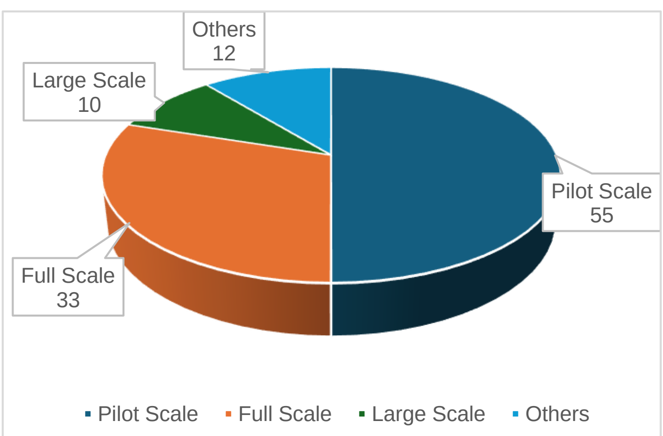

Figure 2. Break-down of papers based on the GR scale.

Earlier literature reviews on GRs concentrated on exploring their potential benefits, components, challenges, trends, and implementation opportunities [1,2,11,12]. Other previous works studied the performance of GRs implemented in different locations and climatic characteristics [4,5,13-15]. This review has also identified that the majority of the research conducted was qualitative based. Therefore, there is a need to quantify the benefits of GRs in order to demonstrate the need of more GR research areas to be investigated. This paper aims to conduct a comprehensive review to quantify GR benefits based on papers published during the last decade (from 2010 onwards) by considering several functional indicators, such as surface and air temperature (thermal reduction) and rainfall retention and peak flow (runoff reduction). Furthermore, this paper provides up-to-date information on each of the GR benefits that have been studied and whose performance has been improved during the last decade.

This paper is structured as follows. An overview of the reviewed papers and a summary of different types of GRs is presented in the next section. This is followed by the quantification of various GR benefits. The paper is concluded with a discussion of the key outcomes of this review and, finally, conclusions are drawn and recommendations from this study are presented.

2. Overview of Literature

2.1. Methodology

This review of GR papers used the Google Scholar and Scopus search engines as the primary search database with a timeframe ranging from 2010 to 2021. Within a set of potential search keywords for GRs, only "green roof" was chosen. Compared to other possible keywords such as "vegetated roof", "cool roof", and "living roof", the selected keyword was able to cover all potential papers and thus satisfy the study objectives. In particular, this selection aims to draw conclusions about how significant each of the GR benefits has been in studies to date. Most relevant papers were identified through an exhaustive abstract-screening procedure. This method enables the filtering process to exclude scholarly works which are not associated with the scope of the present study, such as review papers and papers not focusing on the quantification of GR performance. The search process aimed to identify at least 100 suitable papers. The authors of this review are aware that there are substantially more works and published materials on GRs during the selected time frame. The papers studied in this review were selected based on their relevance in terms of quantifying the benefits of GRs. The work reviewed in this study provides a good snapshot of current research on GRs and ensures that sufficient information is available for the analysis and that a good balance of the number of papers is available from each year, from 2010 onwards.

The information of papers identified in the search process described above will be divided into several categories to facilitate the quantifying process. Firstly, the preliminary categorization is presented in Table A1 (in Appendix A), which provides the reader with an overview of the GR-related research with respect to the location, country, type of GR, methodology used, and GR benefits investigated. Later, this review goes into an in-depth evaluation of GR benefits and attempts to quantify them.

2.2. Types of Green Roof

2.2.1. Traditional Green Roofs

As discussed above, GRs are traditionally divided into three groups: EGR, SIGR, and IGR. The main difference between them is the depth of the substrate layer and the corresponding plants to suit a particular depth. EGRs with numerous favorable characteristics are widely implemented. Figure 3 describes the distribution of papers across the different GR types. It is worth highlighting that EGRs have been extensively studied, with 80 out of the 102 reviewed papers being on EGRs. The strong preference for EGRs has been well documented in previous studies and remains unchanged to date. As already mentioned, EGRs have been thoroughly and widely implemented because of several advantages, such as ease of installation due to their light weight, low initial and operational costs, and less maintenance requirements [16]. A good example of a country where EGRs are highly popular is Germany, where 85% of new GRs constructed annually are EGRs [17]. He, *et al.* [18] studied the changes in temperature and energy consumption in test chambers with extensive green modules on their top surface. Ávila-Hernández, *et al.* [19] collected the experimental data from an EGR on a test box to validate the simulation results of EnergyPlus software. Liu, *et al.* [20] used EGR-based parameters as the inputs of the Storm Water Management Model (SWMM) to assess the GR's capability of mitigating urban flooding for Nanchang in China. Cascone, *et al.* [21] simulated a variety of EGRs through EnergyPlus to comprehensively study the performance of a GR on a building in Catania, in Sicily, Italy. Palermo, *et al.* [22] investigated the hydrological behaviour of a full-scale EGR on top of a building at the University of Calabria, Italy. Carson, Marasco, Culligan and McGillis [10] monitored the retention capacity of three full-scale EGRs for one year and successively developed a model to identify the multi-year hydrological response of these systems.

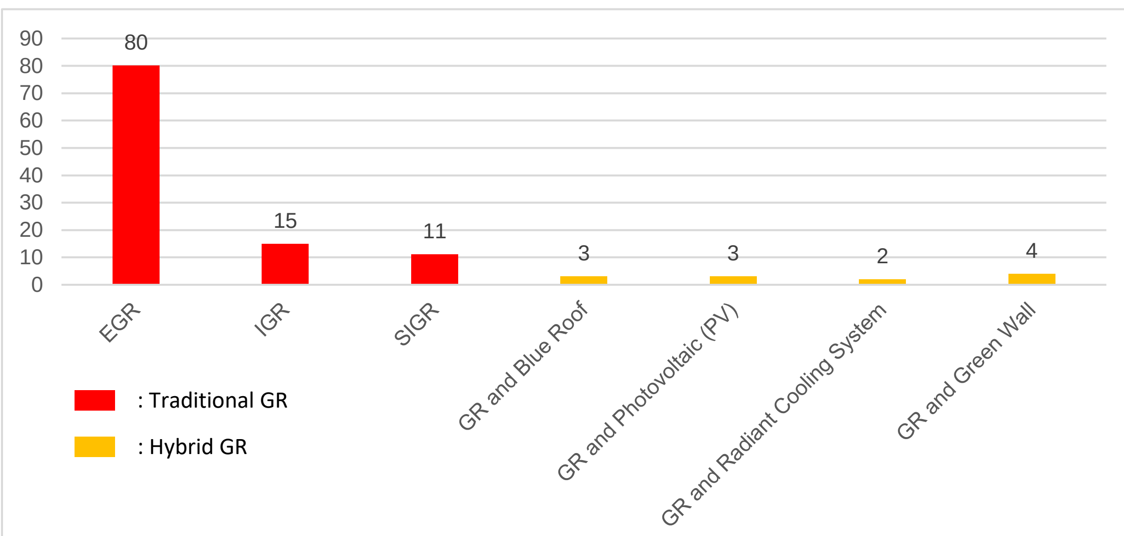

Figure 3. Distribution of papers across each type of GR (EGR: extensive green roof, IGR: intensive green roof, and SIGR: semi-intensive green roof).

On the other hand, SIGRs and IGRs have received less attention from researchers, although they outperform EGRs with regard to ecosystem services, mainly due to their thicker substrate layer. This lack of attention could be because of the stronger structural requirements, higher costs, and frequent maintenance associated with SIGRs. Of the 102 reviewed papers, a limited number of studies have considered SIGRs and IGRs, with only 11 and 15 studies being related to SIGRs and IGRs, respectively. For example, Lee and Jim [23] studied a full-scale IGR with a very deep substrate of 1 m to observe its thermal and cooling performance in Hong Kong. Such a thick substrate can allow the growth and survival of woodland vegetation. Kratschmer, *et al.* [24] examined the impact of various full-scale GRs with thick substrates (up to 0.9 m) on the diversity and abundance of wild bees. Beecham and Razzaghmanesh [25] investigated both the water quantity and quality of several pilot-scale EGRs and IGRs in Adelaide, Australia, with 0.1 m and 0.3 m of substrate depth, respectively. Moreover, researchers have not input the configurations of SIGRs and IGRs into their simulation models due to the low possibility of the application of these GRs. There are some exceptions to this. Morakinyo, *et al.* [26] used ENVI-met and EnergyPlus to simulate and evaluate the reduction of temperature and the energy use of a building installing an IGR system. Baek, *et al.* [27] collected the field data of a pilot-scale SIGR for inputs of the coupled SWMM and HYDRUS model to estimate the runoff reduction throughout an urban sub-basin.

2.2.2. Hybrid Green Roofs

In a broader context, researchers have recently attempted to improve the ecosystem services of this WSUD practice by integrating GRs with other systems. In this review, the term "Hybrid GR" is used to represent such roofs. One of them is the green–blue roof initially developed in Korea [1]. This is a combination of a blue roof and a green roof. A green–blue roof is technically similar to a typical GR, with the addition of one storage layer below the growing medium (Figure 4a). Only three papers (from the 102 reviewed papers) studied this type of roof. These are the studies by Shafique, *et al.* [28], Shafique, *et al.* [29], and Shafique and Kim [30]. This modified GR was reported to significantly mitigate urban flooding and urban heat island phenomena. Additionally, the integration of photovoltaic (PV) modules with GRs is a globally increasing trend among researchers. The integration of these two systems brings benefits in terms of both the electrical production and GR services [31]. More precisely, the evapotranspiration process of GR plants and growing mediums lessens the surface temperature of PV panels as well as their surrounding environment, which improves the electrical yield [32]. PV panels, which partially shade the surface of the GR, enhance GR benefits by limiting the solar radiation and, hence, diminishing the evapotranspiration rate of GRs [2].

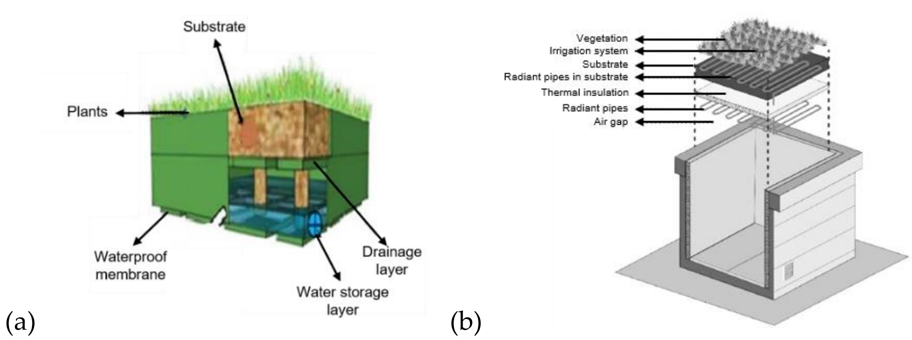

Figure 4. Schematic diagram of (**a**) a typical green–blue roof and (**b**) a pilot-scale green roof integrated with a radiant cooling system.

The other two types of hybrid GRs identified in this review are the GR–green wall system and the integration of GRs with radiant cooling systems. The construction of a vertical greening system along with a living roof is expected to greatly improve the Human Thermal Comfort (HTC) and thus reduce the cooling and heating demand. Only three papers (out of the 102 reviewed papers) considered this type of hybrid GR. Because of the difficulties and challenges associated with carrying out such projects at a building scale, previous studies explored the thermal behaviour of this combination in an experimental room [33] and with pilot-scale prototypes simulating full-scale dwellings [34,35]. In addition, the present study also found two papers examining the performance of a radiant cooling system integrated with a GR (Figure 4b). This type of hybrid GR comprises of a water pipe system (radiant component) and a sprinkler system (evaporative component) in its configuration [36]. It was determined that this hybrid GR performed better than conventional GRs in terms of temperature and energy reduction [36,37].

3. Quantification of Green Roof Benefits

This section attempts to quantify the ecosystem services that a GR can provide. Figure 5 indicates that HTC improvement and runoff reduction are two GR benefits being researched much more often than others during the last decade. Air quality improvement and noise reduction have been studied the least, with only three and two papers, respectively, out of the 102 papers reviewed in the present study. Additionally, further research on energy use reduction, runoff quality improvement, and ecological, social, and economic benefits are also required, as they were insufficiently studied with 22, 18, and 14 papers, respectively. These findings imply an identical trend with those previously reported in the reviews of Vijayaraghavan [2] and Shafique, Kim and Rafiq [1].

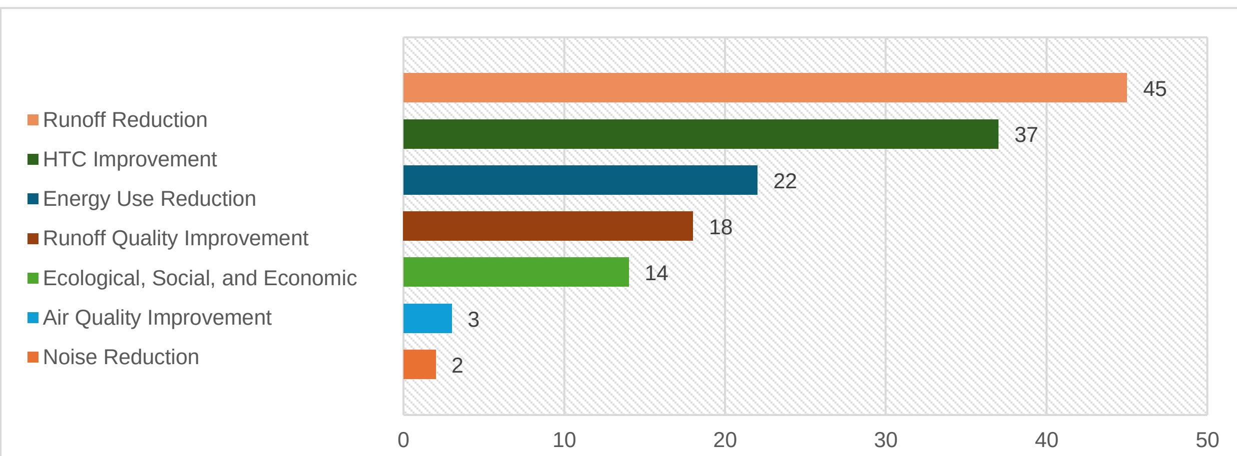

Figure 5. The break-down of papers as per the ecosystem services provided by GRs.

The above-discussed imbalance of GR research focus results from several factors. GR projects associated with temperature and runoff are easily carried out with the availability of numerous monitoring devices and existing simulation models. Consequently, such types of projects vary greatly, from indoor and outdoor experiments to model simulations. They can be also implemented in various methods comprising full-scale GRs, small test cells, and raised

GR test beds. On the other hand, a lesser number of studies on runoff quality could be explained by the requirements of expensive instruments and advanced knowledge to collect and analyze water samples. Though there are 14 papers under the category "Ecological, Social, and Economic", only a small number of them have conducted the cost–benefit analysis to explore the costs of a GR system during its life cycle and its payback period. Meanwhile, fewer works have been done to study ecological and social benefits due to the difficulties in quantifying the recovery of habitat loss, the enhancement of urban biodiversity, and the improved human health and well-being by connecting people to green spaces [1,3,38,39]. By contrast, noise reduction and air pollution mitigation are two GR benefits that are receiving the least attention from researchers. This limitation could be due to the fact that these two benefits require a complex research design and specific knowledge relating to plant biochemistry. In particular, the amount of CO_2, a primary greenhouse gas, that is directly absorbed by GR plants is minimal in comparison with indirect CO_2 reduction from the energy savings provided by GRs [21].

This review referred to the Köppen climate classification system so as to understand the impact of climatic conditions on GR performance. This system divides the global climate into five main groups. The first letters, including A, B, C, D, and E, represent five types of climate: Tropical, Dry, Temperate, Continental, and Polar, respectively. To further describe these climate types, the second and third letters help to divide them into numerous sub-groups based on the precipitation and temperature characteristics. For instance, a sub-group Cfa (known as a humid sub-tropical climate) has the following features: Temperate (C), No dry season (f), and Hot summer (a). The following sub-sections give detailed information about how each of the GR benefits have been studied during last ten years.

3.1. Runoff Reduction

GR has been well known as an effective WSUD treatment due to its capability of holding precipitation in its layers, thus reducing stress on urban drainage systems. The hydrological behaviours of GR vary significantly because of several factors. Among those, rainfall depth appears to be the most influential one. The impact of rainfall depth on the GR retention rate could be identified not only by comparing results between different papers but also by considering individual papers. For example, cumulative rainfall retention by GRs reached a peak of 82.9% among 46 identified papers in Table 1 because a rainfall depth of only 628.2 mm, ranging from 0.8 to 78.8 mm per event, was recorded during the study period of 15 months [40]. Another high retention rate of 73% was observed in the study of Zhang, *et al.* [41] as only 563.7 mm of precipitation during 468 days was monitored. Others reported a smaller amount of rainfall retained greatly by GRs due to significant rainfall events and higher accumulated rainfall depths during the monitoring periods. Some examples are 45.1% [22], 50.2% [42], and 51.4% [43], corresponding to cumulative rainfall depths of 1256.3 mm (1 year), 1892.2 mm (27 months), and 481 mm (5 months), respectively. The lowest retention rate of 11.9% in the study of Wong and Jim [44] was due to the exposure of the GR to heavy rainfall events (more than 300 mm per event) with a total depth of 1102.7 mm in a short study period of 10 months.

Taking runoff reduction, rainfall retention from a single event, and peak flow reduction into account, these parameters demonstrate an identical pattern with the cumulative rainfall retention discussed in the above paragraph. Such a hydrological GR response has been mentioned in plenty of previous reports. Carson, Marasco, Culligan and McGillis [10] found a downward trend in the rainfall retention rate as precipitation increases. Palermo, Turco, Principato and Piro [22], Todorov, *et al.* [45], Speak, *et al.* [46], and Stovin, Vesuviano and Kasmin [42] found that the retention performance of GRs, when analyzing all events, was higher than the retention rate when considering only storm events. On an event-by-event basis, Zhang, *et al.* [47] found an average retention rate of 95%, as only small rainfall events, ranging from 2- to 35.2-mm depths, took place during the study period. Following the study of Todorov, Driscoll and Todorova [45] and Carpenter, *et al.* [48], the retention rates of 95.9% and 96.8% corresponded with rainfall depths ranging between 0.76 and 44.2 mm and 2.5 to 17.8 mm, respectively. Other papers applying large rainfall volumes showed lower retention capacities. Zhang, *et al.* [49], Nawaz, *et al.* [50], Hakimdavar, *et al.* [51], Wong and Jim [44], and Stovin, Vesuviano and Kasmin [42] are good examples. Table 1 summarizes the hydrological performance of GRs from 45 studies. The results from this review are in agreement with those presented in Zheng, Zou, Lounsbury, Wang and Wang [9], namely, that the rainfall volume retained during a single event ranges from 0 to 100% with an average value of 62%.

Table 1. Quantification of runoff reduction caused by green roofs.

Number	Reference	Climate Group	Modelling Software Used	Rainfall Depth (mm) (Rainfall Intensity (mm/h))	Runoff Reduction (%)	Cumulative Rainfall Retention (%)	Rainfall Retention per Single Rainfall Event (%)	Peak Flow Reduction per Single Rainfall Event (%)	Rainfall Retention from Storm Events
1	Barnhart, *et al.* [52]	Cfb	Visualizing Ecosystem Land Management Assessments (VELMA)	N/A	EGR: 10–15 (annual) IGR: 20–25 (annual)	N/A	N/A	N/A	N/A
2	Baek, Ligaray, Pachepsky, Chun, Yoon, Park and Cho [27]	Cfa and Cwa	SWWM and HYDRUS-1D	N/A	N/A	N/A	N/A	N/A	N/A
3	Silva, *et al.* [53]	Aw	N/A	(115.8 to 145.4)	N/A	N/A	68 to 82	59 to 81	N/A
4	Liu, Sun, Niu and Riley [20]	Cwa	SWWM	30 to 70	27 to 42	N/A	41 to 75	8 to 31	N/A
5	Jahanfar, *et al.* [54]	Dfa	N/A	less than 10	N/A	N/A	Control GR: 90 (minimum) PV GR: 61 to 75 (minimum)	N/A	
6	Zhang, Szota, Fletcher, Williams and Farrell [47]	Cfb	N/A	2 to 35.2	N/A	N/A	89 to 95 (average)	N/A	N/A
7	Sims, *et al.* [55]	Dfb	A Richards-based numerical model	N/A	N/A	N/A	N/A	58 (average)	N/A
8	Palermo, Turco, Principato and Piro [22]	Csa	HYDRUS-1D	2 to 120, and 1256.3 (1 year)	N/A	45.1 (1 year)	16.7 to 100 (68 average)	13.3 to 95.2 (56 average)	16.7 to 82.5 (49.6 average)

9	Gong, Yin, Li, Zhang, Wang, Fang, Shi and Wang [40]	Dwa	N/A	0.8 to 78.8, and 628.2 (15 months)	N/A	68.5 to 82.9 (15 months)	12.1 to 100, and (88.1 to 92.9 average)	72.3 to 95.9	N/A
10	Talebi, *et al.* [56]	Cfb, Dwb, Dfa, and Dfb	Penman–Monteith (PM) model and Hargreaves and Samani (HS) model	390 to 1200 (annual)	17 to 47 and 27 to 61 (annual, low and high water-use plants, respectively)	N/A	N/A	N/A	N/A
11	Ferrans, *et al.* [57]	Cfb	N/A	600 to 1200 (annual)	N/A	N/A	85 (average)	N/A	N/A
12	Todorov, Driscoll and Todorova [45]	Dfb	N/A	0.76 to 44.2	N/A	N/A	75 to 99.6 (95.9 average)	N/A	89 (average)
13	Shafique, *et al.* [58]	Dwa	N/A	(50 to 100)	N/A	N/A	10 to 60	N/A	N/A
14	Zhang, Szota, Fletcher, Williams, Werdin and Farrell [41]	Cfb	N/A	563.7 (468 days)	N/A	73 (468 days)	N/A	N/A	N/A
15	Johannessen, *et al.* [59]	Cfb, Dfb, and Dfc	N/A	970 to 3110 (annual)	N/A	11 to 30	N/A	65 to 90 (average)	N/A
16	Soulis, *et al.* [60]	Csa	HYDRUS-1D	13.9 to 74.2	0.1 to 100 (42.8 average)	N/A	N/A	8.7 to 100 (70.2 average)	N/A
17	Johannessen, *et al.* [61]	Cfb, Cfc, Dfb, and Dfc	Water balance model and Oudin Etmodel	N/A	N/A	cold and wet climate: 17 (annual) warm and dry climate: 58 (annual)	N/A	N/A	N/A
18	Brunetti, *et al.* [62]	Csa	HYDRUS-1D	431 (2 months)	25 (2 months)	N/A	N/A	N/A	N/A
19	Carpenter, Todorov, Driscoll and Montesdeoca [48]	Dfb	N/A	2.5 to 17.8	N/A	N/A	96.8 (average)	N/A	N/A
20	Shafique, Lee and Kim [28]	Dwa	N/A	(60) (maximum)	67	N/A	N/A	N/A	N/A
21	Shafique, Kim and Lee [29]	Dwa	N/A	(90) (average)	70 to 100	N/A	N/A	N/A	N/A
22	Karteris, *et al.* [63]	Csa	Regression	less than 96.7	N/A	45 (average)	N/A	N/A	N/A
23	Cipolla, *et al.* [64]	Cfa	SWMM	0.2 to 41.6	N/A	N/A	6.4 to 100 (51.9 average)	N/A	N/A
24	Beecham and Razzaghmanesh [25]	Csa	N/A	11.5 to 56	N/A	N/A	51 to 96 (average)	N/A	N/A
25	Lee, *et al.* [65]	Dwa	N/A	8.5 to 42.5	EGR: 13.8 to 34.4 Semi-IGR: 42.8 to 60.8	N/A	N/A	N/A	N/A
26	Zhang, Miao, Wang, Liu, Zhu, Zhou, Sun and Liu [49]	Cfa	N/A	2.5 to 84.8, and 1116.5 (annual)	N/A	68 (annual)	35.5 to 100 (77.2 average)	N/A	N/A
27	Versini, *et al.* [66]	Cfb	SWMM and Regression	827 (15 months)	N/A	N/A	0.03 m substrate: 0 to 100 (83	N/A	

							average). 0.15 m substrate: 18 to 100 (89 average)		
				10.6 to 112.8	Simulated Roof : 10 to 100 (85 average)		N/A	Simulated Roof: 10 to 100 (85 average)	N/A
					Simulated Basin: 14.4 to 53.9 (25.2 average)		N/A	Simulated Basin: 17.4 to 38.7 (35.6 average)	
28	Yang, *et al.* [67]	Dwa	Regression and HYDRUS-1D	1.8 to 190.4	N/A	38 (4 months)	17 to 100 (78 average)	N/A	N/A
29	Harper, *et al.* [68]	Cfa	Water Balance Model	less than 50	60 (9 months)	N/A	N/A	N/A	N/A
30	Nawaz, McDonald and Postoyko [50]	Cfb	Regression	1 to 84	N/A	39.4 (20 months)	3.6 to 100 (66 average)	N/A	N/A
31	Wong and Jim [44]	Cwa	N/A	0.6 to 344.8, and 1102.7 (10 months)	N/A	11.9 to 14.1 (10 months)	38.9 to 45.3 (average)	40.6 to 58.3 (average)	N/A
32	Razzaghmanesh and Beecham [69]	Csa	N/A	4.2 to 100.2, and 967.8 (2 years)	N/A	N/A	EGR: 74 (average)	EGR: 61.5 (average)	N/A
							IGR: 88.6 (average)	IGR: 70.3 (average)	
33	Hakimdavar, Culligan, Finazzi, Barontini and Ranzi [51]	Cfa	HYDRUS-1D	less than 20, 20-40, and more than 40	N/A	N/A	Average: 85, 48, and 32, respectively	Average: 89, 62, and 51, respectively	N/A
34	Mickovski, *et al.* [70]	Cfb	N/A	N/A	N/A	N/A	69 (average)	N/A	N/A
35	Speak, Rothwell, Lindley and Smith [46]	Cfb	N/A	less than 56.08	N/A	N/A	22 to 100 (65.7 average)	N/A	36.58 to 73.22, and 51.2 (average)
36	Carson, Marasco, Culligan and McGillis [10]	Cfa	Regression	0.25 to 180	N/A	36, 47, and 61 (1 year)	3 to 100, 9 to 100, and 20 to 100	N/A	N/A
37	Nagase and Dunnett [71]	Cfb	N/A	N/A	N/A	N/A	N/A	N/A	N/A
38	Stovin, Vesuviano and Kasmin [42]	Cfb	Regression	1892.2 (27 months)	N/A	50.2 (27 months)	0 to 100 (70 average)	60 (average)	0 to 100, and 43 (average)
39	Qin, *et al.* [72]	Af	N/A	18	N/A	N/A	11.4	65	N/A
40	Buccola and Spolek [73]	Csb	N/A	Heavy: (340)	N/A	N/A	Heavy: 56 (average)	N/A	N/A
				Medium: (30)			Medium: 64 (average)		
41	Beck, *et al.* [74]	Csb	N/A	(74)	N/A	N/A	8.5 to 32.5 (21.1 average)	N/A	N/A
42	Gregoire and Clausen [43]	Dfa	Water Balance Model	481 (5 months)	N/A	51.4 (5 months)	N/A	N/A	N/A
43	Roehr and Kong [75]	Cfb, Csb, and Cfa	Water Balance Model	1200, 380.5, and 1219 (annual)	Low water-use plants: 29, 100,	N/A	N/A	N/A	N/A

					and 28 (annual, respectively) High water-use plants: 58, 100, and 55 (annual, respectively)				
44	Voyde, *et al.* [76]	Cfb	N/A	1093 (1 year)	N/A	66 (1 year)	82 (average)	93 (average)	N/A
45	Palla, *et al.* [77]	Cfa	N/A	Laboratory test: (108 to 194). Field experiment: 8 to 138.2	N/A	N/A	Laboratory test: 52 to 67 Field experiment: 0 to 100 (51.5 average)	Field experiment: 44 to 100 (83.3 average)	N/A

In order to make a proper comparison between different climatic locations, some papers simulated GRs with identical configurations to identify their hydrological behaviours in various weather patterns. Talebi, Bagg, Sleep and O'Carroll [56] recognized the best performance of GR in Regina (Dfb) and Calgary (Dwb), which received the least precipitation (390 and 420 mm, respectively) among six studied Canadian cities, whereas the worst performance was observed in Halifax (Dfb), which had an average annual precipitation of 1400 mm. In the study of Johannessen, Muthanna and Braskerud [59], a GR in Bergen (Cfb) with 3110 mm of annual precipitation could retain total rainfall at only 11%, whereas the accumulated retention rate in Trondheim (Dfc) was 30%. Johannessen, Hanslin and Muthanna [61] considered ten northern European cities. They concluded that the wettest climate (Bergen, Cfb) showed the lowest annual retention rate of 17%; meanwhile, the driest climate (Malmö, Cfb) achieved the highest rate of 58%.

3.2. Human Thermal Comfort (HTC) Improvement

Although GRs are an important WSUD strategy, they also help to address temperature- and heat-related urban issues. The decrease in outer surface temperature (T_s) of a roof deck after GR installation widely fluctuates, between around 5 °C and 40 °C, with a reduction of 15 °C to 20 °C reported the most (Table 2 The difference in T_s between a GR and a bare roof ($\Delta T_s = T_{s\text{-bare roof}} - T_{s\text{-GR}}$) was the highest, at 40 °C in the study of He, *et al.* [78], whereas Sun, *et al.* [79] observed the smallest ΔT_s of 4.2 °C. The variation of a GRs' thermal response depends on many factors, such as the structural design of GRs and the thermal properties of GR materials, and the different climatic conditions that the GR is exposed to. However, some identical patterns, as well as noticeable discrepancies, have been identified in this review.

More specifically, in many studies, while GRs produced the most impressive results in hot climates, they showed the weakest impacts in cold climatic conditions. For instance, following He, Yu, Ozaki and Dong [18], a GR reduced T_s by 21.7 °C and 14.4 °C in summer and winter, respectively. He, *et al.* [80] also reported similar results with the T_s reduction of 35 °C and 15 °C in the hottest and coldest seasons, respectively. Furthermore, in studies considering the impact of climatic conditions on thermal performance, GRs in hot and dry climates demonstrated the highest ΔT_s. For example, Ávila-Hernández, Simá, Xamán, Hernández-Pérez, Téllez-Velázquez and Chagolla-Aranda [19] and Morakinyo, Dahanayake, Ng and Chow [26] utilized a computer-based tool to test the thermal effectiveness of GRs in different climates. They both found that cities in hot desert climates, which are indicated by the BWh sub-group, had the most positive results relative to those in other locations. It was also determined that the GRs in continental climates (Dfa or Dwa) achieved the poorest performance with regard to ΔT_s [30,79,81]. Shanghai, China (Dfa) was found the most-appropriate location to implement GRs, as the greatest ΔT_s was recorded in this city [78,80,82].

Table 2. Quantification of Human Thermal Comfort improvement by green roofs.

Number	Reference	Climate Group	Modelling Software Used	Surface Temperature Reduction—ΔT_S (°C)	Indoor Air Temperature Reduction—$\Delta T_{air.in}$ (°C)	Outdoor Air Temperature Reduction—$\Delta T_{air.out}$ (°C)
1	La Roche, Yeom and Ponce [36]	Csa	Regression	N/A	2.1 (averaged maximum, compared with insulated bare roof)	N/A
2	Ávila-Hernández, Simá, Xamán, Hernández-Pérez, Téllez-Velázquez and Chagolla-Aranda [19]	As (Aw), Am, BSh, BWh, BSk, and Cwb	EnergyPlus	14.5 (maximum)	Maximum: 4.7 (upper level) and 0.9 (lower level)	N/A
3	Feitosa and Wilkinson [35]	Cfa	N/A	N/A	WGBT: −1.9 (nighttime) and 8.3 (daytime)	N/A
4	He, Yu, Ozaki and Dong [18]	Cfa	THERB	Summer maximum: 21.7 (daytime) and −5.3 (nighttime) Winter maximum: 14.4 (daytime) and −9.2 (nighttime)	N/A	N/A
5	Xing, Hao, Lin, Tan and Yang [33]	Cfa	N/A	N/A	−3 (maximum, nighttime)	N/A
6	Cao, *et al.* [83]	Cfa	N/A	Maximum: 11.9 (compared to bare soil roof)	N/A	N/A
7	Tang and Zheng [84]	Cfa	N/A	16.4 (maximum)	3.1 (average)	N/A
8	Cai, *et al.* [85]	Cfa	N/A	Summer: 5.7 (average, sunny) Winter: −1.2 (average, sunny)	Summer: 0.6 (average, sunny) Winter: −1.6 (average, sunny)	N/A
9	Cascone, Catania, Gagliano and Sciuto [21]	Csa	EnergyPlus	19 (maximum)	N/A	N/A
10	Feitosa and Wilkinson [34]	Aw and Cfa	N/A	N/A	Rio de Janeiro, maximum WGBT: 8.1 (daytime) and −2.8 (nighttime) Sydney, maximum WGBT: 12 (daytime) and −1.2 (nighttime)	N/A
11	Park, *et al.* [86]	Dwa	Regression	N/A	N/A	Maximum, 1.5 m above: 22.6 (daytime) and 1.9 (nighttime)
12	Lee and Jim [23]	Cwa	N/A	19.8 (maximum)	N/A	Maximum: 6.21 (0.15 m above), 4.7 (0.50 m above, and 3.1 (1.5 m above)

13	Azeñas, *et al.* [87]	Csa	N/A	N/A	N/A	N/A
14	Morakinyo, Dahanayake, Ng and Chow [26]	BWh, Cfa, Cwa, and Cfb	EnergyPlus and ENVI-met	Maximum: 14 (daytime) and 4 (nighttime)	Maximum, hot climate, 0.7-m substrate: 1.4 (daytime) and 0.3 (nighttime) Maximum, cold climate, 0.3-m substrate: 0.3 (daytime) and −0.1 (nighttime)	Maximum, 1.5 m above, pedestrian level: 0.6 (daytime) and −0.2 (nighttime)
15	He, Yu, Ozaki, Dong and Zheng [80]	Cfa	A coupled heat and moisture transfer model	Summer maximum: 35 (daytime) and −5 (nighttime) Winter maximum: 15 (daytime) and -10 (nighttime)	N/A	Maximum, 0.15 m above: 5 (summer) and 2 (winter)
16	Yeom and La Roche [37]	Csa	N/A	N/A	2 (compared to other test cells)	N/A
17	Shafique and Kim [30]	Dwa	N/A	5 to 9 (average)	N/A	N/A
18	Wilkinson, *et al.* [88]	Aw and Cfa	N/A	N/A	Rio de Janeiro maximum: −4.1 (nighttime) and 6.2 (daytime) Sydney maximum: −1.1 (nighttime) and 12 (daytime)	N/A
19	Bevilacqua, Mazzeo, Bruno and Arcuri [82]	Csa	N/A	Maximum: 34.1 (daytime) and −9.4 (nighttime)	N/A	N/A
20	Foustalieraki, *et al.* [89]	Csa	N/A	Maximum: 21.9 (daytime) and −1.6 (nighttime)	Maximum: 1.1 (summer) and −0.7 (winter)	N/A
21	Boafo, Kim and Kim [81]	Dwa	EnergyPlus	Maximum: 5 (summer) and −6 (winter)	N/A	N/A
22	Gagliano, *et al.* [90]	Csa	The Design Builder software	19 (maximum)	4 (maximum)	N/A
23	Shafique, Kim and Lee [29]	Dwa	N/A	10 (maximum)	N/A	N/A
24	He, Yu, Dong and Ye [78]	Cfa	N/A	Maximum: 30 (free floating) and 40 (air conditioned)	Maximum: 2 (daytime) and −2.5 (nighttime)	5 (maximum, 0.15 m above)
25	Tam, *et al.* [91]	Cwa	N/A	N/A	3.4 (maximum)	N/A
26	Schweitzer and Erell [92]	Csa	N/A	N/A	1.89 (average) and 4.5 (maximum)	N/A
27	Chemisana and Lamnatou [93]	BSk	N/A	14 (maximum)	N/A	N/A
28	Sun, Bou-Zeid, Wang, Zerba and Ni [79]	Dwa and Dfa	PROM	4.2 (summer, averaged daily maximum)	N/A	N/A
29	Peng and Jim [3]	Cwa	ENVI-met and RayMan	N/A	Maximum: 1.6 (Top Floor) and 1.3 (Ground Floor)	Maximum, 1.2 m above: 2.1 (rooftop level) and 1.7 (pedestrian level)
30	Ascione, Bianco, de'Rossi, Turni and Vanoli [16]	Bsh, Csa, Cfb, and Dfb	EnergyPlus	N/A	N/A	N/A

31	Pandey, *et al.* [94]	Cwa	N/A	N/A	Average: 3.9 (DBT) and 4 (WGBT)	N/A
32	Blanusa, *et al.* [95]	Cfb	N/A	Compared with bare soil roof: 14.9 (maximum)	N/A	Compared with bare soil roof: 1.1 (average, 0.1 m above)
33	Qin, Wu, Chiew and Li [72]	Af	N/A	15.3 (maximum) and 7.3 (average)	N/A	0.3 m above: 1.3 (maximum) and 0.5 (average)
34	Jim and Peng [96]	Cwa	N/A	12.5 (maximum)	N/A	Maximum: 4.4 (0.1 m above) and 2.3 (1.6 m above)
35	Pérez, *et al.* [97]	Bsk	N/A	N/A	N/A	N/A
36	Getter, *et al.* [98]	Dfa	N/A	20 (maximum)	N/A	N/A
37	Hui and Chan [99]	Cwa	N/A	4 to 5 (compared to non-PV GR)	N/A	N/A

Owing to the interaction between the surface temperature of the roof membrane and the indoor environment, ($T_{air.in}$), $\Delta T_{air.in}$ ($T_{air.in\text{-}bare\ roof} - T_{air.in\text{-}GR}$), and ΔT_s demonstrate a similar behaviour. However, $\Delta T_{air.in}$ is much smaller than ΔT_s, with respect to both magnitude and amplitude. In accordance with the data presented in Table 2, $\Delta T_{air.in}$ ranged from around 1 °C to 5 °C. The integration of GRs and green walls significantly improved $T_{air.in}$, with a maximum daytime reduction of 6.2 °C and 12 °C in Rio de Janeiro and Sydney, respectively [88]. In alignment with T_s, the $T_{air.in}$ of a living roof was mostly reported as warmer than that of a bare roof during nighttime and wintertime. GRs acting as a heat source could be ideal to reduce heating demands in cold regions, but this is not the case in hot climatic regions.

The ability of GRs to mitigate urban heat island (UHI) effects has been inadequately examined. Of the 37 published works in Table 2, there are few papers researching the decrease in ambient air temperature ($\Delta T_{air.out}$) after GR implementation. Some exceptions are the studies by Park, Kim, Dvorak and Lee [86], Lee and Jim [23], Morakinyo, Dahanayake, Ng and Chow [26], Peng and Jim [3], and Jim and Peng [96], as they undertook an analysis of $T_{air.out}$ above a living roof and a non-living roof. Nevertheless, in addition to different GR characteristics and study locations, they produced greatly divergent outcomes due to the nonidentical set-ups of their measuring devices. He, Yu, Ozaki, Dong and Zheng [80] concluded that the GR was able to reduce air temperature at 0.15 m above the roof by 5 °C in summer and 2 °C in winter. Lee and Jim [23] set thermal sensors to monitor $T_{air.out}$ above the studied roofs at three positions, including 0.15 m, 0.5 m, and 1.5 m. Qin, Wu, Chiew and Li [72] and Peng and Jim [3] reported values of $T_{air.out}$ at 0.3 m and 1.2 m above the roofs, respectively. Park, Kim, Dvorak and Lee [86] reported an outstanding result, as $\Delta T_{air.out}$ reached a peak of 22.6 °C, whereas others observed much smaller $T_{air.out}$ reductions. However, it was similarly detected that a higher reduction was observed closer to plant canopies and the greater effect of GRs occurred during the day and in summer. Moreover, only two papers estimated $\Delta T_{air.out}$ at the pedestrian level after growing plants on building rooftops [3,26]. Future studies similar to that by Köhler and Kaiser [17] are important, since they conducted a comprehensive investigation of GR performance with regard to UHI mitigation with a 20-year monitoring period. They found that although the ambient temperature had an upward trend due to global warming, the temperature of the GR substrate layer remained stable with a slight decrease. Consequently, the potential of GRs to address the UHI effects is still optimistic, and sufficient studies need to be undertaken with an identical approach prior to making generic conclusions.

3.3. Energy Use Reduction

In accordance with thermal reduction, GR reduces the energy that a building consumes for cooling and heating demand. Twenty-two papers were identified in the present study that reported varying results in terms of savings in energy use. However, some similarities can also be observed in Table 3. All publications pointed out a higher decrease in cooling demand than heating demand after implementation of GRs. For example, Cai, Feng, Yu, Xiang and Chen [85] achieved an annual reduction of 11.2% and 9.3% of energy consumption for cooling and heating, respectively. The difference was even larger in Cascone, Catania, Gagliano and Sciuto [21]; the yearly amount of electricity consumed by a GR-integrated building was 35% (cooling) and 10% (heating) less than a building with a conventional roof. Moreover, these two values in Gagliano, Detommaso, Nocera and Berardi [90] were impressive, with maximum decreases of 85% and 48% for cooling and heating requirements, respectively.

Table 3. Quantification of energy use reduction caused by green roofs.

Number	Reference	Climate Group	Modelling Software Used	Energy Performance		
				Energy Reduction	Heat Flux (HF) Reduction—ΔHF	CO2 Emission Reduction
1	Ávila-Hernández, Simá, Xamán, Hernández-Pérez, Téllez-Velázquez and Chagolla-Aranda [19]	As (Aw), Am, BSh, BWh, BSk, and Cwb	EnergyPlus	Maximum: 99% (cooling) and −25% (heating)	N/A	2.5 tons or 45.7% (maximum, annual)
2	He, Yu, Ozaki and Dong [18]	Cfa	THERB	Top floor: 3.6% (cooling) and 6.2% (heating)	Summer maximum: 12.6 (daytime) and −3.1 (nighttime) W/m^2 Winter maximum: 8.4 (daytime) and −5.4 (nighttime) W/m^2	N/A
3	Xing, Hao, Lin, Tan and Yang [33]	Cfa	N/A	18% (heating)	3.1 W/m^2 (average, heating condition)	N/A
4	Tang and Zheng [84]	Cfa	N/A	14.7% (average, cooling)	35.5 W/m^2 (maximum, daytime) and 76.1% (average)	N/A
5	Cai, Feng, Yu, Xiang and Chen [85]	Cfa	Swell BESI2016	Annual: 10.13% (total), 9.3% (heating), and 11.2% (cooling)	Summer: 3.7 W/m^2 or 50% (average, daytime) Winter: −7.5 W/m^2 or 24.6% (average, daytime)	9.35 kg/m2 GR (annual)
6	Cascone, Catania, Gagliano and Sciuto [21]	Csa	FASST	Annual: 20–24% (total), 31–35% (cooling), and 2–10% (heating)	N/A	1.35 kg/m2 GR (annual)
7	Azeñas, Cuxart, Picos, Medrano, Simó, López-Grifol and Gulías [87]	Csa	N/A	N/A	48 to 86% (annual)	N/A

8	Morakinyo, Dahanayake, Ng and Chow [26]	BWh, Cfa, Cwa, and Cfb	EnergyPlus	Maximum. cooling: 5.2% (hot climate, 0.7-m soil thickness) and 0.3% (temperate climate, 0.3-m soil thickness)	N/A	N/A
9	He, Yu, Ozaki, Dong and Zheng [80]	Cfa	A coupled heat and moisture transfer model	N/A	Average: 1.75 W/m^2 (summer) and 0.87 W/m^2 (winter)	N/A
10	Foustalieraki, Assimakopoulos, Santamouris and Pangalou [89]	Csa	EnergyPlus	Annual: 15.1% (total), 18.7% (cooling), and 11.4% (heating)	N/A	N/A
11	Boafo, Kim and Kim [81]	Dwa	EnergyPlus	Annual: 3.7% (total), 5.4% (cooling), and 2.7% (heating)	N/A	N/A
12	Karteris, Theodoridou, Mallinis, Tsiros and Karteris [63]	Csa	EnergyPlus	Maximum: 5% (heating) and 16% (cooling)	N/A	3.5 to 9.1 kg/m2 GR (annual)
13	Gagliano, Detommaso, Nocera and Berardi [90]	Csa	The Design Builder software	Maximum: 85% (cooling) and 48% (heating)	N/A	N/A
14	He, Yu, Dong and Ye [78]	Cfa	N/A	N/A	Maximum daytime: 15 (free floating) and 20 (air conditioning) W/m^2	N/A
15	Schweitzer and Erell [92]	Csa	N/A	N/A	679 kJ/m^2 (average)	N/A
16	Sun, Bou-Zeid, Wang, Zerba and Ni [79]	Dwa and Dfa	PROM	N/A	133 W/m^2 (averaged daily maximum)	N/A
17	Ascione, Bianco, de'Rossi, Turni and Vanoli [16]	Bsh, Csa, Cfb, and Dfb	EnergyPlus	Maximum: 11% (warm climate) and 7% (cold climate)	N/A	N/A
18	Pandey, Hindoliya and Mod [94]	Cwa	N/A	N/A	13.8 W/m^2 and 73.8% (maximum, daytime)	N/A
19	Jim and Peng [96]	Cwa	N/A	2.8×10^4 kWh (cooling, 484 m^2 GR)	33.5 W/m^2 (maximum, daytime)	27.02 tons (summer, at power plant)
20	Pérez, Coma, Solé, Castell and Cabeza [97]	Bsk	N/A	3.6 to 15% (cooling) and −7% (heating)	N/A	N/A
21	Getter, Rowe, Andresen and Wichman [98]	Dfa	N/A	N/A	Average: 167% (summer) and 13% (winter)	N/A
22	Hui and Chan [99]	Cwa	EnergyPlus	6.53×10^4 kWh (6300 m^2 GR, annual)	N/A	N/A

In a broader context, some papers modelled buildings with vegetated roofs in various climates to investigate the climatic influence on the energy performance of GRs. Overall, the energy effectiveness of GRs has reported the greatest savings in hot climates and the least savings in cold climates. Ascione, Bianco, de'Rossi, Turni and Vanoli [16] reported a maximum reduction of 11% in warm climates, whereas 7% was estimated in cold climates.

Morakinyo, Dahanayake, Ng and Chow [26] fulfilled a comprehensive analysis of energy reduction due to GRs with different substrate depths and climatic conditions. As expected, GRs with a deeper substrate (0.7 m) in hot climates (BWh) outperformed GRs with a thinner substrate (0.3 m) in temperate climates (Cfb), with respect to energy savings for cooling at 5.2% and 0.3%, respectively. Ávila-Hernández, Simá, Xamán, Hernández-Pérez, Téllez-Velázquez and Chagolla-Aranda [19] brought a different perspective by investigating the energy behavior of a residential building with a living roof in several Mexican cities. The largest annual energy savings, of more than 90%, was recorded in cities where the cooling demand exceeds the heating demand. In spite of the large energy reduction for cooling, those cities consumed more energy for heating because the cooling effect of the GR was inappropriate for low-average-annual-temperature regions (BSk and Cwb). Finally, the simulation results suggested that GRs should be implemented in warm-climate cities (Am and BWh), which are dominated by cooling demand.

Another parameter used in the studies is heat flux (HF), which is defined as the flow of energy through building envelopes. Many papers considered HF because of its strong correlation with the electricity consumption of a building. In this context, a GR acts as an insulation layer to reduce heat flux moving into a building through the rooftop. This reduction of energy flow (Δ HF = $HF_{\text{bare roof}} - HF_{GR}$) is in agreement with the $\Delta T_{air.in}$ already discussed earlier. More accurately, ΔHF was greater during daytime and hot summers than that during night-time and cold winters. There was a decrease of more than 50% in HF passing through the roof deck under a GR as compared to a conventional roof. The ΔHF in Getter, Rowe, Andresen and Wichman [98] reached an average of 167% in summer, but only 13% in winter. In the study of He, Yu, Ozaki, Dong and Zheng [80], GRs lessened HF by 1.75 W/m^2 and 0.87 W/m^2 in summer and winter, respectively.

Few studies investigating building energy reduction due to GRs also studied the reduction of cardon dioxide (CO_2) concentration caused by a reduction in energy use. In addition to the direct CO_2 absorption by GR plants, the indirect removal of CO_2 is caused by the energy savings. The calculation of CO_2 indirectly absorbed by GR vegetation was mostly based upon the emission factor and the amount of energy saved by the GR installation. Karteris, Theodoridou, Mallinis, Tsiros and Karteris [63] concluded that the implementation of a GR at the municipality level of Thessaloniki city could reduce 65,000 tons of CO_2 yearly. Furthermore, the CO_2 reduction generated by 50% of the building blocks in the city corresponds to the 50-acre forest plantation. Simulation results from Ávila-Hernández, Simá, Xamán, Hernández-Pérez, Téllez-Velázquez and Chagolla-Aranda [19] show that applying GRs could save up to 45.7% of CO_2 annually in Chetumal, which has a high cooling demand. In Wuxi, China, with a humid, subtropical climate (Cfa), each square meter of a GR could reduce 9.35 kg of CO_2 per year [85].

3.4. Runoff Quality Improvement

In addition to runoff reduction, improving runoff quality is another ecosystem service provided by this WSUD strategy. However, this benefit requires further research due to the significant variation among the published results. Globally, researchers are trying to determine whether GRs enhance or degrade the stormwater quality. Several authors have been in agreement, with a conclusion that the runoff quality from GRs is strongly affected by the substrate composition (organic content), substrate depth, GR age, maintenance frequency, and fertilizing methods [1,2]. No standards exist for regulating the runoff quality from GRs

[100]. Therefore, the vast majority of papers on runoff quality in this review used fresh-water standards from the American Public Health Association (APHA) and the United States Environmental Protection Agency (USEPA). A few papers used local guidelines to examine GR outflows, such as Razzaghmanesh, *et al.* [101], with Australian drinking water guidelines and the South Australian Environment Protection Authority's policy on water quality.

Findings from 17 identified studies demonstrate the difference in GR performance associated with runoff quality. GRs performed inconsistently with different types of pollutants and GR systems. Gong, Yin, Li, Zhang, Wang, Fang, Shi and Wang [40] found that GRs reduced the loads of pollutants such as total phosphorus (TP) and total nitrogen (TN), but increased the load of chemical oxygen demand (COD). In contrast, different GR modules in Ferrans, Rey, Pérez, Rodríguez and Díaz-Granados [57] were effective for neutralizing the pH of rainwater, but were unsuccessful in absorbing most of the runoff pollutants, including TP, TN, and several metals. The majority of GR systems identified in this review were reportedly capable of increasing pH values of roof runoff to around 8, a neutral value. Rainwater tends to be acidic, with average pH values of less than 5.6, and hence the neutralization of rainwater by GRs is an environmental benefit that prevents acidic runoff from flowing to receiving water bodies [102,103]. Harper, Limmer, Showalter and Burken [68] detected significant nutrient loads in GR discharge with a decreasing trend of concentration during the monitoring period. Zhang, Miao, Wang, Liu, Zhu, Zhou, Sun and Liu [49] found that GRs washed out ammonium nitrogen, total suspended solids (TSS), and fluoride anions, but was a source of the remaining pollutants. Additionally, the GR in the study by Vijayaraghavan and Raja [100] acted as a sink for all examined heavy metal ions during both un-spiked and spiked artificial rainfall events, whereas the GR was a source of all pollutants in the study by Beecham and Razzaghmanesh [25].

Among abovementioned variables, the composition of GR growing media and the use of fertilizers were found linked the most to the quality of GR runoff. For example, Beecham and Razzaghmanesh [25] pointed out that the outflows from GRs with higher organic matter had higher pollutant concentrations. The lower concentrations of TP and TN in the study of Gregoire and Clausen [43], as compared to other studies, were explained by the slow-release fertilizer, expanded shale, and biosolids media with a high sorption rate of pollutants. Zhang, Miao, Wang, Liu, Zhu, Zhou, Sun and Liu [49] stated that a high concentration of TN in GR discharge could result from the substrate used, which had a nitrogen-rich content. Harper, Limmer, Showalter and Burken [68] observed a greatly noticeable nutrient load in GR runoff due to the excessive nutrients contained in the substrate construction materials. All studied EGR modules of Gong, Yin, Li, Zhang, Wang, Fang, Shi and Wang [40] acted as a sink of TP and TN, but a source of COD. The significant release of COD had a strong connection to the substrate layer, as it contained plenty of turfy soil which had high contents of organic matter. Moreover, the pollutant loads of TP and TN in GR outflows were negligible because of no addition of nitrogen and phosphorus fertilizers.

Aside from the substrate materials and fertilizing practices, researchers also studied other factors potentially correlating to GR runoff quality. For example, Razzaghmanesh, Beecham and Kazemi [101] found that EGRs outperformed IGRs in terms of runoff quality because the thinner substrate of the EGRs restricted its capacity to leach pollutants from the soil media. The concentration of pollutants was the highest at the beginning of the GR operation and consecutively decreased until the end of study period, which is consistent with the finding of Harper, Limmer, Showalter and Burken [68]. Beecham and Razzaghmanesh

[25] compared various types of roofs, including non-vegetated and vegetated beds of EGRs and IGRs. They concluded that non-vegetated EGRs and vegetated IGRs were more effective than non-vegetated IGRs and vegetated EGRs, respectively. While the former was due to the shallower substrate, the latter was from the plant uptake. The authors also highlighted the important role of vegetation in pollutant removal efficiency. In addition, temperature was similarly reported in Buffam, *et al.* [104] and Carpenter, Todorov, Driscoll and Montesdeoca [48] to be linked with the concentration of nutrients in the GR discharge. The quality of stormwater passing through GRs varied seasonally, with the highest concentration during the growing season and the greatest retention during the non-growing season. The mechanism behind this seasonal variation was that the higher temperature in the growing season was promoting the mineralization process in the soil media of the GRs.

3.5. Ecological, Social, and Economic Benefits

One of the biggest challenges confronting the application of GRs is the high installation costs and other costs arising from its operation. Although it is commonly understood that a GR system requires a considerable investment, it provides promising monetary savings after a short payback period as compared to conventional roofs [105]. The financial factor plays an important role in the successful acceptance of GRs since it facilitates approvals from policy makers, investors, and property owners. Therefore, the interest of researchers has also been directed towards economic benefits from the implementation of GRs. For instance, Ávila-Hernández, Simá, Xamán, Hernández-Pérez, Téllez-Velázquez and Chagolla-Aranda [19] made an economic evaluation by considering the electricity and irrigation costs. Their GR in the city of Hermosillo, Sonora could provide a return on investment after only 8.8 years. Cai, Feng, Yu, Xiang and Chen [85] studied the economic benefit of GRs by converting the GR ecosystem services into monetary values. More specifically, they took into account the carbon sequestration, oxygen release, air pollution mitigation, rainwater management, and energy savings. The computed net present value (NPV) showed that a GR could become profitable from the 10th year after its installation. With nearly identical variables, Cascone, Catania, Gagliano and Sciuto [21] performed an economic assessment based on an actual circumstance with a tax deduction of 65%, provided by Italian laws, for GR installation costs. The results show that the payback period varied according to drainage materials and vegetation types. They were 13.4 years for sedum with perlite and 17.9 years for salvia on rubber crumb. On the contrary, some works reported opposite results. In the study of Ascione, Bianco, de'Rossi, Turni and Vanoli [16], cool roofs were preferable with respect to economic benefits. By analyzing the watering and energy costs, GRs required more than 100 years to cover the investment cost. GR costs were even impossible to be paid in some locations. Another study of Berto, *et al.* [106] supported the economic effectiveness of cool roofs over GRs from the private investors' point of view. The contradictory conclusions from the cost assessments are attributed to two facts. The first is the limitation of efforts made to analyze the GR costs, so the knowledge about this GR benefit is not comprehensively understood [2]. The second constraint is the difficulty in quantifying some of the GR ecosystem services, which makes the life-cycle assessment of GR difficult to be justified [1]. Consequently, further studies involving as many GR advantages as possible in the cost–benefit analysis are required prior to making final conclusions. Regardless of all discussed uncertainties, GRs are still believed to be much more superior to other roof types. Berto, Stival and Rosato [106] suggested that without counting the unquantifiable benefits, it was sensibly deduced that GRs could bring huge profits as compared to cool roofs. Vijayaraghavan [2] maintained that the likelihood of profits from a GR system could overcome all of its weakness and losses.

GR is able to promote the urban ecology by attracting wildlife species and restoring the habitat loss caused by urban development [2,3]. Additionally, GR offers numerous social benefits that are advantageous for human health and liveability. The reduction of heat stress, noise pollution, and air pollution play a crucial role in improving human health and well-being. Furthermore, the green spaces generated by GRs improve urban aesthetics and establish recreational activities in urban areas, thus improving social connectivity [1]. Although the ecological and social benefits of GRs are foreseeable, research on them has been insufficient. This is in conformity with a small number of relevant papers identified in this review. The difficulty in measuring such benefits is an explanation for such limited research. The following attempts are noteworthy in this direction. Kratschmer, Kriechbaum and Pachinger [24] studied the correlation of the diversity and abundance of wild bees with GRs. They found that wild bee species were positively affected by floral resources and finer and deeper substrates. Rumble, *et al.* [107] investigated the presence of microarthropods, bacteria, and fungi in GR materials. They observed their survival and the independent colonization during eleven months after the construction of the GR. The species existing in GRs were found linked to both GR construction components and natural communities. Mycorrhizal fungi, which is beneficial for the uptake of nutrients by the plants, was suggested to be commercially added to GR construction. MacIvor and Lundholm [38] also detected the existence of a broad range of insects from five studied IGRs. This finding could encourage the idea of using GRs to improve urban biodiversity. Whittinghill, *et al.* [108] researched the potential of the social benefits of GRs by calculating the food production by EGR plants. Tomatoes, beans, cucumbers, basil, and chives were chosen, and they survived and produced an adequate yield. This horticultural method, which is well known as a part of urban farming, is a promising strategy to address critical social issues such as food security and job opportunities.

3.6. Air Quality Improvement

GRs bring benefits to the air quality in two distinct ways. The first way is the indirect reduction of CO_2 emission from energy savings, which has been already discussed in an earlier section. The second way is through the stomata of GR vegetation to remove this greenhouse gas from the atmosphere [109]. In addition to CO_2, GRs are capable of capturing several air pollutants, consisting of O_3, NO_2, PM_{10}, and SO_2. However, CO_2 has attracted the most attention of researchers. This review found only three papers studying this benefit provided by GRs. This small number is not likely to represent all works completed; however, it could partially reflect the limitation of efforts and interest in this research area. For instance, the large-scale application of GRs in Thessaloniki led to a CO_2 sequestration rate of 3951.52 tons per year, and a total annual CO_2 saving of 12,441 tons [63]. The ability of sequestrating CO_2 depends on the selection of GR plants, and it was determined that spices and aromatic plants outperformed grasses. However, this reduction was not considerable as compared to a year-round CO_2 saving of 65,000 tons by reducing the air-conditioning demand. GRs contribute to diminishing the CO_2 emission by consuming the air pollutants from the atmosphere; nevertheless, this is minimal, relative to the indirect reduction from energy savings [21]. Another study performed by Baraldi, *et al.* [110] examined the GR capability of capturing the air pollutants. They conducted a holistic analysis concerning the physiological features of fifteen GR species comprising shrubs and herbaceous plants. The results reveal that the capacity of mitigating the air pollution varies according to the specific species. Furthermore, all tested species were also found favorable for urban sustainable development as they are not likely to form ozone. Li, *et al.* [111] adopted a mixed methodology to research the effect of GRs on the fluctuation of CO_2 concentration in the ambient atmosphere. According to the field measurement, chamber experiment, and computer simulation, the authors stated that a GR had a large potential to reduce CO_2 emission by up to 2% on a sunny day. They also concluded that the CO_2 absorbing rate greatly depends on the condition of GR plants, sunlight intensity, wind velocity, and GR position.

3.7. Noise Reduction

Another ecosystem service of GR is to establish an acoustic barrier confronting the sound transmission from the outdoor environment to a building. Noise from vehicles and other anthropogenic activities influencing human health and well-being is regarded as noise pollution. GR functions as an additional sound insulation layer as well as an absorber of sound waves passing through the building envelopes. In this review, only two papers were found to investigate this GR benefit. Connelly and Hodgson [112] conducted both a field experiment and a purpose-built field laboratory to investigate the loss of sound transmission through vegetated and non-vegetated roofs. As expected, the difference in sound transmission between the conventional roof and the GR was up to 10, 20, and more than 20 decibels (dB) in the low-, mid-, and high-frequency ranges, respectively. It was also noted that the thicker substrates and the deeper-root plants enhanced the noise reduction, whereas the substrate moisture content caused no major changes. Following Yang, *et al.* [113], they computed the noise reduction at street level by installing a GR on a low-profiled structure. The results show that a GR could successfully attenuate the sound annoyance level by up to 9.5 db. Moreover, the substrate type and depth were found to be not as important as the whole GR system in terms of traffic noise mitigation. Similar to the air quality improvement, this review identified a very small number of papers associated with the noise reduction. Therefore, it could be reasonably deduced that this research area needs more attention.

4. Discussion

4.1. GR Types

As can be seen in Figure 3, the number of papers applying EGRs are 6–7 times more than those applying IGRs and SIGRs. It is well known that EGRs have plenty of advantages that have led to their widespread implementation. On the contrary, the implementation of IGRs faces many challenges, as they require high structural load bearing capacities and high amounts of maintenance. However, with the consideration of the capability of providing ecosystem services alone, IGRs remarkably outperform EGRs. It is also worth noting that SIGRs appear to have a combination of advantages taken from both EGRs and IGRs. Their growing media are thinner and lighter than that of IGRs, and they support a broader range of appropriate plants than what EGRs can. Therefore, SIGRs not only eliminate the disadvantages of IGRs and EGRs but also optimize the GR benefits. Further research should study the potential of intensive and semi-intensive types of GRs, so that they are not disregarded. More efforts to explore alternative materials for light-weight GR systems are also encouraged.

Attempts to establish hybrid GR-based experiments were found to be negligible in this review. Such hybrid GRs are highly recommended because of the encouraging results achieved by them. For example, Hui and Chan [99] found that the T_s of a hybrid photovoltaic GR (PV GR) was that of a traditional GR, due to the shading effect of the PV panels. An increase of 4.3% in power output from the PV panels also resulted from this combined system. Another example of the enhanced performance of hybrid GRs is provided by Chemisana and Lamnatou [93]. They found a maximum ΔT_s of 14 °C as well as a maximum increase of 3.33% in solar energy from the PV system. Yeom and La Roche [37] evaluated the combination of a GR and a radiant cooling system by setting up various test cells. They found a 2-°C lower temperature inside the cell with a GR and radiant pipes as compared to GRs with and without an insulation layer. Additionally, the combination of GRs and green walls provide outstanding thermal and energy reductions as compared to stand-alone GR systems [33-35,88]. In an attempt to improve the runoff retention rate, a system integrating GRs with blue roofs was developed and the runoff outflow rates from the green–blue roof and a control roof were 0.1 L/s and 0.3 L/s, respectively, in the study by Shafique, Lee and Kim [28]. It is worth noting that the outflows from the green–blue roof only occurred a few hours after the beginning of a rainfall event, which helps to alleviate the stress on the urban drainage system.

4.2. GR Benefits

As mentioned in previous sections, urban heat mitigation and runoff reductions have been found to be the most-studied GR benefits. On the other hand, the mitigation of air pollution through the direct CO_2 sequestration of GR plants is a GR benefit that has been inadequately investigated. A barrier to undertake research on this GR benefit is the limited options for the vegetation layer. While EGR keeps receiving the most attention during the last ten years due to several advantages, shallow-root plants in EGRs have a smaller capacity to capture gaseous pollutants and dust particles in the atmosphere [1,2]. Large plants, such as trees with deep roots, could absorb greater amounts of air pollutants, but face many challenges in GR construction and operation during its lifespan. Other than that, the insignificant quantity of CO_2 sequestrated by GR plants could be an explanation for their lesser preference among researchers. Last but not least, the simplest way to conduct such projects is by utilizing the factor values already computed in the literature, which could not produce dependable results. Otherwise, the investigation of this benefit (reduction in air pollution) requires a complex experimental set-up and specific knowledge about the phytology of plants.

Noise reduction is also inadequately researched due to various constraints. One of them could be attributed to the fact that a GR system can only lessen the noise transmitted from traffic into the indoor environment if it is installed on a low-rise building [2]. Along with the rapid urbanization and population growth, multi-storey buildings are being constructed. Consequently, the GRs of both existing and new buildings are positioned far away from the ground level. This reduces the possibility of the application of GRs for noise reduction. Another difficulty could be the lack of standards for measuring the sound transmission through roofs [112]. Moreover, methods for testing the transmission loss are mainly developed for other building components, such as interior walls and exterior facades.

Finally, other GR benefits relating to runoff quality, the ecosystem, and social and economic benefits have been researched more often than the mitigation of noise and air pollution. However, they are still in experimental stages due to various constraints. For example, the question of whether GRs improve or degrade the runoff quality should be properly answered before proceeding to implementation. Additionally, the cost–benefit analysis of GRs pointed out remarkable long-term savings, and many experts have confirmed that the GR benefits outweigh their potential costs. Nevertheless, numerous important benefits were not considered in the economic evaluation because most of them are difficult to convert into monetary values. Consequently, this hinders researchers from carrying out such projects. Hence, future studies are suggested to be conducted with a well-designed approach.

4.3. Innovative GR Construction Techniques and Materials

In spite of unsolved issues, the potential of GRs remains remarkably huge. Considering only the GRs' capability of providing ecosystem services, most studies illustrate positive outcomes. In order to facilitate the widespread implementation of GR, it is suggested that future studies should be directed towards identifying optimal GR designs to satisfy not only the ecosystem services provided by GRs but also their affordability for installing, operating, and maintaining. According to the literature review, it was determined that there exist attempts to explore alternative GR materials. Some of them succeeded in enhancing the GR benefits. For example, Carpenter, Todorov, Driscoll and Montesdeoca [48] obtained a noticeable averaged retention rate of 96.8%, which exceeded the previously-reported values mainly due to the application of an effective drainage layer. Another high retention rate from Todorov, Driscoll and Todorova [45] was also a result of a drainage design that was never applied in other studies. Altering the substrate composition by adding biochar improved both the retention capacity and quality of the GR discharge [74]. On the other hand, the application of modelling software to simulate GR performance was observed during the last decade. Though the accuracy of simulation results compared well with actual field data, their application for the large-scale implementation of GRs is still negligible. The costs and benefits of large-scale implementation of GRs need to be clear to authorities and stakeholders, such as building owners, builders, and developers. Therefore, this is a recommendation for future research studies.

4.4. Inconsistent Impact of Parameters on GR Performance

It is not challenging to find studies on the benefits of GRs relating to UHI mitigation and energy reduction. These two benefits of GRs are quite apparent during the period of the strongest solar radiation (SR). Conversely, they are less desirable at night and in cold weather conditions. Moreover, seasonal and daily thermal behaviours of GRs are even more complicated. He, Yu, Ozaki and Dong [18], He, Yu, Ozaki, Dong and Zheng [80], Bevilacqua, Mazzeo, Bruno and Arcuri [82], and Foustalieraki, Assimakopoulos, Santamouris and Pangalou [89] found a higher T_s of GRs than that of traditional roofs at nighttime in both hot and cold seasons. Additionally, although the maximal T_s reduction in winter is not as impressive as that in summer, ΔT_s still remains positive during winter daytime. Those research outcomes are contrary to others' findings. More precisely, the T_s of a non-vegetated roof was higher than that of a GR at night-time, following Morakinyo, Dahanayake, Ng and Chow [26] and Cascone, Catania, Gagliano and Sciuto [21]. A warmer roof deck underneath the GR was observed in winter at daytime, following Boafo, Kim and Kim [81] and Cai, Feng, Yu, Xiang and Chen [85]. A combined effect of great heat storage and thermal inertia of GR components is likely to explain a warmer skin temperature of outer roof decks at night [18]. Oppositely, Cascone, Catania, Gagliano and Sciuto [21] stated that the evapotranspiration process allows GRs to release the heat accumulated during a hot summer day, which helps to maintain a lower T_s of a GR at night. The negative ΔT_s at night during summer could lead to a higher cooling demand, though this is preferable to save the electricity for heating during cold seasons. On the other hand, attempts to study this topic have not yet been made. Consequently, solutions from future research are needed to avoid any unexpected impacts of GRs.

Among many attempts to study the HTC improvement, the vast majority of them analyzed the indoor dry-bulb temperature (DBT), which is also known as air temperature. On the other hand, the wet-bulb globe temperature (WBGT), which is a combined effect of air temperature and relative humidity, has received less attention. Human discomfort is primarily affected by WBGT and, hence, this variable should be involved in future works (rather than simply analyzing DBT). Moreover, the studies about whether the $T_{air.in}$ improved due to the construction of GRs has been limited. Though energy savings after GR installation has been generally agreed upon, it is worthwhile to investigate the possibility of a GR-based passive-cooling system.

Another noteworthy finding is the differences in the experimental setups of measuring devices from one study to the other. It is understandable that the position of measuring devices strongly depends on the specific research aims. However, this review suggests that future research needs to apply consistent measurements for accuracy of result comparisons and performance evaluations between different studies. For example, this review detected a difference in the height of sensors for measuring the air temperature above the plant canopy. Additionally, previous studies published ΔT_s values with various positions of thermal sensors. The explanations for those chosen sensor positions are also missing. In order to properly understand the effects of GRs, an adequate number of studies with identical and appropriate experimental designs are required.

Palermo, Turco, Principato and Piro [22] and Gregoire and Clausen [43] stated that the inconsistency in published runoff reduction was due to differences in the catchment size, the length of the study period, the data-analysis approach, and the hydraulic characteristics of the GR materials. Nevertheless, no consensus about how those variables influence the GR capability of reducing runoff have been reached yet. For example, Zhang, Miao, Wang, Liu, Zhu, Zhou, Sun and Liu [49] and Razzaghmanesh and Beecham [69] highlighted the importance of an antecedent dry weather period (ADWP) in the retention capability of GRs. In contrast, Zhang, Szota, Fletcher, Williams and Farrell [47], Ferrans, Rey, Pérez, Rodríguez and Díaz-Granados [57], and Hakimdavar, Culligan, Finazzi, Barontini and Ranzi [51] concluded that the substrate storage capacity and initial substrate moisture content were more related to the retention performance, whereas the impact of ADWP was negligible. They also found that the selection of high water-use plants, followed by the high evapotranspiration (ET) rate, was not as important as the substrate type. In contrast, Johannessen, Muthanna and Braskerud [59] raised another debate, as they reported opposite results as the ET process made greater variations in GR performance than different GR configurations did. Kaiser, *et al.* [114] highlighted the importance of ET by applying some solutions to increase the rate of ET. Such disputes could be resolved with extensive knowledge acquired from future works. Furthermore, Sims, Robinson, Smart and O'Carroll [55] maintained that the high retention rates in some studies resulted from the inclusion of rainfall events generating no runoff (100% retention) in the data analysis. This review recommends that all future research should apply a precipitation threshold to exclude small events with no discharge from GRs so that a proper conclusion about the runoff retention capacity of a GR system could be reached.

5. Conclusions

Among numerous WSUD strategies, GRs are a popularly used practice implemented to deal with the adverse impacts of climate change and to tackle various issues arising from rapid urbanization and increases in population. This paper reviewed a broad range of GR literature investigating all ecosystem services that a GR system can provide. They are HTC improvement, energy saving, runoff reduction, runoff quality enhancement, noise reduction, air quality improvement, and ecological, social, and economic benefits. This review aimed to provide readers with in-depth knowledge of GR performance during the last 10 years through the quantification of the provided benefits.

The key observations, conclusions, and recommendations that are provided on the basis of this study are as follows:

(a) Countries such as the USA and various European countries have implemented GRs quite popularly. This review also indicates that China is also taking up GRs in a big way. GRs have not been popular in developing countries due to a lack of local research about the methods for constructing GRs and their benefits. The high initial cost of construction is also a constraint in developing countries;
(b) An imbalance of GR research focuses was identified, wherein Human Thermal Comfort and runoff-related benefits were well researched when compared to other benefits. At the same time, further studies need to be undertaken on inadequately studied GR benefits, such as reduced noise and air pollution;
(c) It was found that EGR has been more commonly implemented because of numerous advantages over other types of GR. However, if only the capability of providing ecosystem services is considered, IGRs very clearly outperform EGRs. On the other hand, the intermediate type of GR, namely SIGRs, appear to have a combination of advantages taken from both EGRs and IGRs;
(d) The effectiveness of hybrid GRs was clearly observed as compared to traditional GRs. The main hybrid GRs identified in this review include photovoltaic GRs, green–blue roofs, GRs integrated with radiant cooling systems, and GRs combined with green walls. However, further studies to quantify the benefits of hybrid GRs are recommended;
(e) It is recommended that future studies are undertaken to improve upon well-known GR benefits by discovering more innovative GR construction techniques and materials. Further studies are also recommended to explore GR components that are economical as well as environmentally friendly;
(f) The impact of key influential GR parameters (e.g., substrate type and their water-holding capacity, the type of plants, and evapotranspiration rate, etc.) on its performance was continually highlighted in this review. Many studies reported contradictory outcomes on varying some of these parameters, and hence, further studies are recommended;
(g) In spite of the existence of reliable modelling tools, their application to study the large-scale implementation of GRs (at a city-wide scale, catchment scale or municipality scale) has been restricted. As a result, more research and studies are necessary to transform the GR concept into one of the widespread and popularly used WSUD strategies;

(h) Recommendations to address GR limitations and obstacles in taking up GRs have been identified in this literature review.

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Appendix A

Table A1. An overview of green roof papers reviewed in this study.

No.	Reference	Country	Type of GR	GR Benefit	Type of Modelling
1	Barnhart, Pettus, Halama, McKane, Mayer, Djang, Brookes and Moskal [52]	USA	EGR [1] IGR [2]	Runoff Reduction	Model simulation
2	Liu, *et al.* [115]	China	SIGR [3]	Runoff Quality Improvement	Field experiment
3	Feitosa and Wilkinson [35]	Australia	GR and Green Wall	HTC [4] Improvement	Field experiment
4	He, Yu, Ozaki and Dong [18]	China	EGR	HTC Improvement Energy Use Reduction	Field experiment and model simulation
5	La Roche, Yeom and Ponce [36]	USA	GR and Radiant Cooling System	HTC Improvement	Field experiment and model simulation
6	Ávila-Hernández, Simá, Xamán, Hernández-Pérez, Téllez-Velázquez and Chagolla-Aranda [19]	Mexico	EGR	Ecological, Social, and Economic HTC Improvement Energy Use Reduction	Field experiment and model simulation
7	Liu, Sun, Niu and Riley [20]	China	EGR	Runoff Reduction	Model simulation
8	Silva, K Najjar, WA Hammad, Haddad and Vazquez [53]	Brazil	EGR	Runoff Reduction	Field experiment
9	Baek, Ligaray, Pachepsky, Chun, Yoon, Park and Cho [27]	South Korea	SIGR	Runoff Reduction	Field experiment and model simulation
10	Talebi, Bagg, Sleep and O'Carroll [56]	Canada	EGR SIGR	Runoff Reduction	Model simulation
11	Gong, Yin, Li, Zhang, Wang, Fang, Shi and Wang [40]	China	EGR	Runoff Quality Improvement Runoff Reduction	Field experiment
12		China	EGR	HTC Improvement	

	Cai, Feng, Yu, Xiang and Chen [85]			Energy Use Reduction Ecological, Social, and Economic	Field experiment and model simulation
13	Jahanfar, Drake, Sleep and Margolis [54]	Canada	GR and PV [5]	Runoff Reduction	Field experiment
14	Palermo, Turco, Principato and Piro [22]	Italy	EGR	Runoff Reduction	Field experiment and model simulation
15	Sims, Robinson, Smart and O'Carroll [55]	Canada	EGR	Runoff Reduction	Field experiment and model simulation
16	Xing, Hao, Lin, Tan and Yang [33]	China	GR and Green Wall	HTC Improvement Energy Use Reduction	Field experiment
17	Cao, Hu, Dong, Liu and Wang [83]	China	EGR	HTC Improvement	Field experiment
18	Baraldi, Neri, Costa, Facini, Rapparini and Carriero [110]	Italy	IGR	Air Quality Improvement	N/A
19	Tang and Zheng [84]	China	EGR	HTC Improvement Energy Use Reduction	Field experiment
20	Zhang, Szota, Fletcher, Williams and Farrell [47]	Australia	EGR	Runoff Reduction	Indoor experiment
21	Cascone, Catania, Gagliano and Sciuto [21]	Italy	EGR	HTC Improvement Energy Use Reduction Ecological, Social, and Economic	Model simulation
22	Feitosa and Wilkinson [34]	Brazil Australia	GR and Green Wall	HTC Improvement	Field experiment
23	Johannessen, Muthanna and Braskerud [59]	Norway	EGR	Runoff Reduction	Field experiment
24	Park, Kim, Dvorak and Lee [86]	South Korea	EGR	HTC Improvement	Field experiment and model simulation
25	Shafique, Kim and Kyung-Ho [58]	South Korea	EGR	Runoff Reduction	Field experiment
26	Berto, Stival and Rosato [106]	Italy	EGR	Ecological, Social, and Economic	Model simulation
27	Lee and Jim [23]	Hong Kong	IGR	HTC Improvement	Field experiment
28	Zhang, Szota, Fletcher, Williams, Werdin and Farrell [41]	Australia	EGR	Runoff Reduction	Indoor experiment
29	Azeñas, Cuxart, Picos, Medrano, Simó, López-Grifol and Gulías [87]	Spain	EGR	HTC Improvement Energy Use Reduction	Field experiment
30	Kratschmer, Kriechbaum and Pachinger [24]	Austria	EGR SIGR IGR	Ecological, Social, and Economic	Field experiment
31	Rumble, Finch and Gange [107]	UK	EGR	Ecological, Social, and Economic	Field experiment
32	Todorov, Driscoll and Todorova [45]	USA	EGR	Runoff Reduction	Field experiment
33	Ferrans, Rey, Pérez, Rodríguez and Díaz-Granados [57]	Colombia	EGR	Runoff Reduction Runoff Quality Improvement	Field experiment
34	Morakinyo, Dahanayake, Ng and Chow [26]	Hong Kong Japan Egypt France	IGR	HTC Improvement Energy Use Reduction	Model simulation

35	He, Yu, Ozaki, Dong and Zheng [80]	China	EGR	HTC Improvement Energy Use Reduction	Field experiment and model simulation
36	Yeom and La Roche [37]	USA	GR and Radiant Cooling System	HTC Improvement	Field experiment
37	Shafique and Kim [30]	South Korea	GR and Blue Roof	HTC Improvement	Field experiment
38	Wilkinson, Feitosa, Kaga and De Franceschi [88]	Australia Brazil	GR and Green Wall	HTC Improvement	Field experiment
39	Johannessen, Hanslin and Muthanna [61]	Norway Iceland Sweden UK	EGR	Runoff Reduction	Model simulation
40	Bevilacqua, Mazzeo, Bruno and Arcuri [82]	Italy	EGR	HTC Improvement	Field experiment
41	Foustalieraki, Assimakopoulos, Santamouris and Pangalou [89]	Greece	EGR	HTC Improvement Energy Use Reduction	Field experiment and model simulation
42	Soulis, Valiantzas, Ntoulas, Kargas and Nektarios [60]	Greece	EGR	Runoff Reduction	Field experiment and model simulation
43	Boafo, Kim and Kim [81]	South Korea	EGR	HTC Improvement Energy Use Reduction	Model simulation
44	Cipolla, Maglionico and Stojkov [64]	Italy	EGR	Runoff Reduction	Field experiment and model simulation
45	Buffam, Mitchell and Durtsche [104]	USA	EGR	Runoff Quality Improvement	Field experiment
46	Karteris, Theodoridou, Mallinis, Tsiros and Karteris [63]	Greece	SIGR EGR	Air Quality Improvement Energy Use Reduction Runoff Reduction	Model simulation
47	El Bachawati, *et al.* [116]	Lebanon	EGR IGR	Ecological, Social, and Economic	Model simulation
48	Gagliano, Detommaso, Nocera and Berardi [90]	Italy	EGR	HTC Improvement Energy Use Reduction	Model simulation
49	Shafique, Kim and Lee [29]	South Korea	GR and Blue Roof	Runoff Reduction HTC Improvement	Field experiment
50	Shafique, Lee and Kim [28]	South Korea	GR and Blue Roof	Runoff Reduction	Field experiment
51	Carpenter, Todorov, Driscoll and Montesdeoca [48]	USA	EGR	Runoff Reduction Runoff Quality Improvement	Field experiment
52	He, Yu, Dong and Ye [78]	China	EGR	HTC Improvement Energy Use Reduction	Field experiment
53	Tam, Wang and Le [91]	Hong Kong	EGR IGR	HTC Improvement Ecological, Social, and Economic	Field experiment
54	Brunetti, Šimůnek and Piro [62]	Italy	EGR	Runoff Reduction	Field experiment and model simulation
55	Nawaz, McDonald and Postoyko [50]	UK	EGR	Runoff Reduction	Field experiment and model simulation
56	Harper, Limmer, Showalter and Burken [68]	USA	EGR	Runoff Reduction Runoff Quality Improvement	Field experiment and model simulation

57	Yang, Li, Sun and Ni [67]	China	EGR	Runoff Reduction	Field experiment and model simulation
58	Versini, Ramier, Berthier and De Gouvello [66]	France	EGR	Runoff Reduction	Field experiment and model simulation
59	Zhang, Miao, Wang, Liu, Zhu, Zhou, Sun and Liu [49]	China	EGR	Runoff Reduction Runoff Quality Improvement	Field experiment
60	Lee, Lee and Han [65]	South Korea	EGR SIGR	Runoff Reduction	Field experiment Indoor experiment
61	Vijayaraghavan and Raja [100]	India	EGR	Runoff Quality Improvement	Field experiment
62	Beecham and Razzaghmanesh [25]	Australia	EGR IGR	Runoff reduction Runoff Quality Improvement	Field experiment
63	Hakimdavar, Culligan, Finazzi, Barontini and Ranzi [51]	USA	EGR	Runoff Reduction	Field experiment and model simulation
64	Razzaghmanesh and Beecham [69]	Australia	EGR IGR	Runoff Reduction	Field experiment
65	Razzaghmanesh, Beecham and Kazemi [101]	Australia	EGR IGR	Runoff Quality Improvement	Field experiment
66	Vijayaraghavan and Joshi [117]	India	EGR	Runoff Quality Improvement	Field experiment
67	Schweitzer and Erell [92]	Israel	EGR	HTC Improvement Energy Use Reduction	Field experiment
68	Vijayaraghavan and Raja [118]	India	EGR	Runoff Quality Improvement	Field experiment
69	Wong and Jim [44]	Hong Kong	EGR	Runoff Reduction	Field experiment
70	Chemisana and Lamnatou [93]	Spain	GR and PV	HTC Improvement	Field experiment
71	Carson, Marasco, Culligan and McGillis [10]	USA	EGR	Runoff Reduction	Field experiment and model simulation
72	Speak, Rothwell, Lindley and Smith [46]	UK	SIGR	Runoff Reduction	Field experiment
73	Sun, Bou-Zeid, Wang, Zerba and Ni [79]	China USA	EGR	HTC Improvement Energy Use Reduction	Field experiment and model simulation
74	Connelly and Hodgson [112]	Canada	EGR	Noise Reduction	Field experiment Indoor experiment
75	Peng and Jim [3]	Hong Kong	EGR IGR	HTC Improvement	Field experiment and model simulation
76	Whittinghill, Rowe and Cregg [108]	USA	EGR	Ecological, Social, and Economic	Field experiment
77	Ascione, Bianco, de'Rossi, Turni and Vanoli [16]	Spain UK The Netherlands Italy Norway	SIGR EGR	Ecological, Social, and Economic HTC Improvement Energy Use Reduction	Model simulation
78	Pandey, Hindoliya and Mod [94]	India	EGR SIGR IGR	HTC Improvement Energy Use Reduction	Field experiment
79		UK	SIGR	HTC Improvement	Field experiment

	Blanusa, Monteiro, Fantozzi, Vysini, Li and Cameron [95]				Indoor experiment
80	Mickovski, Buss, McKenzie and Sökmener [70]	UK	EGR	Runoff Reduction	Indoor experiment
81	Qin, Wu, Chiew and Li [72]	Singapore	SIGR	HTC Improvement Runoff Reduction	Field experiment
82	Stovin, Vesuviano and Kasmin [42]	UK	EGR	Runoff Reduction	Field experiment and model simulation
83	Nagase and Dunnett [71]	UK	EGR	Runoff Reduction	Indoor experiment
84	Bianchini and Hewage [119]	Canada	EGR IGR	Ecological, Social, and Economic	Model simulation
85	Jim and Peng [96]	Hong Kong	EGR	HTC Improvement Energy Use Reduction	Field experiment
86	Vijayaraghavan, Joshi and Balasubramanian [102]	Singapore	EGR	Runoff Quality Improvement	Field experiment
87	Pérez, Coma, Solé, Castell and Cabeza [97]	Spain	EGR	HTC Improvement Energy Use Reduction	Field experiment
88	Yang, Kang and Choi [113]	UK	EGR	Noise Reduction	Indoor experiment
89	Gregoire and Clausen [43]	USA	EGR	Runoff Reduction Runoff Quality Improvement	Field experiment and model simulation
90	MacIvor and Lundholm [38]	Canada	IGR	Ecological, Social, and Economic	Field experiment
91	Tsang and Jim [120]	Hong Kong	EGR	Ecological, Social, and Economic	Model simulation
92	Alsup, *et al.* [121]	USA	EGR	Runoff quality Improvement	Field experiment
93	Beck, Johnson and Spolek [74]	USA	EGR	Runoff Quality Improvement Runoff Reduction	Indoor experiment
94	Buccola and Spolek [73]	USA	EGR	Runoff Quality Improvement Runoff Reduction	Indoor experiment
95	Getter, Rowe, Andresen and Wichman [98]	USA	EGR	HTC Improvement Energy Use Reduction	Field experiment
96	Hui and Chan [99]	Hong Kong	GR and PV	HTC Improvement Energy Use Reduction	Field experiment and model simulation
97	Palla, Gnecco and Lanza [77]	Italy	SIGR EGR	Runoff Reduction	Field experiment Indoor experiment
98	Voyde, Fassman and Simcock [76]	New Zealand	EGR	Runoff Reduction	Field experiment
99	Roehr and Kong [75]	Canada China	EGR	Runoff Reduction	Model simulation
100	Li, Wai, Li, Zhan, Ho, Li and Lam [111]	Hong Kong	IGR	Air Quality Improvement	Indoor experiment, Field experiment, and model simulation
101	Alsup, Ebbs and Retzlaff [103]	USA	EGR	Runoff Quality Improvement	Indoor experiment
102	Niu, *et al.* [122]	USA	EGR	Ecological, Social, and Economic	Model simulation

[1] Extensive Green Roof, [2] Intensive Green Roof, [3] Semi-intensive Green Roof, [4] Human Thermal Comfort, [5] Photovoltaic.

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2.2. Biochar amendment in green roof substrate: A comprehensive review on benefits, performance, and challenges

2.2.1. Introduction

The second component of this chapter delves into the application of biochar in green roofs. Biochar, a carbon-rich material produced through the pyrolysis of biomass in an oxygen-deficient environment, offers several environmental benefits. The biochar production process contributes to carbon dioxide reduction by sequestering carbon that would otherwise be released through natural decomposition or conventional biomass conversion. Notably, biochar is a stable carbon form with minimal atmospheric escape. The incorporation of biochar into agricultural soils and geotechnical structures, such as green roofs, yields significant advantages. Due to its favorable physicochemical properties, biochar enhances water retention, soil fertility, microbial activity, and carbon sequestration. Consequently, biochar holds significant potential for augmenting green roof performance. The first review paper identified this as a critical research gap, underscoring its importance within the study's objectives.

To inform the research presented in Chapters 4 and 5, a comprehensive literature review of biochar in green roof systems was conducted. Notably, a similar review was absent at the time of this research, and the application of biochar to green roofs remained relatively unexplored. Approximately 75 papers were systematically reviewed to assess performance, identify research trends, and delineate knowledge gaps and challenges associated with biochar-green roof systems. A key finding from this review highlighted the limited research investigating the impact of various biochar parameters, such as amendment rates, application methods, and particle sizes, on green roof performance. To address these knowledge gaps, Chapters 4 and 5 were designed. Chapter 4 focuses on the influence of biochar on green roof runoff retention and quality, while Chapter 5 explores its impact on vegetation performance. The knowledge acquired through this review informed the research methodologies and experimental designs employed in subsequent chapters, establishing a foundation for future research on biochar-enhanced green roofs. Expanding the knowledge base on biochar-amended green roofs is essential to facilitate widespread adoption of this sustainable technology.

This chapter contains the following journal paper, which is the second of the two review papers included in this chapter:

- 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/app1416742.

2.2.2. Declaration of co-authorship and co-contribution: papers incorporated in thesis by publication

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DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

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Surname: Nguyen First name: Cuong

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2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

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[redacted]	22/08/2024

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

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3. There are no other authors of the publication according to these criteria;

4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

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Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Cuong Ngoc Nguyen	80	Conceptual ideas, research, data analysis, experiments, writing.	[redacted]	22/08/2024
Hing-Wah Chau	5	Feedback and discussion on research and writing	[redacted]	21/08/2024
Nitin Muttil	15	Critical comments and discussion on conceptual ideas & research methodologies	[redacted]	22/08/2024

Updated: September 2019

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2.2.3. Biochar amendment in green roof substrate: A comprehensive review on benefits, performance, and challenges

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,*]

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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

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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

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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.

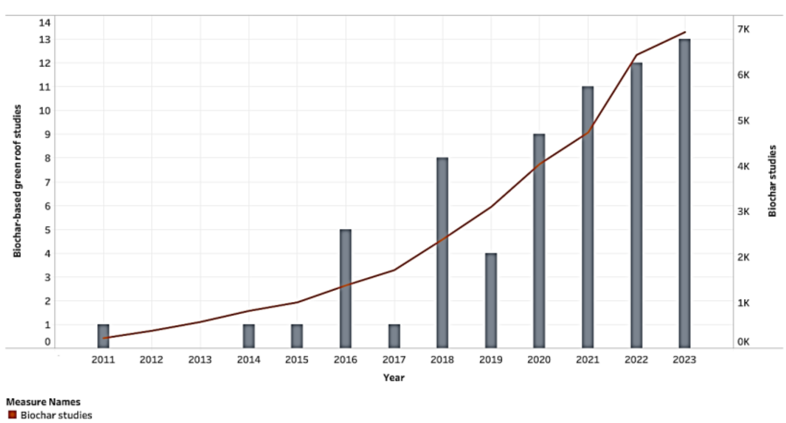

Figure 1. The number of studies on biochar-amended green roofs and biochar recorded in the Scopus database by year of publication from 2011 to 2023.

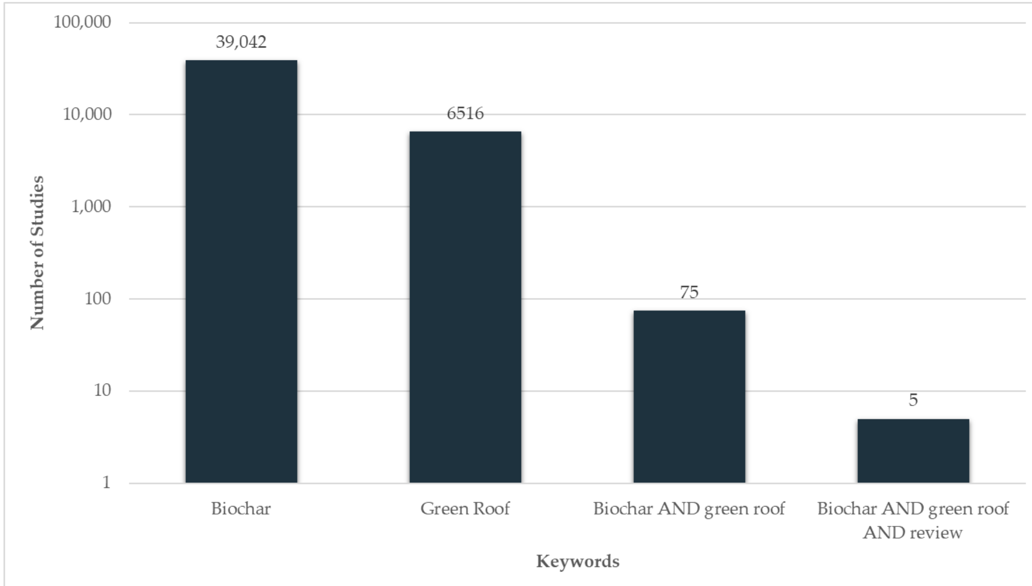

Figure 2. The number of studies on green roofs and biochar using different search keywords in the Scopus database.

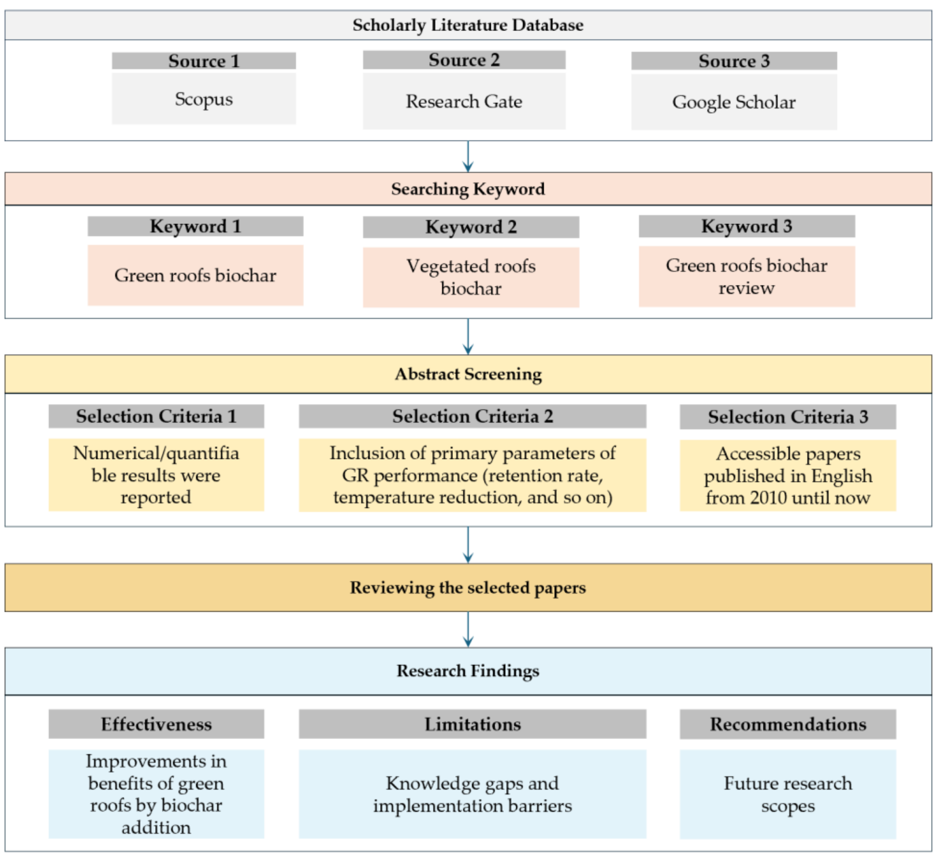

Figure 3. A flow chart depicting the reviewing methodology used in this research.

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 [54,54]. 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 explains the mechanism of biochar in altering structures of GR substrates and improving 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.

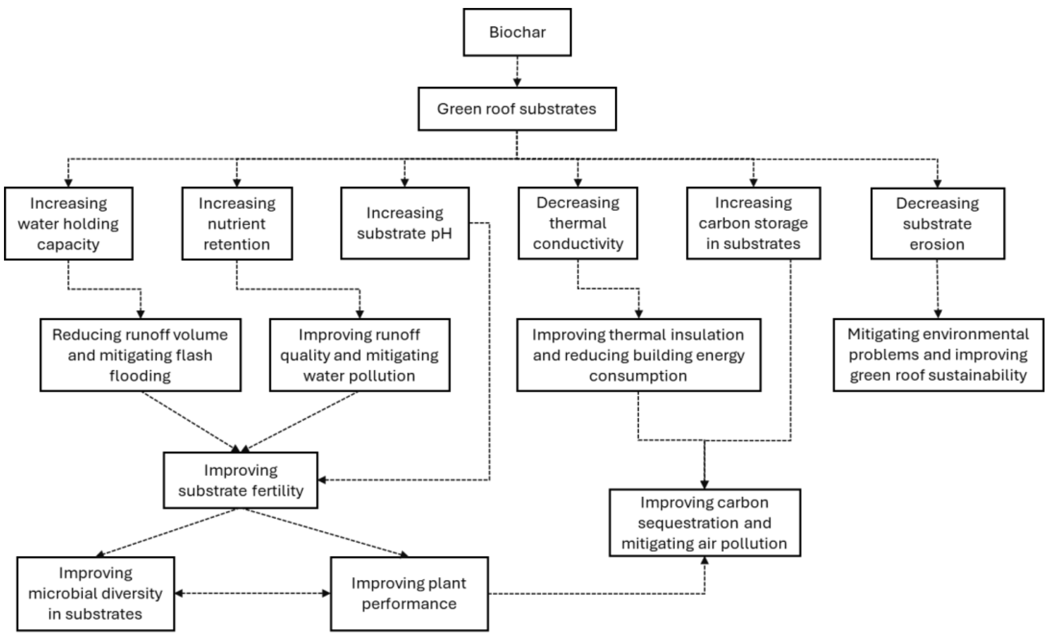

Figure 4. A flow chart illustrating the benefits of biochar in green roofs.

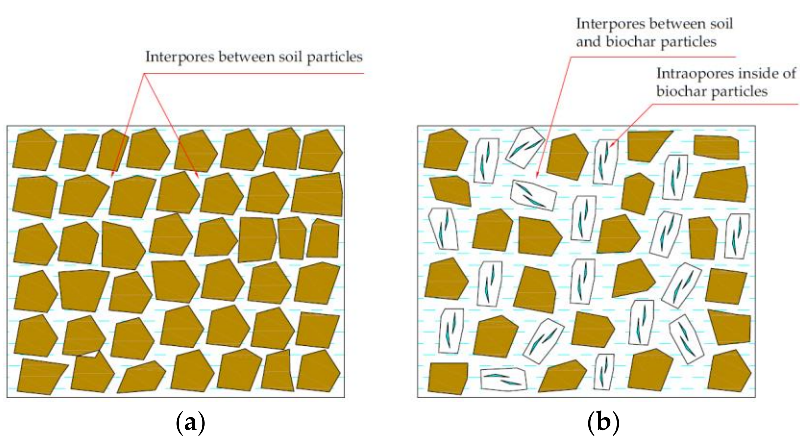

Figure 5. Mechanisms by which biochar increases soil porosity and improves water-holding capacity: (**a**) low-porosity soil structure without biochar, (**b**) high-porosity soil structure due to inter-pores between soil and biochar and intra-pores within biochar particles [56].

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.

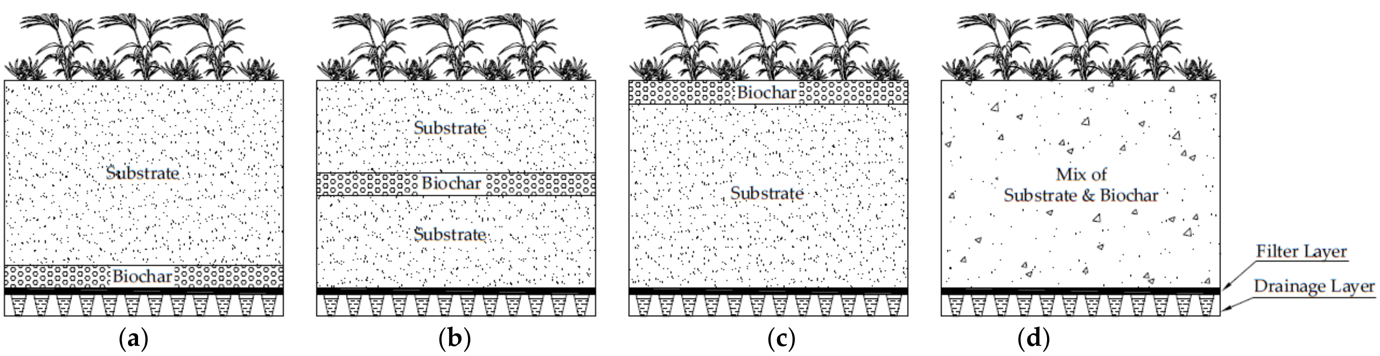

Figure 6. Commonly used biochar application methods in green roofs: (**a**) biochar at the bottom of the substrate, (**b**) biochar in the middle of the substrate, (**c**) biochar at the top of the substrate, and (**d**) biochar thoroughly mixed with the substrate.

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.

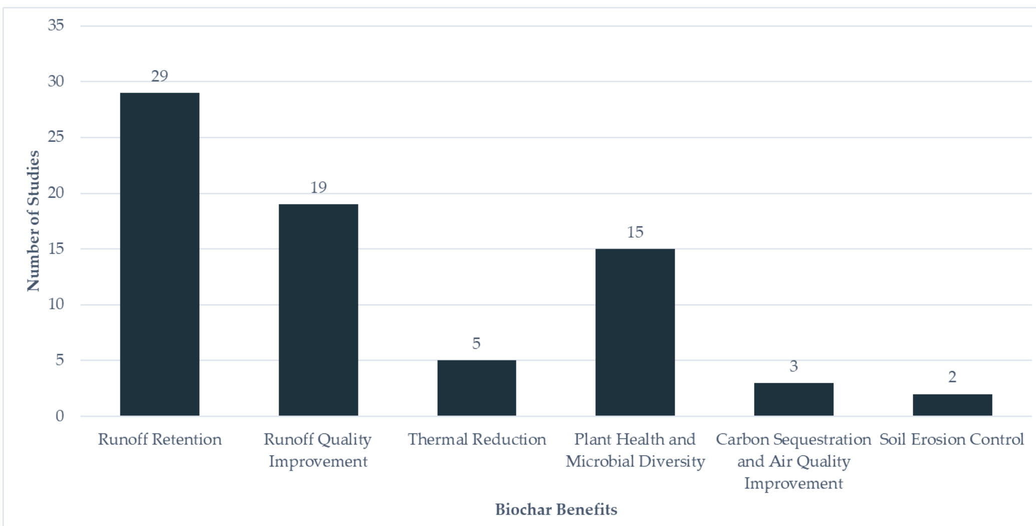

Figure 7. The number of studies examining the benefits of biochar in green roofs.

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)
[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})
[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, recycled brick, 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 ($m^{-2}year^{-1}$)
[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		
[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 the light 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/m²/year, which was higher than 6.47 kg C/m²/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.

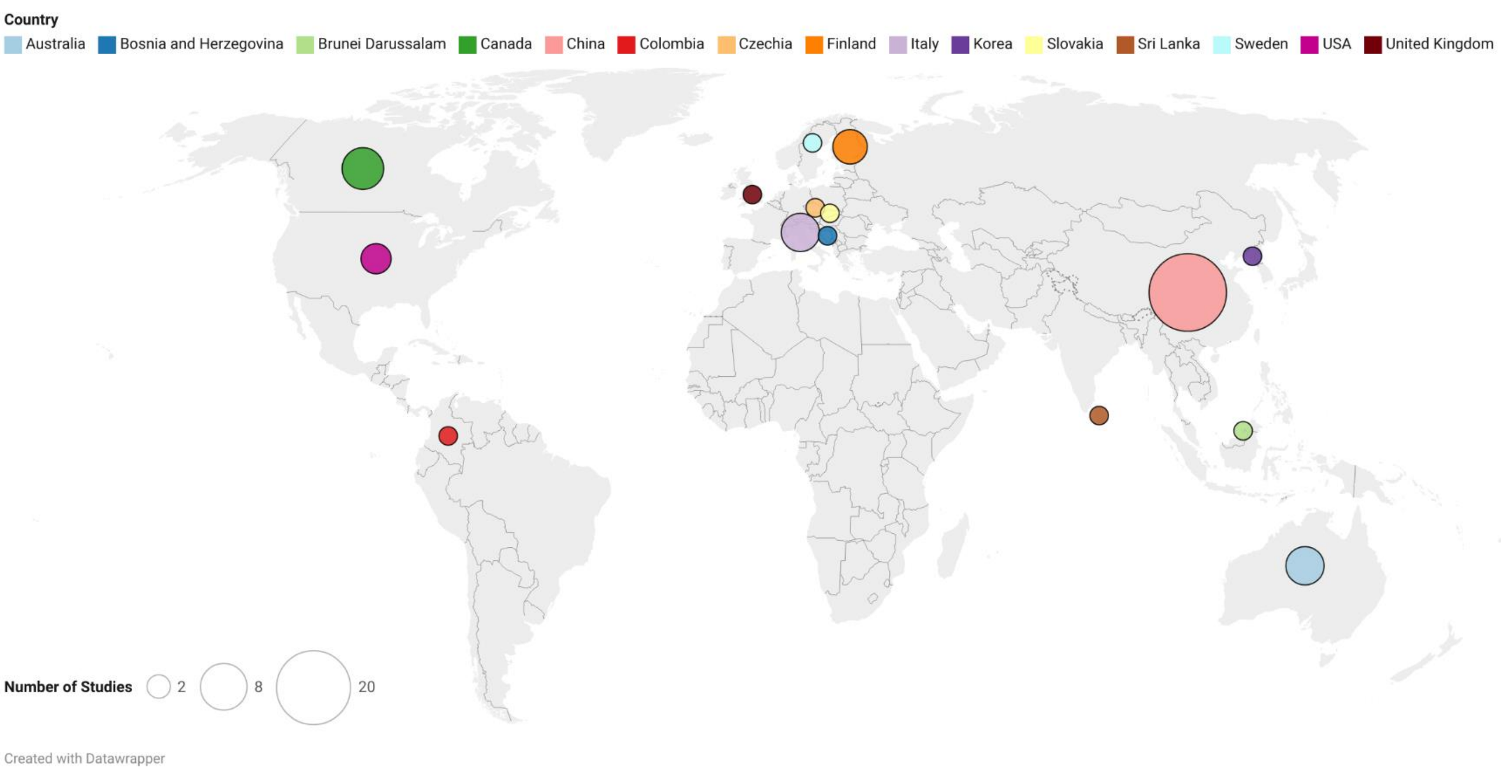

Figure 8. The number of studies on biochar-amended green roofs by country.

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 makes 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 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) The utilization of biochar in GRs faces several barriers. In addition to inconsistent and limited research information, high manufacturing costs, policy-related constraints, and environmental concerns are major challenges that need to be addressed before biochar can be widely implemented in GRs.
(h) The application of life cycle assessment (LCA) and cost analysis of biochar in GRs is highly recommended. These approaches can provide deeper insights into the environmental benefits and the economic feasibility of biochar-amended GRs.

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Chapter 3

Development of a model simulating the hydrological performance of large-scale green roofs

3.1. Performance Evaluation of Large-Scale Green Roofs Based on Qualitative and Quantitative Runoff Modeling Using MUSICX

3.1.1. Introduction

This chapter investigates the hydrological performance of large-scale green roofs in terms of runoff quantity and quality through the application of computer modeling. The research presented herein aligns with the broader study objectives outlined in Chapter 1. As highlighted in the first literature review, the application of computer modeling to assess large-scale green roof performance remains limited, impeding the widespread adoption of this GI strategy due to uncertainties surrounding its benefits. To bridge this knowledge gap, the MUSIC stormwater modeling software was employed to simulate the hydrological behavior of a hypothetical scenario where green roofs are installed on all suitable rooftops within the Footscray Park campus of Victoria University, Melbourne, Australia. The potential green roof area for each building was assessed, and the existing impervious and pervious surface areas of the campus were incorporated as input parameters to accurately evaluate green roof effectiveness. Two modeling approaches were developed based on 50-year precipitation data from the nearest weather station and a typical extensive green roof design featuring a 15-mm substrate depth. This green roof type is widely adopted due to its affordability, low maintenance requirements, and minimal structural demands. Model accuracy was ensured through rigorous calibration against local MUSIC guidelines and hydraulic parameters derived from previous green roof studies. Simulation results align with previous findings, demonstrating the positive influence of large-scale green roofs on runoff quantity and quality. However, achieving stormwater quality targets established by local guidelines may necessitate the integration of green roofs within a broader stormwater treatment train. A simplified modeling framework is provided to facilitate integration into decision-making processes.

This chapter contains the following journal paper:

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3.1.2. Declaration of co-authorship and co-contribution: papers incorporated in thesis by publication

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3.1.3. Performance Evaluation of Large-scale Green Roofs based on Qualitative and Quantitative Runoff Modelling

Article

Performance Evaluation of Large-scale Green Roofs based on Qualitative and Quantitative Runoff Modelling using MUSICX

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Abstract: Green roofs (GR) are known as one of the most effective Water Sensitive Urban Design (WSUD) strategies to deal with numerous environmental and social issues that urbanized cities face today. The overall quality of research on GRs has significantly improved and an increasing trend is observed in the amount of research over the last decade. Among several approaches, the application of modelling tools is observed to be an effective method to simulate and evaluate the performance of GRs. Given that studies on GR at a catchment scale are limited, this paper aims to provide a simple but effective framework for estimating the catchment-scale impacts of GR on runoff quantity and quality. MUSICX, an Australian-developed software that possesses advantages of a conceptual model is chosen as the modelling tool in this study. While MUSICX has built-in meteorological templates for Australian regions, this tool also supports several climate input file formats for the application by modelers in other parts of the world. This paper presents two different modelling approaches using the Land Use node and Bioretention node in MUSICX. The steps used for model calibration are also provided in this paper. The modelling results present the annual reductions in runoff volume, Total Suspended Solid (TSS), Total Phosphate (TP), and Total Nitrogen (TN) load. The largest reduction of roughly 30% per year were observed in runoff volume and TN load. The annual runoff reduction rate reported in this study is close to that of other published results. Similar research outcomes quantifying benefits of GRs play a major role in facilitating the widespread implementation of GRs due to the awareness of both positive and negative impacts of GRs. Future studies are recommended to concentrate on modelling impacts of implementing GRs at a large scale (i.e., scales exceeding single-building scale) to fill the research gaps and enhance the modelling accuracy.

Keywords: green roof, eWater, MUSICX, runoff quantity, runoff quality, large-scale implementation.

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1. Introduction

Rapid urbanization and population growth have become the rising global concerns. They challenge the existing urban infrastructure and cause several social and environmental issues. One of the most pronounced impacts is the significant increase in the impervious surface in built-up areas. In terms of stormwater management, it causes more flash flooding in terms of increasing frequency and intensity, and the pollution of stormwater runoff to receiving water channels. Additionally, the reduction of vegetation cover results in the urban heat island (UHI) effect due to more significant solar heat absorption, the degradation of the natural habitat, and loss of biodiversity. As a result, an appropriate solution is required to address the concerning situation.

Among various Green Infrastructure (GI) practices, Green Roofs (GR), also known as living roofs, which are recently introduced, offers a variety of ecosystem services. The temperature and stormwater runoff volume reductions have been widely documented as GR benefits [1-3]. Other GR services include enhancing runoff quality, mitigating air and noise pollution, recovering urban ecology, and improving social and economic aspects. GRs are generally divided into two main groups: Intensive Green Roofs (IGR) and Extensive Green Roofs (EGR) with the substrate depth of more than 30 cm and less than 15 cm, respectively [1,2]. Each type of GR is suitable for specific purposes and site conditions based on their different advantages. While IGR supports a wide range of plants and prevails over EGR in terms of ecosystem services, EGR is a lighter system that can be widely implemented due to its affordability, less maintenance, and easy installation without structural reinforcement [2,4-6]. Semi-intensive Green Roof (SIGR), which has 15 cm to 30 cm of the substrate thickness, is a combined GR system that takes advantages of both EGR and IGR [1].

Some attempts have been made to integrate GR with other systems. This combined system is described as "Hybrid GR" in this paper. One of the noteworthy hybrid GR systems is the photovoltaic GR (PV GR) which was studied by Hui and Chan [7] and Chemisana and Lamnatou [8]. Whereas Hui and Chan [7] found the surface temperature (T_s) of PV GR was 5^0C cooler than that of the traditional GR due to the shading effect of PV panels, a substantial difference of 14^0C between PV GR and the concrete roof was monitored by Chemisana and Lamnatou [8]. The improved electricity productivity from PV panels, which are believed to be due to the cooling effect of GR, were also detected. Another integrated GR system is the blue GR initially introduced in South Korea. This system has the same design as the conventional GR except for a larger storage layer. The runoff outflow from the blue GR was 0.1 l/s compared to 0.3 l/s from the normal roof in the study of Shafique, *et al.* [9]. Additionally, the combination of GR and green wall brings outstanding thermal and energy reductions as compared to stand-alone GR systems [10-13]. In spite of the above-mentioned improvements, studies on GRs are insufficient and further research is required before making firm conclusions regarding their use.

Though GRs have been well-studied for decades to quantify numerous ecosystem services that they provide, the implementation of GRs still remain restricted by barriers and challenges. More specifically, the lack of local GR research, especially in developing countries due to costly GR installation, could make building owners and authorities unaware of GR benefits [1]. Another noticeable constraint is the safety concern regarding the weight of a GR system. Given that most of the urban areas consist of existing buildings, the retrofitting of GRs must be carried out by considering whether any structural reinforcements are required or not. Moreover, there exist a lot of ambiguities and uncertainties about the capabilities of GRs. Nguyen, Muttil, Tariq and Ng [3] pointed out that published results of GR services were inconsistent in different studies. Those issues need to be resolved by future research which is conducted locally to match with specific climate characteristics. Valuable information from local research is prerequisite to motivate policy makers issuing financial incentives regarding the GR application. Addressing all of the discussed problems contributes to the feasibility of the widespread implementation of GR.

Applying simulation tools is a well-known approach to investigate the effectiveness of a GR system before the actual implementation at a building scale or even at a catchment scale. They provide investors and other stakeholders with what gains and losses GR can generate and then contribute to the decision-making process. Simulation tools are extensively used to study the relationship between GR parameters. They are also able to model building-scale GR behaviors as compared to its actual performance to analyze the model accuracy. By contrast, a relatively smaller number of papers were conducted to study the effectiveness of GR at large scales [3]. In this study, the term "large-scale" refers to studies considering the application of GRs at scales that exceed the single-building scale, such as the city-wide scale, municipal scale, or catchment scale. Significant efforts are required to stimulate the thorough adoption of the GR concept as a part of Water-Sensitive Urban Design (WSUD).

Existing models are generally distinguished according to different approaches including the empirical-based precipitation-runoff (P-R) relationship, conceptualization, and physical-based numerical models [14,15]. Each of them has its own advantages and disadvantages, which requires a comprehensive understanding to apply them in particular circumstances and purposes. The principle of the conceptual model is the conceptualization of physical rainfall-runoff processes; hence, each parameter is responsible for components of the physical process. Therefore, conceptual models are suitable for different levels of users greatly due to their simplicity [14]. However, the limitation of conceptual models is that they need to be properly calibrated to produce accurate results. On the other hand, physical-based models such as Storm Water Management Models (SWWM) and HYDRUS are more complicated with a significant number of parameters; thus, they produce outputs at a high level of accuracy. Nevertheless, the complexity of these models leads to several computational constraints and difficulties for non-modeling users [16,17]. While they are ideally suited for detailed design, conceptual models are preferably used for conceptual-level planning [18]. In general, none of models clearly prevail over others and the vast majority of them must be well calibrated against climate conditions in the area of interest [16].

Among several available tools, Model for Urban Stormwater Improvement Conceptualization (MUSIC) is Australia's most popular stormwater management tool [18]. In spite of MUSIC's extensive use in Australia, the application of this tool for GR research is limited. Table 1 illustrates some recent papers that have used MUSIC, with only two of them simulating GR. This could be because of MUSIC's lack of a built-in module for modelling GRs. Some recent studies include those undertaken by Hannah, *et al.* [19] and Liebman, *et al.* [20], which provide valuable information and a foundation for future studies. MUSIC with Australian built-in meteorological and climate data is suitable to assess impacts of WSUD systems as part of preliminary design at a catchment scale [16]. MUSIC, a conceptual model, has advantages over complex physical-based models due to its simplicity and low computational requirements, allowing modeling of large-scale GRs and long-term continuous simulations [17,21]. Though MUSIC is designed with available meteorological data templates for Australian regions, it is easily accessible by modelers from other parts of the world. MUSIC supports a range of rainfall and evapotranspiration input file formats for the worldwide application. Therefore, the developed MUSIC models could be internationally applied with appropriate local climate data.

Considering the above discussed gaps, there exist many opportunities for future research, which motivates the present study. This research aims to develop modeling approaches to effectively simulate the hydrological performance of GRs, especially at large-scales like at the catchment scale. Additionally, the developed model was applied to evaluate the effectiveness of installing GRs on all buildings' rooftops at the Footscray Park campus of

Victoria University (VU), Melbourne. More specifically, the performance of large-scale GRs at the VU's campus was assessed through the reduction of runoff volume and the runoff quality targets based on the Environment Protection Authority (EPA) Victoria Guidance. EGRs are chosen in this study due to numerous well-documented benefits provided by the widespread implementation of such GRs. Although eWater MUSIC can model the stormwater runoff from many types of urban surfaces such as paved roads, roofs, and landscapes, there is no built-in module or package in MUSIC to model GRs. Subsequently, the outcomes of this study would contribute to understanding the impact of GRs in terms of runoff quantity and quality at a catchment scale. The widespread application of GR would cost a lot in terms of effort and investment; consequently, it requires sufficient technical information from such studies to foresee potential gains and losses [22]. Given that MUSIC has some limitations due to its conceptual nature [18], the selection of this tool is mainly based on the primary research aim of introducing a simple approach to assess impacts of GRs that can provide accurate results, especially at the initial stage of conceptual design. Moreover, the framework proposed in this paper could be easily included in decision-support tools that can be used by different stages of decision making [23].

Table 1. A summary of application of MUSIC in recent studies.

Study	Location	Type of WSUD Treatments	Reduction in TSS/TP/TN (%)	Flow Reduction (%)
Zhang, Bach, Mathios, Dotto and Deletic [21]	Brisbane/ Melbourne/ Perth, Australia	Bio-retention cells, wetlands, and ponds	85/ 60/ 45	N/A
Ghofrani, *et al.* [24]	Tarwin Lower, South Gippsland, Victoria, Australia	Rainwater tanks, bio-retention cells, vegetative swales, and infiltration systems	94.4	16
Noh, *et al.* [25]	Cameron Highlands, Pahang, Malaysia	Wetlands, bio-retention cells, on-site detention, sediment basin, and gross pollutant traps	65-83/ 52-78/ 40-66	N/A
Schubert, *et al.* [26]	The Little Stringybark Creek (LSC) watershed, Melbourne, Victoria, Australia	Rainwater tank, infiltration systems, and bio-retention cells	N/A	60 for storms ≤ 2h; and 30 for storms > 2h and ≤ 12h
Montaseri, *et al.* [27]	ACT, Australia	Swales, rainwater tanks, bio-retention cells, infiltration system, and wetlands	80/ 75/ 70	N/A
Hannah, Wicks, O'Sullivan and de Vries [19]	Bannockburn, Central Otago, New Zealand	Green Roof	73.9/ -12.9/ 87	62
Liebman, Wark and Mackay [20]	Western Sydney, Australia	Green Roof	N/A	22 and 56 for 12.5% and 37.5% GR coverage, respectively

2. Methodology

2.1. Site Description

Victoria University's (VU) Footscray Park campus is located in the western suburbs of Melbourne. The city of Melbourne has a temperate oceanic climate (Köppen climate classification Cfb). It has warm summers and mild winters with the average annual precipitation of around 650 mm. Some experimental GR plots were successfully constructed on Building M at VU's Footscray Park campus during the end of 2020. These GRs are an initial stage of a project aimed at developing the university into a green, sustainable, and climate-smart campus. Figure 6 illustrates the GR plots, indicating the area, layout, types of vegetation, content of the growing media and the constructed green roof itself. Specifications of these actual GRs will be taken for modeling purposes (details of which are presented later). Though some hydrologic parameters of the plots cannot be determined, this research attempts to calibrate the MUSIC model as close as possible to the actual constructed GR.

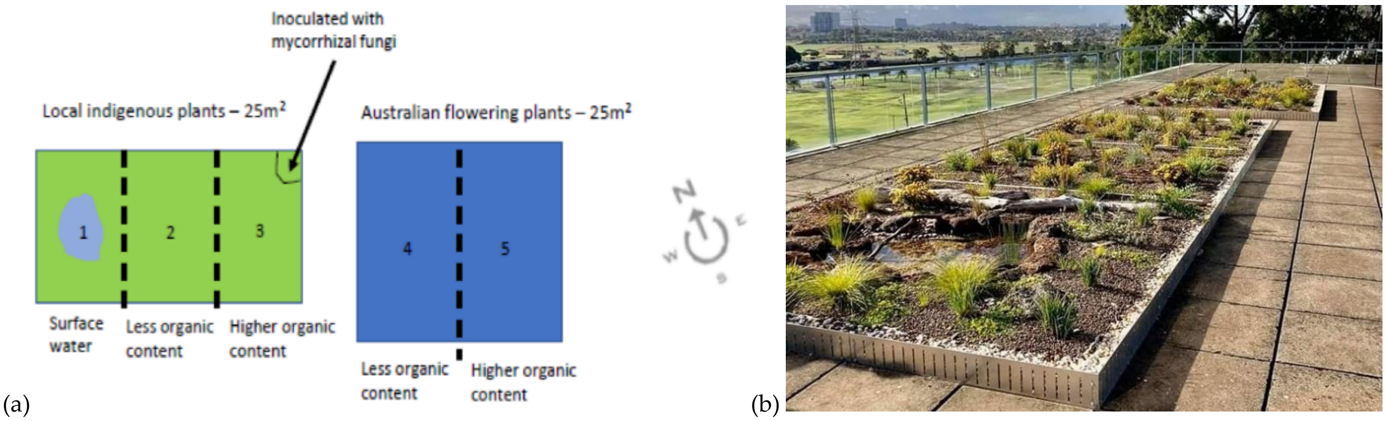


Figure 6. Details of green roof plots on Building M at Victoria University's Footscray Park Campus: (a) Green roof design, (b) Actual constructed green roof.

Table 2 provides detailed information about the VU campus's catchment characteristics. Figure 7 further describes the VU campus's existing plan by providing information about flat roof area, landscape area, and the existing stormwater drainage system. The VU campus has a total roof area of 22,018 m^2; however, only 13,159.5 m^2 are available for potential GR installation. The estimation of the potential GR area is based on the aerial image provided by the Google Earth database. Only flat roof areas are considered as potential GR area. Areas suitable for GR is further calculated by considering existing fixtures and footpaths for GR maintenance access. Effective Impervious Area (EIA), which is an important parameter in MUSIC, is the impervious area effectively connected to a drainage system. EIA is recommended to be adequately estimated with accurate drainage system details. Since such data is missing, the EIA value of 0.7 for education public use zone from MUSIC guidelines by Melbourne Water [28] will be used.

Table 2. Catchment characteristics of VU's Footscray Park Campus

ID	Area (m2)
Total Roof Area	22018
Total Flat Roof Area	15873
Potential GR Area	13159.5
Roof Area Without GR	8858.5
Pervious Area (Landscape)	8526
Impervious Area (Road, Paved Pathway, ...)	26456
Effective Impervious Area	18519.2
Pervious Area + Ineffective Impervious Area	16462.8
Total VU Catchment Area	57000

Figure 7. Details of flat roof areas, landscape areas, and stormwater drainage system at VU's Footscray Park Campus.

2.2. Data Collection

Though MUSIC has a built-in rainfall template for Melbourne, it is strongly recommended to use local climate data for accurate modeling. Melbourne Water [28] suggested the input of pluvial data at a 6-minute timestep for a minimum of 10 years. The average monthly potential evapotranspiration (PET) data is also inputted to MUSIC. The pluvial data is collected at the Melbourne Regional Office – Weather station 86071 (37.81° S, 144.97° E) which is 6 kilometers far from the area of interest, VU Footscray Park campus. The required PET data will be extracted from the closest grid to the coordinates of station 86071 to match with the 6-minute pluvial data at the previous step. The spatial resolution of the gridded PET data is 0.1 degrees or approximately 10 kilometers. Pluvial and PET data for 50 years from 1960 to 2010 is taken to ensure 100% of the data availability.

2.3. Proposed Framework

Figure 8 presents the proposed framework for developing a GR model using eWater MUSICX for evaluating the performance of GRs at a large-scale in terms of runoff quantity and quality parameters.

The following sections explain the required input data, the data sources, and the identification of parameters for model calibration.

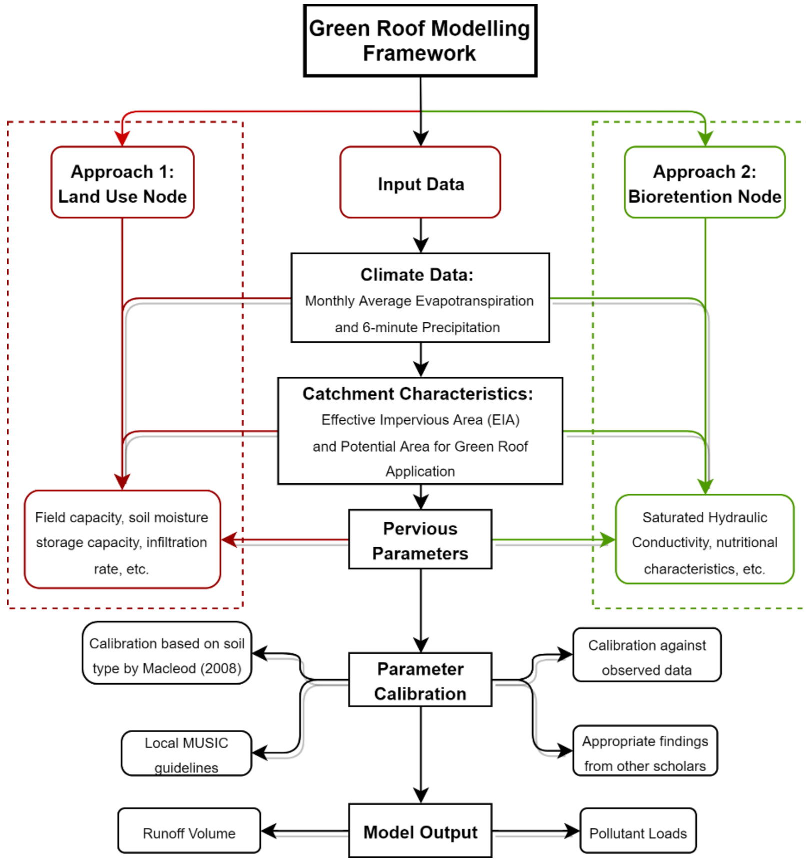


Figure 8. A framework for evaluating the performance of large-scale green roofs in terms of runoff quantity and quality.

2.3.1. Simulation Settings

MUSICX with numerous improvements in modeling algorithms as compared to classic MUSIC versions is chosen to be used in this present paper. It is stated that there exist no obvious advantages of a model over another, and the accuracy of both conceptual and physical hydrological models must be assured by proper calibrations [16]. On the other hand, among existing GR plots at the VU campus, the chosen one has a 150 mm substrate; a mixed substrate of Light Expanded Clay Aggregate (LECA) (80%), mulch (15%), and coir chips (5%); a geofabric filter layer, and a drainage layer comprising of VersiDrain drainage trays and Atlantis Flo-cell. Figure 9 illustrates a VU GR system used for modeling inputs. The VU GR is designed to be a lightweight system with innovative products. LECA is a lightweight material with a high capacity of water absorption. Atlantis Flo-cell is a light-weight product to provide structural support and water storage. The light-weight VersiDrain trays enhance the drainage layer by storing more than 11 liters of water per square meter.

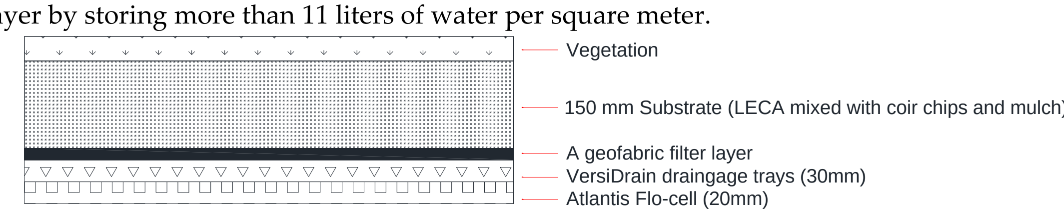


Figure 9. A cross-section of VU's green roof selected for modeling in this study.

The 50-year rainfall and PET data from 1/1/1960 to 31/12/2010 are selected for the simulation. This period meets the requirements of Melbourne Water [28] MUSIC guidelines in terms of data quality, data availability, and minimum data period. The 6-minute rainfall data from BoM for the chosen period is shown in Figure 10. The following sections describe the calibration process of the model through a variety of guidelines and values reported by other scholars. Flow data and substrate's hydraulic characteristics obtained from soil testing are missing in the present study are would be part of future work that would be udertakento improve the model's validity.

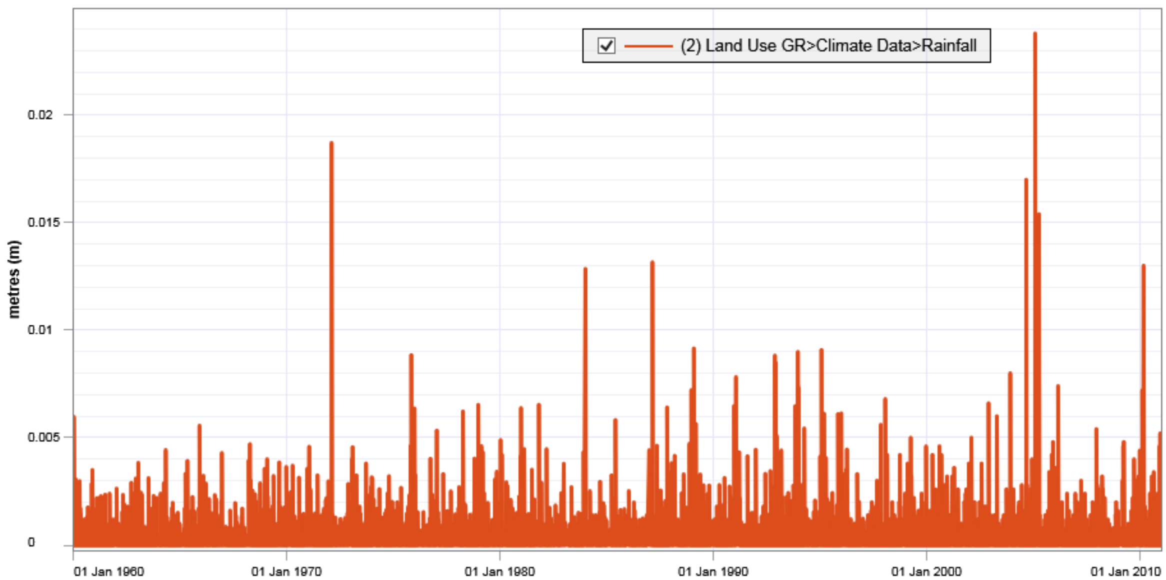


Figure 10. The 6-minute rainfall data during the study period from 1/1/1960 to 31/12/2010.

2.3.2. Land Use Node Approach

A land use node is a basic node in MUSIC. This type of node is not a treatment node that cannot be used to treat stormwater runoff. The reason for choosing this node to model GR is its capability to modify the physical characteristics of the GR substrate. More particularly, its setting allows users to input parameters to reflect the hydrological performance of the used substrate such as Field Capacity (FC) and Soil Storage Capacity (SSC).

The calibration of pervious area parameters based on soil properties (Table 3) for MUSIC inputs is guided by Macleod [29]. This study has become a useful guidelines for calibrating soil-relating parameters in MUSIC at a base level in case of unavailable on-site flow data [20,30]. The soil information in Macleod [29] was obtained from in-field tests and available soil data from previous-published results.

The substrate used for GR plots at the VU campus which has a thickness of 150 mm is a mix of Light Expanded Clay Aggregate (LECA), coir chips, and mulch. LECA is a light -weight material with a high capacity for water absorption. SSC and FC are computed with respect to "Light Clay" which is dominant in the VU GR substrate. 200 of "a" is the MUSIC default value and is suitable for the moderately-structured clay. 3 of "b" is of the single-grained light clay. Daily recharge rate indicates the percentage of excess water above FC that is drained to the layer below substrate (drainage layer of GR) on a day. 90% of "a" is suitable for GR with a shallow and rapidly-drained substrate. The daily baseflow rate describes the percentage of groundwater (water in the drainage layer of GR) that flows into local water bodies daily. Given that soil textures identify "b" values from Macleod [29] and the definition of "b" is not developed for a non-soil drainage layer of GR, a very small value of 5% is used to present no outflows unless the drainage storage is full of water.

Table 3. Settings of soil characteristics of green roof in MUSIC's land use node.

Parameters	Value	Reference
Soil Moisture Storage Capacity (mm)	29.46	[29]
Field Capacity (mm)	26.71	[29]
"a" coefficient (mm/day)	200	[29]
"b" coefficient	3	[29]
Daily Recharge Rate (%)	90	[29]
Daily Baseflow Rate (%)	5	[29]

Since there are no modifications for nutrient content of GR substrate in the land use node, the only solution to produce reliable runoff quality results is to input the pollutant concentration data for the urban surface type of landscape. Pollutant concentration parameters of the GR land use node are taken from Melbourne Water [28] MUSIC guidelines. Other important pervious and impervious parameters for the Melbourne area are also obtained from the guidelines.

2.3.3. Bioretention Node Approach

In general, GR and Bioretention systems share a similar concept and design. They both have water surface storage, a planted soil layer, and a drainage layer [31]. They also provide huge benefits for stormwater absorption and filtration [32,33]. Bioretention has a thick substrate and a great detention depth with 0.1-0.15m of topsoil layer above 1-1.25m of engineered substrate layer [34]. Oppositely, GR, especially EGR, has a nominal detention depth and a shallow substrate which are only favorable for the growths of drought-tolerant plants. Though the bioretention node is the closest available treatment node to GR, this node requires extensive modifications to reflect the hydrological performance of a typical GR.

TN and Orthophosphate are not only essential for the plant establishment but also the source of pollutants leaching from the GR or bioretention systems. Payne, *et al.* [35] recommend limiting the content of TN and Orthophosphate below 1000 mg/kg and 80 mg/kg, respectively. Without soil nutrient information, TN and Orthophosphate content of 400 mg/kg and 40 mg/kg are considered sufficient by Mainwright and Weber [36]. These minimal values could interfere with the establishment of plants within a bioretention system. Nevertheless, they would probably be adequate for GR greatly due to less organic content. The nutritional characteristics of GR substrates used in other studies were also found and summarized in Table 4 for further justification. The nutrient content values are chosen within the range reported in Table 4 and appropriate with the VU GR substrate composition (no added fertilizer and minimal compost by hardwood mulch). It is noteworthy that the GAF substrate in [37] contains very high initial P concentration. Additionally, the substrates used in [38] and [39] have high TP values caused by the high percentage of compost from animal waste.

Saturated Hydraulic Conductivity (SHC) for a bioretention system ranges from 100-300 mm/hr in the Facility for Advancing Water Biofiltration (FAWB) guidelines [35]. Given that the growing medium gradually becomes compacted and accumulates sediments, 50% of the recommended SHC should be applied [36]. However, GR is a very shallow substrate with a far higher SHC than bioretention. Numerous papers reporting SHC values of different substrates were identified to justify the calibration of SHC for modeling GR in MUSIC (Table 5). Most of them are derived from laboratory experiments. Considering expanded clay as the dominant part in the VU substrate mix and the reduction over time, 700 mm/hr of SHC was inputted into MUSIC modeling. The SHC value for GR is remarkably higher than that for bioretention, which facilitates water infiltration to avoid water flow and ponding on the surface even in heavy rainfall [40-42]. 700 mm/hr is within the range of 36 to 4200 mm/hr recommended by the FLL German guidelines [43], whereas 150 to 2500 mm/hr is the satisfactory range for a GR substrate [44].

Table 4. Nutritional characteristics of green roof substrates reported in other studies.

Study	Total Nitrogen (mg/kg)	Total Phosphorous (mg/kg)	Substrate Composition
Kotsiris, Nektarios, Ntoulas and Kargas [38]	132/ 250/ 36	56.68/ 202.8/ 8.90	Pumice, peat and clinoptilolite zeolite (65:30:5)/ pumice, compost, and zeolite (65:30:5)/ sandy loam soil, perlite, and zeolite (30:65:5)
Nektarios, Amountzias, Kokkinou and Ntoulas [39]	180/ 240	116.6/ 125.1	Pumice, perlite, compost, and clinoptilolite zeolite (50:20:20:10)/ Soil, pumice, perlite, compost, and clinoptilolite zeolite (15:40:20:20:5)
Harper, Limmer, Showalter and Burken [37]	NA	60/ 46 and 219/ 212 (Fresh/ 9 months old)	Arkalyte/ GAF
Arellano-Leyva, *et al.* [45]	NA	23.50/ 37.10	Gravel, volcanic rock mixed with clay, coconut fiber, compost, and soil with sandy loam texture

Table 5. Saturated Hydraulic Conductivity values for different substrate types as reported in literature.

Study	Saturated Hydraulic Conductivity - SHC (mm/hr)	Substrate Composition
Sims, *et al.* [46]	604.8	Expanded shale (coarse and fine) 50%, compost (bark and peat moss) 25%, and sand, limestone, and expanded clay
Voyde, *et al.* [47]	1224	Pumice 4–10 mm (20%), Pumice 1–7 mm (20%), Expanded clay (40%), and Composted bark fines (20%)
Hakimdavar, Culligan, Finazzi, Barontini and Ranzi [44]	756	Expanded shale based
Hamouz, *et al.* [48]	1432	LECA based
De-Ville, *et al.* [49]	2100	LECA (80%), loam (10%), and compost (10%)
Arellano-Leyva, López-Portillo, Muñoz-Villers and Prado-Pano [45]	351.8 ± 275.9/ 571.1 ± 290.9	Gravel, volcanic rock mixed with clay, coconut fiber, compost, and soil with sandy loam texture
Todorov, *et al.* [50]	17000, 1080, 684 (2009, 2010, 2012)	NA
Palermo, Turco, Principato and Piro [40]	0, 1667, and 1250 (min, max, value)	A mineral soil with 74% gravel, 22% sand, 4% silt, and clay

Other parameters are adjusted to properly model GR, including lined base; zero exfiltration rate; underdrain present; and minimal extended detention depth, and unlined filter media perimeter. From MUSIC V6 and MUSICX, a new algorithm using a ratio named "PET scaling factor" has been developed based on field experiments on biofilters. \This ratio allows the precise prediction of PET values which varies seasonally. The MUSIC default value of PET scaling factor is 2.1, which is taken from Carex in Greenhouse conditions. A smaller ratio of 1.5 is selected in this study to be respective to low-water-use plants of GR. Table 6 describes the input values for the bioretention node representing GR.

Table 6. Settings for soil characteristics of green roof bioretention node.

Parameters	Value	Reference
Saturated Hydraulic Conductivity (SHC) (mm/hr)	700	[28], [36], and [35]
TN Content (mg/kg)	200	[35] and [36]
Orthophosphate Content (mg/kg)	30	[35] and [36]
Is base lined?	Yes	NA
Exfiltration Rate (mm/hr)	0	NA
Underdrain Present	Yes	NA
Extended Detention Depth (m)	0.05	NA
Unlined Filter Media Perimeter (m)	0.01	[36]
Vegetated with Ineffective Nutrient Removal Plants	Yes	NA
PET scaling factor	1.5	NA

3. Results

3.1. GR Land Use Node

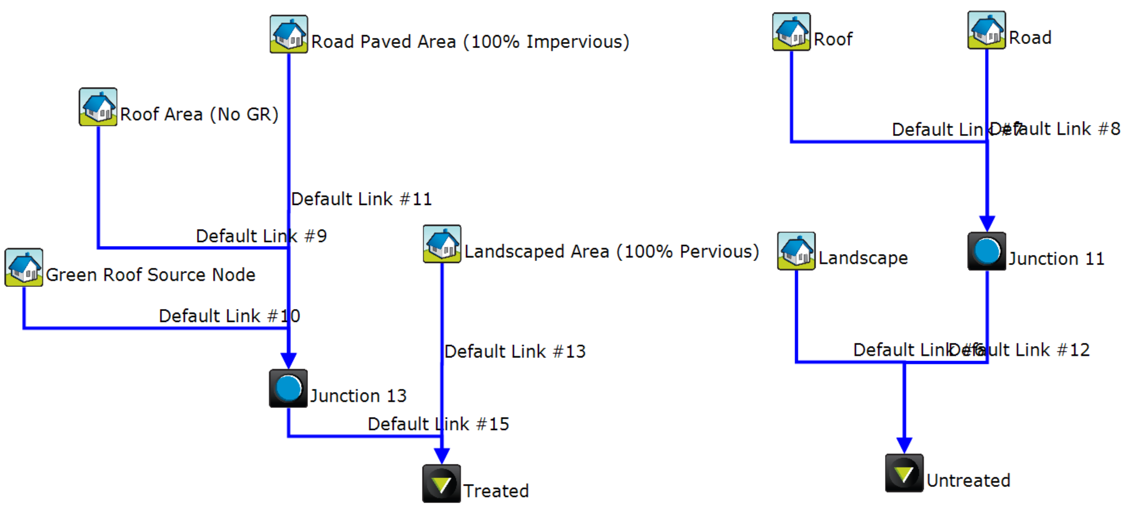
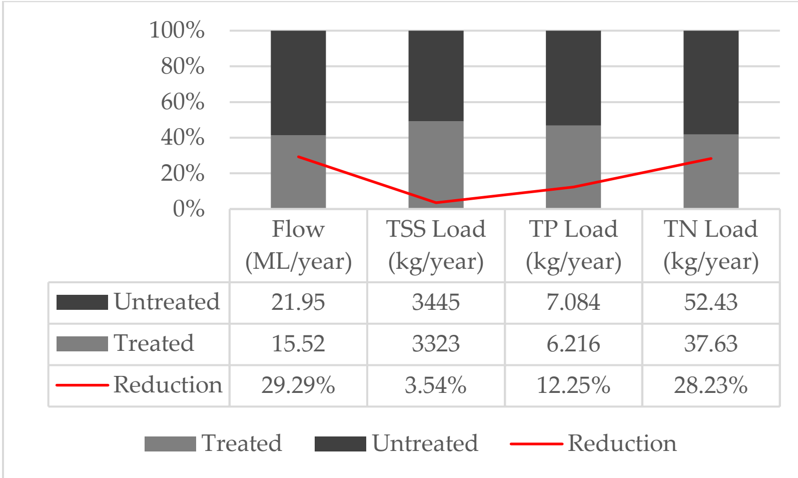


Figure 11. MUSIC schematic of green roof modeling using the 'Land Use' node.

Figure 11 illustrates the MUSIC layout of green roof modeling based on the 'Land Use' node. Due to the lack of a particular treatment node, 2 separate diagrams in the same model were created for the performance comparison. One including a source node representing green roof ends up with a receiving node named "Treated". Another one describing different surface types at the VU campus catchment without green roof treatment is finished by a receiving node named "Untreated". The results from these two receiving nodes "Treated" and "Untreated" are revealed in Figure 12. As the expectations, the "Treated" node completely outperformed the "Untreated" one. The presence of green roof brings significant benefits, especially the reductions of flow volume and TN load of 29.29% and 28.23%, respectively.



	Flow (ML/year)	TSS Load (kg/year)	TP Load (kg/year)	TN Load (kg/year)
Untreated	21.95	3445	7.084	52.43
Treated	15.52	3323	6.216	37.63
Reduction	29.29%	3.54%	12.25%	28.23%

Figure 12. The green roof treatment effectiveness using the Land Use node approach.

3.2. GR Bioretention Node

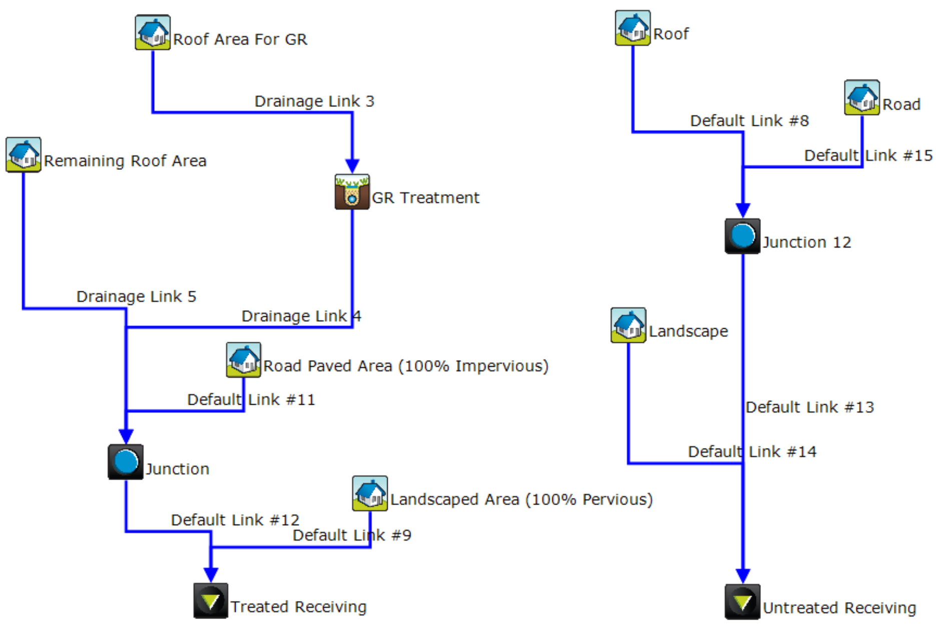
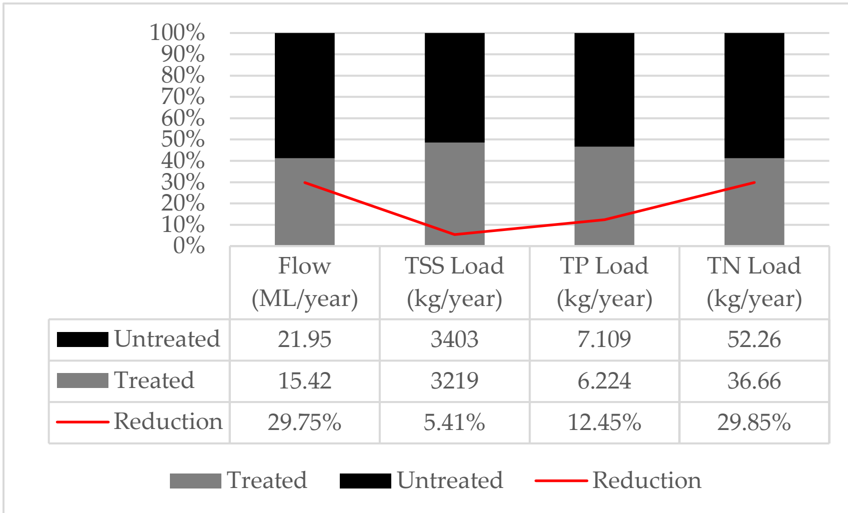


Figure 13. MUSIC schematic of green roof modelling using the 'Bioretention' Node.

Figure 13 is the illustration of the MUSIC schematic diagram used to investigate the hydrological performance of GR through a bioretention node. Compared to the land use-based approach, the bioretention-based one requires only one diagram since MUSIC understands bioretention as a treatment device and then directly produces outputs regarding the impacts of the treatment on the modeled catchment. However, another diagram without green roof treatment is still created for the purpose of comparing time-series outflows. Figure 14 summarizes the simulation results by using the bioretention-based method. According to this, the application of GR continues to lead to positive changes in both runoff quantity and quality. Flow volume (ML/year) and TN load (kg/year) remain the greatest reductions as compared to others.



	Flow (ML/year)	TSS Load (kg/year)	TP Load (kg/year)	TN Load (kg/year)
Untreated	21.95	3403	7.109	52.26
Treated	15.42	3219	6.224	36.66
Reduction	29.75%	5.41%	12.45%	29.85%

Figure 14. Green roof treatment effectiveness based on the Bioretention Node approach.

4. Discussion

4.1. Model Results

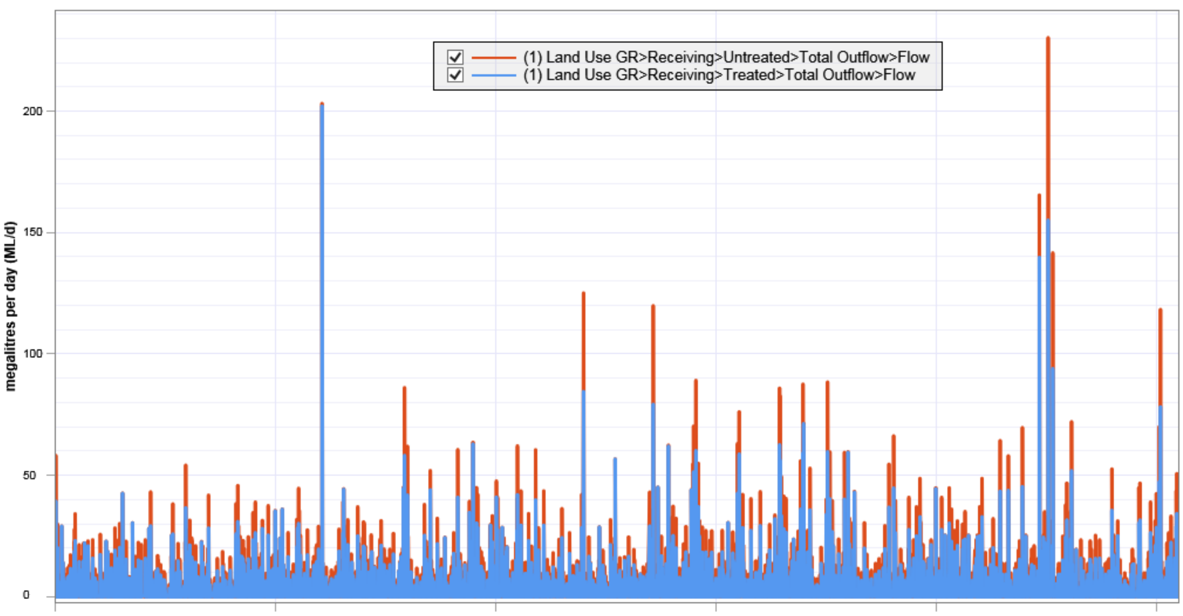


Figure 15. Comparison of outflow volume between treated and untreated scenarios using the Land Use node.

The hydrological behaviors of GR were similarly simulated by using land use node and bioretention node. Figure 12 and Figure 14 show the negligible differences between these two approaches. This implies that they are likely to be used interchangeably to investigate the large-scale effects of GR in MUSIC. The small impacts of GR on the mitigation of TSS were worthy of attention. This could be explained by sediments primarily sourced from ground and road surfaces, whereas green roofs cover a small portion of the VU catchment. Additionally, the reductions of TSS, TP, and TN did not meet stormwater management objectives according to the Environment Protection Authority (EPA) Victoria Guidance (TSS: 80%, TP: 45%, and TN: 45%) [51]. The poor performance of VU's large-scale GRs in terms of runoff quality could be due to the insignificant area of GRs with only around 23% of the total catchment area of the VU's campus. The large area of ground and hard surfaces greatly contributes to the pollution sources of TSS, TP, and TN. Thus, the combined application of GR and other WSUD devices should be considered to meet numerous runoff quality objectives. A treatment train including different measures such as GRs, water tanks, bioretention, swales, and ponds is highly recommended to reach the targets. For example, a variety of stormwater treatment devices was proposed to be applied in a 3.9 ha residential area in Canberra, Australia [27]. The optimal scenario of bioretention, infiltration systems, swales, wetlands, and water tanks reduced loads of TSS, TP, and TN by 80%, 76%, and 65%, respectively. Noh, Mohd Sidek, Haron, Puad and Selamat [25] tested the performance of a treatment train of wetlands, bioretention, on-site detention, sediment basin, and gross pollutant traps in Cameron Highlands District, Malaysia. The simulation results from MUSIC showed the considerable reductions of 65-83%, 52-78%, and 40-66% for TSS, TP, and TN, respectively. Figure 15 illustrates a remarkable change in runoff volume before and after the application of GR on all existing buildings at the VU Footscray park campus. The annual runoff reduction is around 30% in both studied approaches in this paper. This is comparatively similar to other published results. For example, Versini*, et al.* [52] reported an averaged runoff reduction of 25.2% using a coupled conceptual and SWMM model. Roehr and Kong [53] reported 29% and 28% of runoff reduction per year by large-scale EGR using low-water-use plants with the annual precipitation of 1200mm and 1219 mm, respectively. A water balance model was applied in this study. Runoff reduction from the application of EGR throughout a Chinese city in Liu*, et al.* [54] fluctuates from 27% to 42% in different rainfall events, which was simulated by SWMM. However, a study of Barnhart*, et al.* [55] published a lower runoff reduction of only 10% to 15% and 20% to 25% yearly for EGR and IGR scenarios, respectively. Similar to runoff quality, runoff quantity could be further diminished by combining GRs with other stormwater devices such as rainwater tanks and bioretention systems. Additionally, the results from [20] and [19] using MUSIC to model GR are not comparable to this current study, since they were done at a building scale. Figure 16 further describes the difference between them in terms of cumulative flow volume. The difference of runoff quantity from the untreated scenarios hardly can be seen, whereas runoff volume treated by GR-bioretention node is slightly higher than that by GR-land use node.

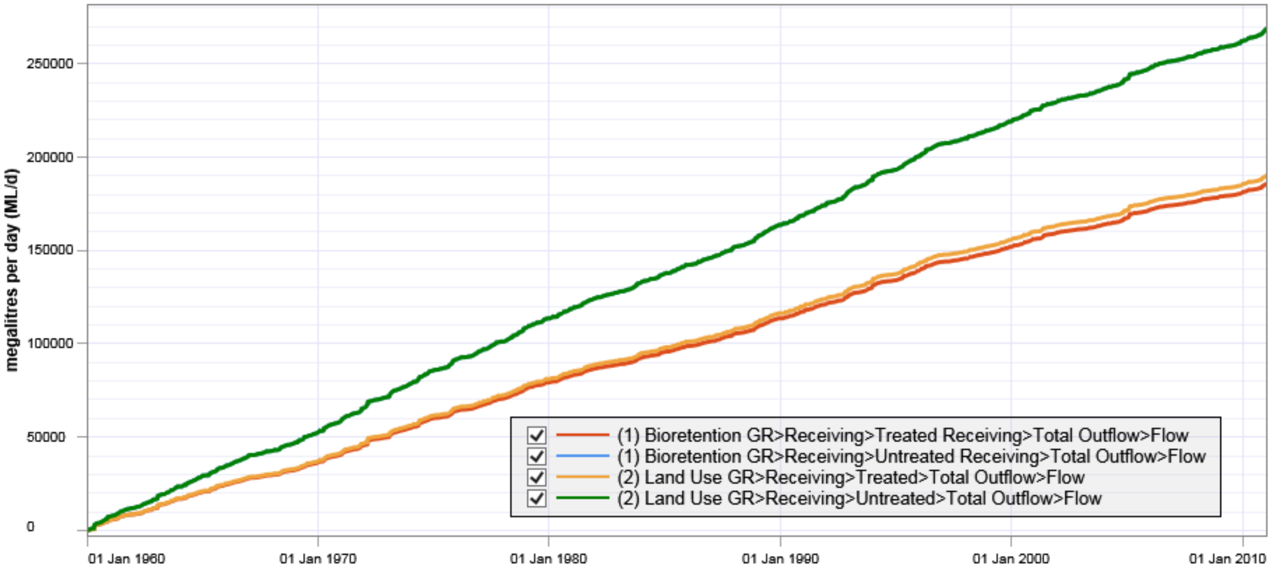


Figure 16. Cumulative runoff volume from the Land Use Node and Bioretention Node approaches.

In some cases where modelers seek to obtain the accurate results of runoff quantity, the land use-based method is preferably significantly used due to several hydraulic substrate characteristics that can be modified. Moreover, the land use node settings allow users to adjust the flow movements in the drainage layer as closely as possible to a typical GR system. When modelers focus on the improvement of runoff quality, the bioretention-based method should be applied. The bioretention node considerably differs from the land use node and it is a treatment device provided by MUSIC. Hence, it is capable of treating rainwater by its vegetated substrate. Accordingly, this node's settings comprise nutritional characteristics such as TN and Orthophosphate content, and selections of either Effective or Ineffective nutrient removal plants. There is a noticeable difference between reductions of TSS and TN loads between the two adopted methods. It is also noting that this node has inputs of SHC and PET scaling factor for specific plants, which play a major role in estimating runoff quantity. Nevertheless, the model calibration against the monitoring data remains necessary to ensure the model's accuracy and validity, which is discussed further in the following section. The above-suggested approaches should only be adopted when experimental data is not available.

4.2. Model Calibration

As stated previously, the calibration process is crucial in any model development. Regarding stormwater modeling, it requires the calibration based on the flow data from the WSUD devices and climate parameters at the area of interest. Additionally, physical characteristics are required prior to the model calibration. The measurements of those parameters through soil tests have been reported to be expensive and time-consuming [56]. Moreover, a model is likely to perform effectively only within the timeframe in which it is completely adjusted to match the monitoring data through the model calibration process. Given that GR hydraulic properties are highly-various parameters over time, the developed models must deal with the ambiguous performance outside of the simulation period. The downward trend of SHC values is a good example of the significant changes in the substrate characteristics during its lifetime. Todorov, Driscoll and Todorova [50] reported SHC values of 17000, 1080, and 684 mm/hr in 2009, 2010, and 2012, respectively. SHC of the substrate used in De-Ville, *et al.* [57] was reduced from 10740 to 2658 mm/hr in five years. Nevertheless, flow monitoring data and soil testing are importantly required, which is missing in the present study. They are still parts of future works to strengthen the connection between the VU GR designs and the modelling settings, thereby enhance the modelling accuracy.

The parameter values used in model settings are even more complex. SHC and other parameters are well calibrated to reproduce the observed data accurately. Therefore, they are different from the values either measured in the laboratory or provided by the supplier. The calibrated SHC in Versini, Ramier, Berthier and De Gouvello [52] is 104.7 mm/hr, which is far less than 1158 mm/hr reported by the green roof supplier. Other papers using HYDRUS and SWMM modeling also reported similar calibrated values fluctuating only from 100 to 200 mm/hr for SHC [54,56,58]. Since there are no published calibrated SHC for MUSIC modeling, 700 mm/hr of SHC in this study was derived from other scholars' values measured in laboratory only. Elliott and Trowsdale [16] stated that no obvious advantages exist of a model over another, and the accuracy of both conceptual and physical hydrological models must be assured by proper calibrations. Future studies on GR modeling by MUSIC are suggested to measure hydraulic characteristics combining with the inflow/ outflow data from actual experiments to enhance the model validity.

It could be attributed to the fact that HYDRUS and SWMM are two physical-based modeling software studied the most by researchers. Some noteworthy studies were carried out in [15], [56], [52], [58], [54], and [59]. By contrast, their applications to large-scale simulation of GI devices remain limited corresponding to a minimal number of papers studying green roof at the catchment scale [3]. Versini, Ramier, Berthier and De Gouvello [52] pointed out that most efforts have been done to reproduce observed data of experimental GRs and investigate the catchment-scale hydrological effects of GR through a simple extrapolation method. The complexity of physical-based models could explain this modeling gap. For example, computational constraints confront the application of SWMM in long-term continuous simulation at the catchment scale [18,56]. To be successfully implemented, SWMM is required to correctly calibrate approximately 12 parameters [15,60]. HYDRUS is not even suited for large-scale urban modeling due to the high computational requirements of fine temporal and spatial scales [17,23]. On the other hand, the nature of MUSIC is a conceptual-based model; hence, it has its advantages over physical-based ones. A long continuous simulation period due to low computational costs and proper input values calibration could offset its simplicity. In general, none of models totally prevail over others. A model is likely to perform efficiently in specific situations with appropriate modeling objectives.

4.3. Inclusion of Irrigation into Green Roof MUSIC Modeling

The irrigation is required to maintain the establishment and survival of GR vegetation. Therefore, it adds a considerable water volume to GR systems, resulting in more runoff and affecting GR's hydrological performance. The irrigation demand is thus reasonably involved into modeling. However, MUSIC does not have a specific function to simulate the irrigation. Liebman, Wark and Mackay [20] successfully included the irrigation demand by modifying the rainfall template in MUSIC and using an imported node. Regardless of the substantial impact of irrigation on green roof hydrological performance, it is impossible to include irrigation in large-scale modeling in this study due to limitations of the currently-used MUSICX version. Future studies are suggested to add irrigation to the rainfall template applied to a model containing GR only. The imported node containing outputs of the GR-only model will be consecutively inputted into the main model for the whole catchment with the unmodified rainfall template.

With the release of newer versions of MUSICX, the following steps are suggested to be applied for an approximate estimation of irrigation demand. The calculation of irrigation requires Crop Evapotranspiration (ETc). The ETc equation is:

$$ETc = ETo \times Kc$$

where ET_o (mm d^{-1}) is the reference evapotranspiration and K_c is the crop coefficient for specific crops.

PET and ET_o differ in terms of their developments, concepts, and equations, and they are used for different purposes [61]. Up to date, researchers are still struggling with using these two confusing terms. Referring to their concepts and development history, PET is utilized in the fields of hydrology and meteorology, while ET_o is commonly used for irrigation and agriculture [61]. The ET_o equation according to FAO-56 Method is:

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \quad [62]$$

where T is the mean air temperature (°C), u_2 is wind speed (m s^{-1}) at the height of 2 meters above the ground, R_n is the net radiation flux (MJ m^{-2} d^{-1}), G is the sensible heat flux into the soil (MJ m^{-2} d^{-1}), Δ is the slope of the saturated vapor pressure curve, γ is the psychrometric constant (kPa $°C^{-1}$), e_s is the mean saturation vapor pressure (kPa), and e_a is the actual vapor pressure (kPa).

The calculation of ET_o is substantially complicated and requires the availability of various climate datasets. When data required to calculate ET_o is incomplete, PET, designed to be appropriate with MUSIC algorithms, is recommended for irrigation estimation.

The equation for the irrigation demand on a day is:

$$Irrigation\ Demand\ (mm) = \frac{PET \times Kc - R \times Er}{Ei}$$

where E_i is the irrigation system's efficiency, R is the rainfall depth on a day, and E_r is the rainfall effectiveness. The values suggested by Connellan [63] for E_I, E_R, and K_c are 0.75 (for sprinkle system), 0.5, and 0.4 (for drought-tolerant plants), respectively.

In practice, the irrigation interval should be calculated to determine when the irrigation is required based on the Plant Available Water (PAW) and the Percentage Allowable Depletion (PAD). An Excel spreadsheet calculates the irrigation interval based on the Plant Available Water (PAW) and the Percentage Allowable Depletion (PAD).

$$PAW = \frac{Root\ Zone\ Depth\ (mm) \times Avaiable\ Water\ Holding\ Capacity\ (mm/h)}{1000} \quad [63]$$

PAW is calculated to be 18.75 mm using the Root Zone Depth of 150 mm and Available Water Holding Capacity of 125 mm/h for Light Clay [29]. Connellan [63] also suggests using the PAD of 50%, which allows the irrigation to take place when the soil moisture is below 9.375 mm. This approach reflects the actual irrigation practice in which plants are not irrigated daily.

This method was successfully tested with the data period of 10 years. Many excel functions were used to deal with a huge number of calculation steps. Irrigation days and irrigation depths were explicitly determined. They were consecutively combined with the MUSIC 6-minute rainfall data to reflect the precise amount of water going through GR. Nevertheless, the inclusion of irrigation in a more extended data period is difficult given the limitations of Excel and other software may be needed to do this regularly. More particularly, this case requires advanced skills to load and edit complete data of a large csv file. It would be preferable if an add-on program, plug-in or feedback loop were implemented in MUSIC to support representation of irrigation.

5. Conclusions

GRs have been extensively used in the recent past as compared to other varieties of GI as a potential strategy to address several social and environmental issues. GR has been significantly studied during the last decade and the results show both its advantages as well as disadvantages. Due to the existing research gap related to assessing GR performance at a large-scale (i.e., scales exceeding single-building scale), this paper attempts to investigate the hydrological effect of the implementation of GRs on the Footscray campus of Victoria University in Melbourne, Australia. The simulation is carried out by eWaterMUSIC, which is a widely-used Australian modelling tool. MUSIC possessing advantages of a conceptual model with built-in Australian climate data and has a huge potential to effectively simulate the hydrological response of GR at large scales. This paper aims to provide a simple but effective framework to inform investors and policy makers about the benefits of GRs, which is a prerequisite for widespread implementation of GRs. Additionally, this paper attempted to evaluate the impacts of large-scale GRs on runoff quantity and quality at the VU's campus. The simulation results showed a positive performance of GRs with the reduced runoff volume and improved runoff quality. On the other hand, the combined use of GRs and other stormwater treatment devices is required to meet runoff quality objectives according to local stormwater guidelines.

The following is a summary of key observations and recommendations obtained from this study:

a) The modelling results show that GR is effective in reducing runoff volume, TSS load, TP load, and TN load. While the largest reductions of roughly 30% are of runoff volume and TN load, the smallest reduction is of TSS load in both studied approaches;
b) Land use node and bioretention node approaches can be used interchangeably since the difference in MUSIC modelling outputs was found to be not substantial.
c) The land use node-based method is recommended to be applied when modelers focus on studying runoff quantity due to several simulation settings of GR substrate's hydraulic characteristics. On the other hand, the bioretention node-based method is preferable in runoff quality-related research because of the modifications of plant types and nutritional characteristics of the GR substrate.
d) In this paper, the importance of model calibration is highlighted. Though no soil testing and flow monitoring data were obtained to calibrate the MUSIC-GR model, they are still part of future work to strengthen the connection between the VU GR design and modelling settings, thereby enhancing the modelling accuracy. On the other hand, the concerns about the low accuracy of a model even with properly-calibrated parameters have also been discussed.
e) The application of GR for the entire VU campus area did not meet runoff quality objectives as set out in the EPA Victoria guidelines. Therefore, it is recommended that a treatment train including GR and other WSUD strategies be implemented to meet several stormwater management objectives.
f) Irrigation for the GR vegetation contributes to a substantial amount of GR runoff. This paper provides an explicit recommendation to include irrigation into MUSIC to model GR more accurately.

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Chapter 4

Investigate the performance of newly established biochar-amended green roofs in terms of stormwater management (runoff quantity and quality)

4.1. A Field Study to Investigate the Hydrological Characteristics of Newly Established Biochar-Amended Green Roofs

4.1.1. Introduction

Chapter 4 focuses on the efficacy of biochar in enhancing green roof stormwater retention and quality. The application of novel materials, such as biochar, to green roof systems was identified as a primary research objective in the preceding literature reviews (Chapter 2). The initial study within this chapter assessed the capacity of biochar-amended green roof substrates to reduce runoff volume. Insights derived from the second literature review significantly informed the experimental design. Six 1 m x 1 m galvanized steel green roof test beds were established on the rooftop of Building M of Victoria University's Footscray Park Campus, Melbourne, Australia. Five test beds incorporated varying biochar treatments, while one served as a control. The study examined the influence of two biochar application methods, two particle sizes, and two amendment rates. While the test beds were exposed to natural environmental conditions, hydrological performance was evaluated under controlled rainfall conditions to precisely quantify water input. A nozzle-based rainfall simulator was employed to replicate natural rainfall characteristics. To facilitate runoff volume measurement, the test beds were elevated above the roof surface. Runoff retention rates and outflow delays were recorded and analyzed across nine simulated rainfall events, encompassing medium, heavy, and extreme intensities. Analysis of the collected data enabled the identification of optimal biochar-green roof configurations for effective stormwater management. The study also explored the influence of biochar variables on green roof performance and provided recommendations for future research. Dissemination of positive research findings is crucial for raising awareness of biochar-green roof systems among researchers, urban planners, investors, and the broader community.

This chapter contains the following journal paper:

- 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. https://doi.org/10.3390/w16030482.

4.1.2. Declaration of co-authorship and co-contribution: papers incorporated in thesis by publication

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DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS

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2. CANDIDATE DECLARATION

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3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

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1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
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3. There are no other authors of the publication according to these criteria;

4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

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Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Cuong Ngoc Nguyen	80	Conceptual ideas, research, data analysis, experiments, writing.	[redacted]	20/05/2024
Hing-Wah Chau	5	Feedback and discussion on research and writing		21/08/2024
Nitin Muttil	15	Critical comments and discussion on conceptual idea & research methodologies		22/08/2024

Updated: September 2019

water

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4.1.3. A Field Study to Investigate the Hydrological Characteristics of Newly Established Biochar-Amended Green Roofs

Article

A Field Study to Investigate the Hydrological Characteristics of Newly Established Biochar-Amended Green Roofs

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Abstract: Green roofs (GRs) have been researched for decades, yet their implementation remains constrained due to several reasons, including their limited appeal to policymakers and the public. Biochar, a carbon-rich material, has been recently introduced as an amendment to GR substrate to enhance the performance of GRs through reduced runoff volume, improved runoff quality, and increased soil fertility. This paper aims to investigate the impact of biochar amendment on the hydrological performance of newly established GRs. An amount of six 1 m × 1 m GR test beds were constructed, which included five biochar-amended GR test beds, and one conventional test bed (without any biochar in its substrate). The water retention capacity and runoff outflow delay of the six test beds were studied with the application of rainfall using a nozzle-based simulator. Biochar was found to increase the water retention capacity and effectively delay runoff outflow in the biochar-modified GRs. After nine artificial rainfall events of 110.7 mm rainfall in total, 39.7 to 58.9 L of runoff was retained by the biochar-amended GRs as compared to 37.9 L of runoff retained by the conventional GR. Additionally, the test bed without biochar quickly started releasing runoff after 300 to 750 s, whereas test beds with fine biochar particles could delay runoff outflow by 700 to 1100 s. The difference between the non-biochar and biochar test beds varies according to the biochar-related variables such as particle sizes, amendment rates, and application methods. The observational data illustrated that the GR test bed with medium biochar particles applied to the bottom layer of the GR substrate was the optimal biochar-GR design. This selection was determined by the combined performance of high retention rates, long runoff outflow delays, and few other factors, such as less biochar loss caused by wind and/or water.

Keywords: biochar; green roof; green infrastructure; stormwater; runoff volume; hydrological experiment

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1. Introduction

Green roofs (GRs) are commonly known to be one of the most effective green infrastructures (GI) strategies to counter the impacts of multiple global concerns like climate change and rapid urbanization [1,2]. A typical GR system consists of the following layers from top to bottom: vegetation, substrate, filter layer, and drainage [3]. There are three main types of GR: extensive GR (EGR), semi-intensive GR (SIGR), and intensive GR (IGR) [4]. EGR has a substrate thickness of less than 15 cm, which is favorable for drought-tolerant plants. EGR has a huge potential to be implemented thoroughly due to its affordability, easy installation on existing buildings without structural reinforcement, low investment costs, and moderate maintenance [5,6]. Oppositely, IGR outperforms EGR in terms of ecosystem services due to a thicker substrate. However, there are several obstacles preventing the application of IGR. They are issues relating to extreme load-bearing capacity, high initial costs, and intensive maintenance [7]. The SIGR having a medium substrate depth takes advantage of both the EGR and IGR. SIGR is appropriate for the survival of medium-root plants and lawns, and does not require comprehensive maintenance [8]. The recognition of GRs has been increasing in the last two decades due to a considerable number of global efforts [9]. An imbalanced research focus with regards to GR benefits has been reported in the literature with the greatest attention towards runoff and temperature reductions [10-12]. GR studies have been mostly conducted in the USA and many European countries, which result in the insufficient awareness of GR potential in other countries. Given that the performance of GRs significantly varies according to local climate and availability of material, research needs to be improved in terms of both quantity and quality at a local level [12]. An insufficient number of studies at a local scale limit the widespread implementation of GRs because of inadequate information available for investors and policymakers.

GRs provide numerous eco-system services comprising runoff retention, runoff quality improvement, enhanced thermal comfort, noise reduction, air purification, and economical and environmental benefits [13]. Among them, runoff retention has been studied the most [10]. Rainwater is absorbed by the substrate layer and then is either consumed by the plants or is lost to the atmosphere through evapotranspiration. Excess water from intense rainfall events is either stored in the drainage layer of the GR or flows into the roof's drainage system. This mechanism helps to reduce the stress on the stormwater infrastructure by attenuating runoff volume and peak flow. This ability of GRs to retain rainwater (which in turn leads to delayed runoff outflow) has been examined in numerous studies. For example, Palermo, *et al.* [14] studied the hydrological responses of a full-scale EGR. They found that 68% (fluctuating from 16.7 to 100%) of rainwater was retained by the GR in a single rainfall event. The average peak-flow reduction per event was 56% ranging from 13.3 to 95.2%. A similar finding was obtained for a full-scale EGR in the study by Cipolla, *et al.* [15], which had an average retention rate of 51.9% ranging from 6.4 to 100% on an event-by-event basis. Similar studies can also be found in [16-22]. In addition, GRs have been significantly researched in test beds. The hydrological performance of pilot-scale GRs is comparable to that of full-scale GRs. An excellent example is the study by Stovin, *et al.* [23], wherein the authors studied a 3 m^2 EGR test bed. The average rainfall retention and the peak-flow reduction were 70% and 60%, respectively. The 1 m^2 EGR test bed of Zhang, *et al.* [24] achieved a higher retention rate of 77.2%, which fluctuated from 35.5 to 100%. GR test beds are a convenient choice for researchers to easily collect observational data and study the impacts of different parameters on the performance of GRs. Some relevant studies are [6,25-29]. However, a wide range of runoff retention/reduction rates have been reported and some parameters affecting GRs remain controversial [10]. This inconsistency could be due to the variation in hydraulic characteristics caused by different GR materials, study areas, monitoring period, climate conditions, and data analysis methods [14,30]. For instance, an agreement on the impact of antecedent dry weather period (ADWP) on water retention in GRs has not yet been reached [22,24-26,31]. Zhang, Szota, Fletcher, Williams and Farrell [25] highlighted the importance of substrates when compared to evapotranspiration (ET); whereas the studies by Johannessen, Muthanna and Braskerud [28] and Kaiser, *et al.* [32] stated that ET had a greater impact when compared to that by other parameters. Furthermore, some studies reported rainfall events that produced zero runoff, leading to exceptional average retention rates [14]. Certain studies reported that more than 90% of the rainwater was retained by the GR, attributed to a significant occurrence of small rainfall depths throughout the study period [25,33-35]. Conversely, Wong and Jim [19] reported a low retention capacity due to numerous intense rainfall events, reaching a maximum depth of 344.8 mm.

Several researchers have shown interest in innovative technologies to improve the ecosystem services provided by GRs. The integration of GRs with other systems was found to be effective in various studies. For instance, La Roche, *et al.* [36] successfully enhanced the cooling performance of GRs by combining GRs with a radiant/evaporative cooling systems. The surface temperature of a hybrid photovoltaic GR (PV GR) was observed to be 5 °C cooler than that of a stand-alone GR in [37]. Furthermore, a 4.3% enhancement in the electricity production of the PV panels was also observed. Similar findings were found in other studies [38-40]. Green-blue roofs and green wall-integrated GRs are other well-documented systems. Biochar, a carbon-rich material, is manufactured by burning biomass, such as woody materials, crop residues, or municipal solid wastes, in an oxygen-deficient environment [41-43]. Biochar has been recently introduced to GRs and other fields of application (for e.g., agriculture). The benefits of biochar have a strong connection to its highly-porous structure [44]. Biochar is able to retain more water and nutrients, improve soil fertility and plant health, and allow for the diversity of microbial community [45].

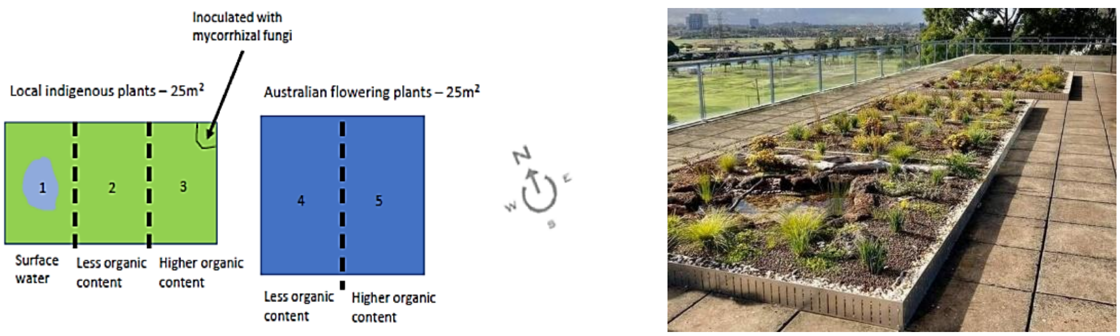
Despite biochar having a huge potential in enhancing GRs, the hydrological performance of biochar-amended GRs has been insufficiently understood due to limited research and a consequent lack of information. Consequently, the study presented in this paper aims to investigate the effectiveness of biochar in improving runoff retention and the delaying of runoff in GRs. Runoff retention refers to the ability of GRs to retain or capture rainfall and prevent it from immediately flowing as runoff. The higher the retention rate is, the lower the runoff volume is. Runoff outflow delay refers to the phenomena where rainfall is delayed from immediately contributing to runoff after a rainfall event. A biochar-amended GR system with high-runoff retention and long runoff outflow delay can have various benefits, including reducing stormwater runoff, improving water quality, and providing additional moisture for vegetation. Additionally, this research also aims to study the influence of different biochar-related variables (including application methods, amendment rates, and biochar particle sizes) on the hydrological performance of GRs. To achieve these objectives, six 1 m^2 GR test beds with varying characteristics were established. Data on the volume of runoff and runoff outflow delay for each test bed were collected during several artificial rainfall events. A pressurized nozzle-based rainfall simulation system was employed to generate an artificial rainfall. Acknowledging the distinctions between artificial and natural rainfall events [46], this study attempted to replicate the characteristics of a natural rainfall as closely as possible. Further details about the rainfall simulation system are provided in Section 2.2. It is worth mentioning that the influence of plant characteristics on the hydrological performance of GRs requires a comprehensive analysis, which is beyond the scope of the current study. However, the plant conditions were consistent across each test bed throughout the monitoring period, thereby limiting the influence of plants on the results.

This paper is structured as follows. Section 2 presents the methods and materials used in this study, which includes details about the experimental site, information regarding setting up of the GR test beds, selection of biochar types, design of the rainfall simulation system, and data collection methods. This is followed by the results presented in Section 3. A detailed discussion on the results is provided in Section 4, and finally the conclusions drawn from this study are presented in Section 5.

2. Method and Materials

2.1. Site Description

The experiments undertaken in this study were conducted on the roof of Building M at the Footscray Park campus of Victoria University (VU), Victoria, Australia. The study area is influenced by the temperate oceanic climate (Köppen climate classification Cfb) with warm summers and mild winters. The average amount of precipitation received annually is roughly 650 mm. A 50 m^2 GR divided into 5 different growing spaces (Figure 1) was initially constructed. It was observed that the existing roof conditions of the building were not favorable for the acquisition of runoff-related experimental data. Hence, six 1 m^2 GR test beds were subsequently constructed (Figure 2). Galvanized steel trays measuring 1 m × 1 m were used, which were elevated to a height of 0.3 m above the roof tiles using a metal frame.



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

Figure 1. The 50 m^2 green roof on top of Building M at Victoria University, Footscray Park Campus: (**a**) the green roof construction plan, (**b**) the green roof one month after completion.

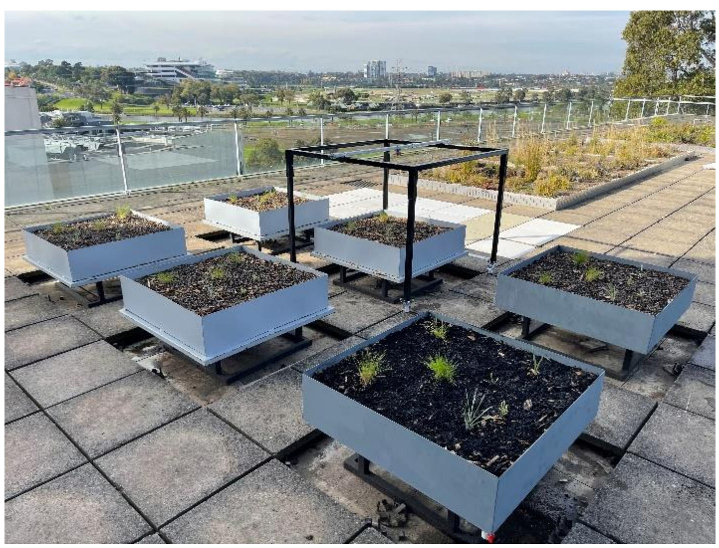


Figure 2. The six 1 m × 1 m green roof test beds on top of Building M at Victoria University, Footscray Park Campus.

The substrate of the six GR test beds was based on the initial 50 m^2 GR. The 150 mm substrate consisted of a mix of light expanded clay aggregate (LECA), hardwood mulch, and coir chips with a volumetric percentage ratio of 80:15:5, respectively. These test beds have a filter layer (non-woven geo-textile membrane) and a drainage layer (20-mm Atlantis Flo-cell and 30-mm Versidrain trays). The materials chosen in this study were not only to provide a high water retention capacity but also to avoid adding a lot of weight to the structure below. LECA is a light-weight material with a large water absorption capacity (18% by weight). Atlantis Flo-cell is a lightweight and effective drainage solution that has considerable water storage. The mini reservoirs of Versidrain that were placed on top of the Atlantis Flo-cell can store 11 L of water per square meter.

In addition to the unmodified test bed (GR-0), there are five other test beds that were amended by the biochar in different ways. An amendment rate of 7.5% *v*/*v* 1–3 mm biochar particles (hereafter referred to as medium biochar) evenly mixed with other substrate components was applied in GR-7.5M-M. In GR-7.5B-M, 7.5% *v*/*v* medium biochar particles were applied at the bottom layer of the substrate. GR-15M-M used the mixing of biochar at an amendment rate of 15% *v*/*v* medium biochar. Less than 1 mm particle biochar (hereafter called fine biochar) was applied in GR-7.5M-F and GR-7.5T-F by using mixed and top-dressing biochar application methods, respectively. The characteristics of all GR test beds are summarized in Table 1.

Table 1. Characteristics of the six green roof test beds constructed for this study.

GR Test Bed	Biochar Amendment Rate (%)	Biochar Application Method	Biochar Particle Size
GR-0	0	NA	NA
GR-7.5M-M	7.5	Mixed	Medium
GR-7.5B-M	7.5	Bottom Layer	Medium
GR-15M-M	15	Mixed	Medium
GR-7.5M-F	7.5	Mixed	Fine
GR-7.5T-F	7.5	Top Dressing with Water	Fine

Two common wallaby grasses (Rytidosperma caespitosum), two common everlasting wildflowers (Chrysocephalum apiculatum), and two Billy Buttons wildflowers (Pycnosorus globosus) were pre-grown at a nursery and moved to each test bed on the 5 May 2023. Additionally, one Lomandra longifolia Tanika and one Lomandra Lime Tuff were added per test bed on the 1 July 2023, to increase the plant coverage area prior to the experiments. The quantity and size of each type of plant were consistent across the test beds at the time they were planted. The experiments were conducted once the plants had successfully adapted to the new growing environment of the LECA-based substrate after about two months.

2.2. Biochar Selection

Biochar was procured from the supplier, Green Man Char, in Melbourne. The feedstock used for manufacturing biochar was woody materials, particularly from eucalyptus with the pyrolysis target temperature of 500–550 °C. According to the literature, 7.5% *v*/*v* is a reasonable amendment rate of biochar considering plant survival, water retention, and affordability. For example, Li, *et al.* [47] recommended a 5–7% biochar dose to avoid plant mortality and obtain a good water retention capacity. Beck, *et al.* [48] applied a 7% biochar dose to deal with the limited availability of biochar. Wang, *et al.* [49] found that the amendment rate of 5% biochar was optimal for GR substrates since it positively impacted plant growth, whereas 15% biochar acted as a root-barrier layer that prevented root expansion. However, the effects of biochar amendment rates on water retention have been a subject of controversy in previous studies [50-55]. Therefore, one test bed with a 15% biochar dose was investigated in this research to discover the advantages and disadvantages of increasing the amount of biochar.

Regarding particle sizes of biochar, small particles were found to overperform the large particles in terms of water retention due to higher porosity and specific surface area [56]. Nevertheless, very fine biochar reduced the infiltration rate and caused substrate waterlogging, which led to flooding on the surface of the GR. Fast drainage is an important hydraulic characteristic of GRs, especially during the wet seasons [57,58]. In addition, small particles are less resistant to water and wind erosion when compared with large particles [59]. Hence, granulated biochar with a medium particle size (2–2.8 mm) was recommended by Liao, *et al.* [60]. Moreover, small biochar particles were also recommended to be amended to medium to coarse textured substrates [56,58,61]. As a result, this research excluded large biochar particles and focused on studying fine to medium sized ones. Fine (up to 1 mm) and medium (1–3 mm) biochar particles (Figure 3) procured from Green Man Char were used in this study.

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

Figure 3. Biochar: (**a**) Fine particles (less than 1 mm), (**b**) Medium particles (1–3 mm).

With regard to the application methods of biochar, mixing, top layer, and middle layer are three popular treatments in numerous studies [51,54,56,62-67]. While mixing and middle-layer methods imply high labor costs, the top-layer biochar application method is exposed to strong winds and other severe weather conditions causing biochar loss over time, especially fine biochar particles [65]. Furthermore, the effectiveness of biochar is affected by the application method. For instance, bottom-layer biochar had a better performance than the top-layer biochar in terms of both runoff quantity and quality in the study of Kuoppamäki, Hagner, Lehvävirta and Setälä [67]. Therefore, for this research, it was decided to compare the mixing and bottom-layer methods. Additionally, one test bed applied fine biochar particles through top-dressing with water. The biochar manufacturer suggested using this treatment to enhance the functions of well-established GRs or to restore failed GRs. This could be attributed to the fact that small biochar particles can work their way into the GR substrates faster than larger particles do. Together with the vegetation, the top-dressing biochar test bed was left for two months before the experiments were conducted. The irrigation helped fine biochar particles to penetrate the substrate gradually. A proper comparison, thus, could be made between top-dressing and mixing methods.

2.3. Rainfall Simulation

To precisely control the experimental inputs, a rainfall simulation system was constructed. It was a pressurized system including a spray nozzle attached to a PVC pipe that was connected to a water tap. Dunkerley [46] had undertaken a comprehensive review of the validation of rainfall simulation for the runoff-related research. He explicitly highlighted the significant differences between artificial and natural rainfall. Artificial rainfall is continuous with constant and extreme intensity, whereas intensities of natural rainfall highly fluctuate with interruptions. The conventional (unpressurized) rainfall simulator depends on gravity to create water droplets, which requires a fall height of nearly 9.1 m to reach the terminal velocity of natural raindrops [68]. In contrast, the pressurized simulator uses pressure from the water mains to form droplets, which does not rely on gravity, and provides a wide range of droplet sizes [69]. Therefore, properly simulating rainfall with an unpressurized simulator is challenging as compared to a pressurized simulator [70]. Considering all factors, this study opted for a nozzle-based rainfall simulation system to assess the hydrological behaviors of the GR test beds.

The selected spray nozzle was the MPL 0.21M-B manufactured by Spray Nozzle Engineering, Melbourne. This nozzle has a full-cone spray pattern and provides large droplets, a spray angle of 77°, and a flow rate of 0.82 L/minute at a 3-bar pressure. When it is installed 600 mm above the target surface, it can have a spray coverage of roughly 1000 mm, which was appropriate for the 1 m² test beds utilized in this study. Figure 4 provides an illustration of the nozzle-based rainfall simulator above a GR test bed.

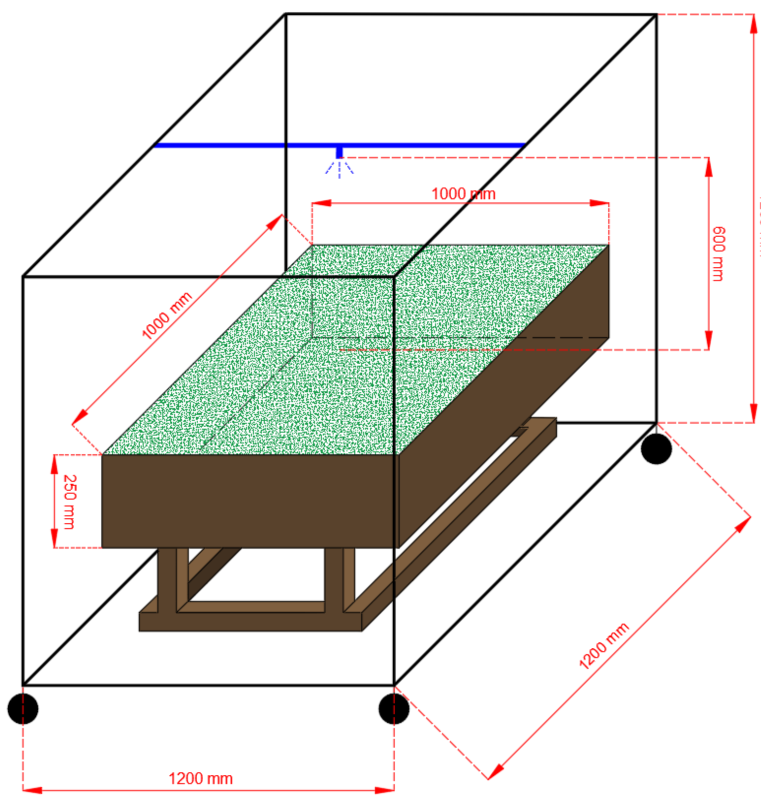


Figure 4. Illustration of the rainfall simulation system above a GR test bed.

2.4. Data Collection and Analysis

A drainage hole was placed at the bottom corner of every test bed. A plastic container positioned under the drainage hole records the runoff volume drained from the test beds. The runoff collection is continued until there is no runoff production for at least five minutes. Small rainfall events, especially those less than 5 mm in depth and hardly producing any runoff, have been observed in plenty of studies [14,24,25,33,34]. Therefore, this study focused on investigating medium, high, and extreme rainfall events. A total of nine artificial rainfall events per test bed were simulated. For a catchment area of 1 m^2, the rainfall depth in millimeters (mm) is equal to the water volume in liters (L). The nozzle was attached to a PVC pipe that was connected to the water mains through a 5 m hose. Since the pressure of the tap water was identified as roughly 4.5 bar, a pressure reducer was employed to bring it down to 3 bar. Medium to extreme rainfall events were simulated by altering the simulation duration. Considering the intermittent characteristic of natural rainfall, gaps of 2 min were introduced after every 5 min of simulation. A similar method was applied in the study of Holko, *et al.* [71]. Together with the simulation gaps, the selection of MPL 0.21M-B with a low flow rate was an attempt to generate more realistic rainfall intensities. Numerous papers were identified for unrealistically reproducing rainfall intensities exceeding those of extreme events [46,72].

To ensure an accurate comparison between the test beds, each experimental event was conducted on the same day. A soil moisture meter was also used to understand the impacts of soil moisture on rainfall retention before every event (hereafter called initial soil moisture). Soil moisture was measured at several locations of a test bed and at the same depth. The antecedent dry weather period (ADWP), which is another important parameter determining the water retention capacity, was also recorded. The first experiment was carried out on 31 July 2023, when the vegetation was three months old. Table 2 presents information about the characteristics of the nine simulated rainfall events. Medium, high, and extreme rainfall events were represented by simulation durations of 10, 15, and 20 min, respectively, with 2 min gaps every five minutes. With the exception of Medium A and Medium B events that were conducted on the same day to examine the response of GRs to two consecutive rainfall events, all other events were conducted on different days within the one month study period.

The amount of water retained by the GR test beds was calculated by subtracting the volume of runoff from the volume of rainfall. The runoff outflow delay, which was recorded in seconds, was the amount of time from the beginning of a simulation until a test bed started producing runoff. This parameter helps to understand the capability of GR in delaying runoff and reducing stress on the drainage system. The observational data were analyzed using line and bar graphs as well as box plots. By employing these statistical methods, the hydrological performance of all GR test beds was thoroughly assessed and compared. Moreover, the relationship between rainfall depth and retention rate was also described. The conclusions regarding the impacts of biochar on GRs and the optimal biochar-GR design were derived from high runoff retention rates and long runoff outflow delays. Furthermore, other factors such as low infiltration rates leading to substrate waterlogging and biochar loss were also considered.

Table 2. Characteristics of the nine artificial rainfall events.

Event	Date (Time)	Simulation Runtime (min)	Estimated Rainfall Depth (mm)	Antecedent Dry Weather Period (Days)	Previous Rainfall Depth (mm)
Medium A	31/07/2023 (9 a.m.)	10	8.2	0	3
Medium B	31/07/2023 (2 p.m.)	10	8.2	0	8.2

Medium C	10/8/2023 (8 a.m.)	10	8.2	0	Light rain until 7AM *
High A	3/8/2023 (8 a.m.)	15	12.3	2	8.2
High B	4/8/2023 (10 a.m.)	15	12.3	0	12.3
High C	14/8/2023 (11 a.m.)	15	12.3	0	3.4
Extreme A	7/8/2023 (10 a.m.)	20	16.4	2	12.3
Extreme B	11/8/2023 (9 a.m.)	20	16.4	0	8.2
Extreme C	21/8/2023 (9 a.m.)	20	16.4	2	5.4

Note: * No recorded rainfall data.

3. Results

Table 3 presents data on various hydrological parameters, such as initial soil moisture, rainfall volume, runoff retention, and runoff outflow delay, for the six GR test beds during medium, high, and extreme rainfall events.

Table 3. Hydrological performance of the six green roof test beds under nine artificial rainfall events.

Event	Test Bed	Initial Soil Moisture (1 to 10)	Estimated Rainfall Volume (L)	Runoff Volume (L)	Runoff Retention (%)	Runoff Outflow Delay (s)
Medium A 31/07/2023 (9 a.m.)	GR-0	3 ± 1	8.2	4.8	41.46%	470
	GR-7.5M-M	5 ± 1	8.2	3.85	53.05%	620
	GR-7.5B-M	5 ± 1	8.2	3.3	59.76%	930
	GR-15M-M	8 ± 1	8.2	3.4	58.54%	570
	GR-7.5M-F	10 ± 2	8.2	2.7	67.07%	1200
	GR-7.5T-F	10 ± 2	8.2	4.5	45.12%	740
Medium B 31/07/2023 (2 p.m.)	GR-0	5 ± 2	8.2	6.7	18.29%	340
	GR-7.5M-M	7 ± 2	8.2	6.4	21.95%	420
	GR-7.5B-M	7 ± 2	8.2	3.9	52.44%	720
	GR-15M-M	10 ± 2	8.2	5.9	28.05%	350
	GR-7.5M-F	15 ± 3	8.2	6.2	24.39%	570
	GR-7.5T-F	12 ± 3	8.2	5.2	36.59%	590
Medium C 10/8/2023 (8 a.m.)	GR-0	5 ± 1	8.2	5.2	36.59%	405
	GR-7.5M-M	5 ± 1	8.2	4.4	46.34%	570
	GR-7.5B-M	5 ± 1	8.2	4	51.22%	720
	GR-15M-M	7 ± 2	8.2	4.8	41.46%	390
	GR-7.5M-F	10 ± 1	8.2	2.6	68.29%	1260
	GR-7.5T-F	8 ± 2	8.2	2.8	65.85%	1020
High A 3/8/2023 (8 a.m.)	GR-0	2 ± 1	12.3	7.5	39.02%	630
	GR-7.5M-M	3 ± 1	12.3	7.35	40.24%	750
	GR-7.5B-M	5 ± 1	12.3	5.5	55.28%	1050
	GR-15M-M	5 ± 2	12.3	5.75	53.25%	850
	GR-7.5M-F	8 ± 2	12.3	4.8	60.98%	1335
	GR-7.5T-F	8 ± 2	12.3	4.4	64.23%	1200
High B 4/8/2023 (10 a.m.)	GR-0	2 ± 1	12.3	6	51.22%	660
	GR-7.5M-M	5 ± 1	12.3	7.8	36.59%	690
	GR-7.5B-M	5 ± 1	12.3	6.2	49.59%	940
	GR-15M-M	7 ± 2	12.3	5.5	55.28%	750
	GR-7.5M-F	9 ± 2	12.3	6.5	47.15%	1200
	GR-7.5T-F	8 ± 2	12.3	6.2	49.59%	1110
High C 14/8/2023 (11 a.m.)	GR-0	4 ± 1	12.3	8.1	34.15%	525
	GR-7.5M-M	8 ± 1	12.3	7.9	35.77%	660
	GR-7.5B-M	4 ± 1	12.3	6.2	49.59%	900
	GR-15M-M	8 ± 1	12.3	7.5	39.02%	645
	GR-7.5M-F	7 ± 1	12.3	4.5	63.41%	1185
	GR-7.5T-F	5 ± 1	12.3	4	67.48%	1125

Extreme A 7/8/2023 (10 a.m.)	GR-0	1 ± 1	16.4	11.7	28.66%	570
	GR-7.5M-M	1 ± 1	16.4	11.2	31.71%	690
	GR-7.5B-M	4 ± 2	16.4	10	39.02%	900
	GR-15M-M	5 ± 2	16.4	11.5	29.88%	540
	GR-7.5M-F	8 ± 2	16.4	8.8	46.34%	1320
	GR-7.5T-F	7 ± 2	16.4	8.6	47.56%	1140
Extreme B 11/8/2023 (9 a.m.)	GR-0	3 ± 1	16.4	12.1	26.22%	555
	GR-7.5M-M	4 ± 1	16.4	11.6	29.27%	510
	GR-7.5B-M	4 ± 1	16.4	10.5	35.98%	885
	GR-15M-M	8 ± 2	16.4	11.9	27.44%	420
	GR-7.5M-F	8 ± 2	16.4	9	45.12%	1230
	GR-7.5T-F	7 ± 2	16.4	8.2	50.00%	1060
Extreme C 21/8/2023 (9 a.m.)	GR-0	5 ± 1	16.4	10.7	34.76%	750
	GR-7.5M-M	4 ± 1	16.4	10.5	35.98%	810
	GR-7.5B-M	5 ± 1	16.4	9.7	40.85%	990
	GR-15M-M	6 ± 2	16.4	9.9	39.63%	840
	GR-7.5M-F	7 ± 2	16.4	8.3	49.39%	1320
	GR-7.5T-F	5 ± 1	16.4	7.9	51.83%	1410

3.1. Runoff Retention

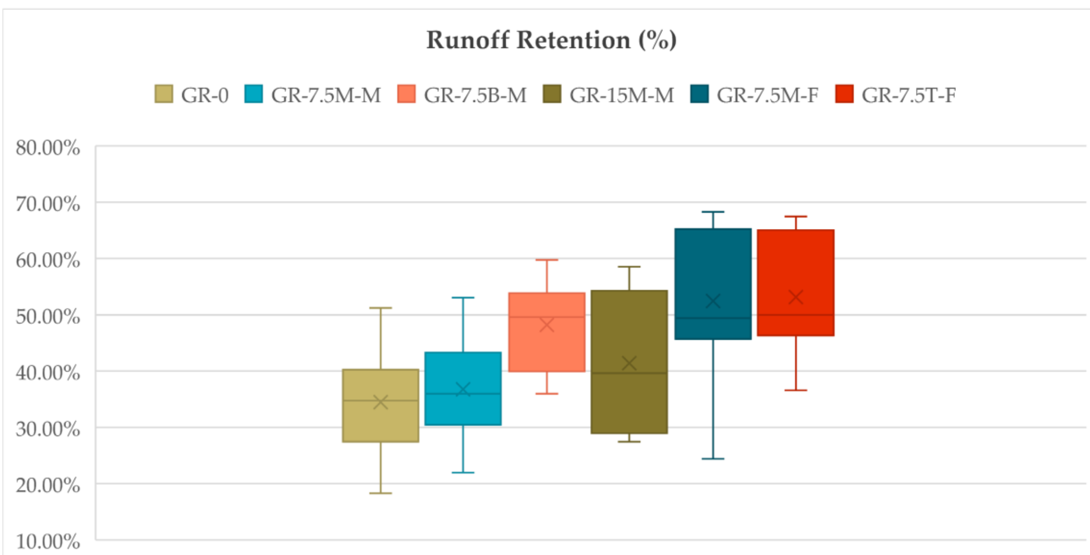


Figure 5. Runoff retention performance of the six green roof test beds for the nine artificial rainfall events.

The hydrological responses of the six GR test beds in terms of runoff retention during the monitoring period are shown in Figure 5. The box plot provides a summary of the overall performance of each GR test bed in terms of retention rates, considering the maximum, minimum, mean, and median values after nine simulated events. As expected, the application of biochar enhanced the water retention rates of GRs. While a moderate improvement was observed in GR-7.5M-M and GR-15M-M, runoff volume was significantly alleviated by GR-7.5B-M, GR-7.5M-F, and GR-7.5T-F. The maximum retention rate of 68.29% was reached by GR-7.5M-F in the Medium C event. In contrast, GR-0 had the poorest retention rate of only 18.29% in the Medium B event. With the same application method of mixing and medium biochar particles, the higher amendment rate of biochar in GR-15M-M slightly improved the water retention as compared to GR-7.5M-M in most events. However, 7.5% *v*/*v* biochar at the bottom layer of the GR7.5B-M substrate outperformed 15% *v*/*v* biochar mixed in the GR-15M-M substrate. For the entire study period, the highest retention capacity was achieved by fine biochar particles of GR-7.5M-F and GR-7.5T-F with the average of 52–53%. In general, the differences in rainfall retention between the six GR test beds were identical under different rainfall depths. The only exception was found in the High B event when GR-0 and GR-15M-M had the best retention performance.

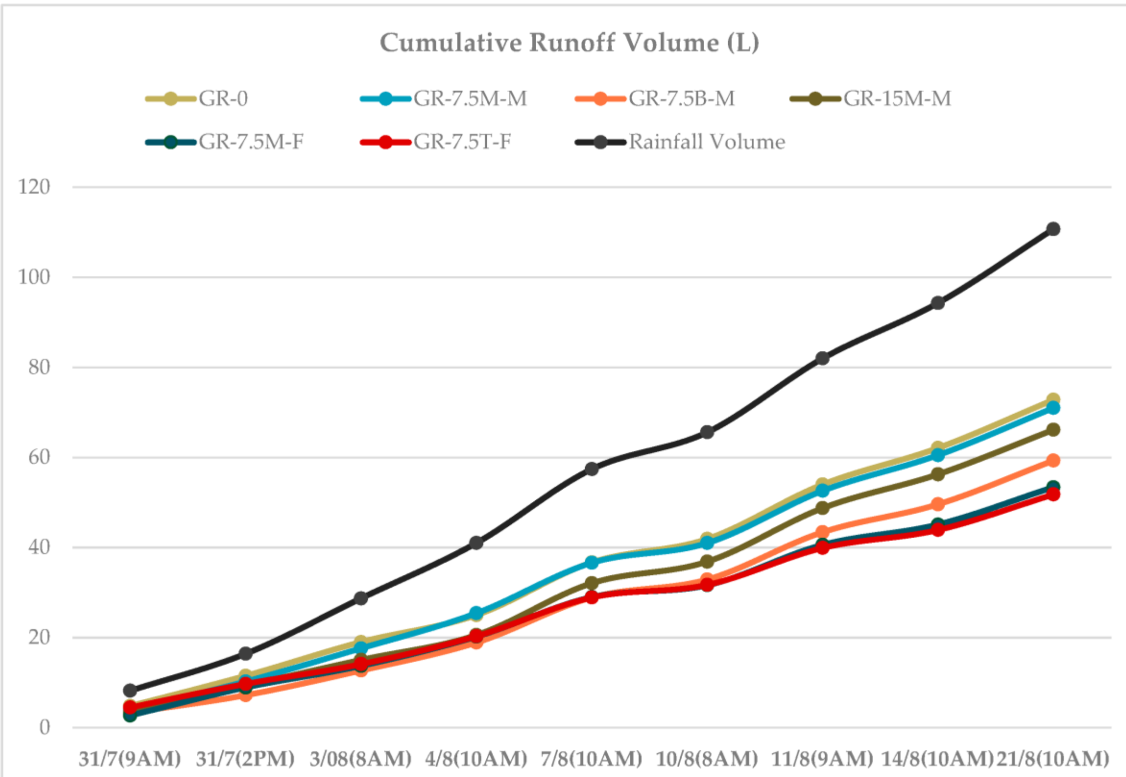


Figure 6. Cumulative runoff volume of the six green roof test beds after nine artificial rainfall events.

Figure 6 further elucidates the overall retention performance of the six test beds. The graph illustrates the cumulative rainfall volume and the comparison of runoff volume from different GR test beds under the nine artificial rainfall events. From 31 July 2023 to 21 August 2023, a total of 110.7 L of artificial rainfall was generated per test bed. The lowest and highest cumulative runoff reductions of 34.24% and 53.21% were recorded in GR-0 and GR-7.5T-F, respectively. The retention rates in this study are lower than those previously reported by other researchers. For instance, *Todorov, Driscoll and Todorova [33]* obtained an average retention of 95.9 ± 3.6% ranging from 75% to 99.6%. Furthermore, average retention rates of 68% (16.7% to 100%), 78% (17% to 100%), 66% (3.6% to 100%), and 70% (0% to 100%) were reported in [14,17,18,23], respectively. This could be attributed to the unrealistic rainfall intensity generated by a pressurized simulator and the omission of low rainfall-depth events in the present study. For example, GRs in the study of *Jahanfar, et al. [73]* achieved a retention rate of at least 90% from events with less than 10 mm in depth. Additionally, the average amount of retained rainwater in [6,24,25,34] was significantly high, primarily due to the inclusion of numerous small intensity events producing zero runoff.

3.2. Runoff Outflow Delay

Across the nine different events, the performance of the six GR test beds in delaying runoff outflow remained consistent. Figure 7 shows the amount of time in seconds before a test bed starts producing runoff in a rainfall event. The graph illustrates which GR test bed exhibited a tendency for longer runoff outflow delays during different medium, high, and extreme rainfall events. In most events, runoff was delayed the most by fine biochar particles of GR-7.5M-F and GR-7.5T-F with an average of 1200 s. They only observed a substantial drop to about 600 s during the Medium B event. The exceptional delays of fine biochar particles of GR-7.5M-F and GR-7.5T-F could raise concerns about the infiltration reduction. GR-0 quickly started releasing runoff after 300 to 750 s, which was the shortest outflow delay. The 7.5% *v*/*v* amendment rate of medium biochar particles in GR-7.5M-M slightly improved the runoff outflow delay. The increase in the amount of medium biochar particles to 15% *v*/*v* in GR-15M-M did not result in a noticeable difference. However, GR-7.5M-M tended to have a slightly longer delay than GR-15M-M. In contrast, moving 7.5% *v*/*v* medium biochar particles to the bottom of the GR-7.5B-M substrate resulted in a remarkable enhancement. GR-7.5B-M was able to delay runoff by 700 to 1100 s and it performed consistently in all events.

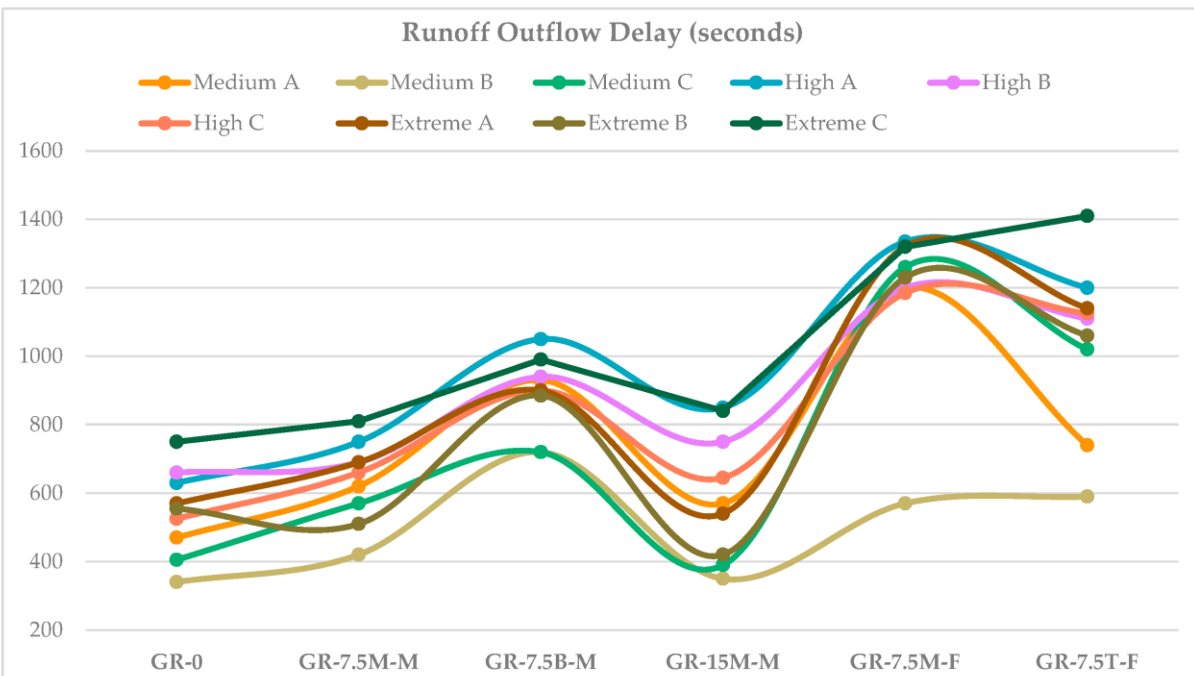


Figure 7. Runoff outflow delays for the six green roof test beds during the nine artificial rainfall events.

4. Discussion

4.1. Biochar Variables: Application Method, Amendment Rate, and Particle Size

In accordance with the previous findings [50-52], the higher amount of biochar led to a higher water retention capacity of GRs. Though D'Ambrosio, Mobilia, Khamidullin, Longobardi and Elizaryev [51] used a modeling software to investigate the 15 cm depth biochar-amended GRs, comparable results were observed regarding the enhanced retention capacity associated with a higher quantity of biochar. A higher retention capacity by increasing biochar application rate was also observed in the study of Valagussa, Gatt, Tosca and Martinetti [52], wherein they tested 15 cm depth GR substrates with two different biochar types. In the present study, GR-15M-M (15% biochar *v*/*v*) retained 4.63% (on average) more rainwater than GR-7.5M-M (7.5% biochar *v*/*v*). Regarding the runoff outflow delay, the performance of GR-15M-M was lower than that of GR-7.5M-M. However, the difference was negligible. It could be concluded in this study that the hydrological performance marginally improved by increasing the quantity of biochar from 7.5% to 15%. Hence, it is strongly recommended to consider the addition of 5–7.5% *v*/*v* biochar in future projects, addressing the constraints posed by the limited availability and high manufacturing cost of biochar [47,48,58,74]. On the other hand, a contradictory finding was also reported in the study by Goldschmidt [53]. The increase in the biochar application rate from 2.5% to 10% did not result in an increase in the retention capacity of 60 cm × 29 cm biochar-GR plots. Therefore, a preliminary assessment of a biochar-GR system is necessary before considering its widespread application.

The significance of the biochar application method was emphasized in this research. Taking both the retention rate and the outflow delay into account, the performance of the bottom biochar GR test bed (GR-7.5B-M) was consistently outstanding. As compared to GR-7.5M-M ,and even GR-15M-M, GR-7.5B-M retained 11.42% and 6.79% (on average) more rainwater and had 257 s and 298 s (on average) longer outflow delays, respectively. With a similar biochar particle size (medium), the bottom-layer biochar prevailed over the mixed biochar in this study. The bottom-layer biochar also outperformed the top-layer biochar in the study of Kuoppamäki, Hagner, Lehvävirta and Setälä [67]. In their study, GR test plots with a dimension of 0.4 m × 0.5 m and two different types of plants (Sedum and meadow) had higher water retention rates when biochar was applied at the bottom layer of the GR substrate. However, further research is required to gain an in-depth knowledge about the bottom-layer-biochar method, by investigating different biochar particle sizes and amendment rates. Additionally, the performance of fine biochar particles was relatively similar when they were either thoroughly mixed in the GR-7.5M-F substrate or mixed with water and then applied on the substrate surface of GR-7.5T-F. Under the impact of rainfall/irrigation, fine biochar particles on the substrate surface tended to quicky move downward into the substrate mix within only two months after the application. These two GRs also performed exceptionally better than other GRs in this research. Top-layer biochar was also suggested to be applied in [65], due to lower labor costs associated with the mixing methods. They also recommended replacing unprocessed biochar with processed biochar applied on the GR substrate surface to mitigate biochar loss. Future research attempts are encouraged, since only a limited number of studies on methods of applying biochar were found in the literature.

Regarding biochar particle sizes, two of the studied test beds featuring fine biochar particles outperformed others in terms of both water retention and runoff outflow delay. This result was in line with previous findings. For example, Werdin, Conn, Fletcher, Rayner, Williams and Farrell [58] used soil columns to study two types of biochar with three biochar particle sizes (less than 2 mm, 2–10 mm, and mix) and four amendment rates (10, 20, 30, and 40% *v*/*v*) and concluded that fine particles (<2 mm) had the highest water retention. Liao, Drake and Thomas [60] investigated different sizes of processed and unprocessed biochar by mixing them (4.5% *w*/*w*) into 8 cm depth substrates of 71 cm^2 GR test plots. They found that the smaller, unprocessed biochar particles led to higher water retention rates. Nevertheless, the trend was not consistent in the case of the processed biochar. The notable improvement in retention performance observed with fine biochar particles compared to large particles may be attributed to increases in porosity and specific surface area [56]. However, concerns arising from fine biochar particles are substrate waterlogging during high-intensity events and consequent potential for biochar loss. Fine particles diminish the filtration rate and the air-filled porosity (AFP), leading to waterlogging [58]. The slow water releasing of fine biochar particles caused the greatest decline in the retention rate of GR-7.5M-F from 67.07% in the Medium A event to 24.39% in the Medium B event. The fast drainage of an EGR plays a major role in avoiding waterlogging, adversely influencing plant health [57,75]. Wang, Garg, Zhang, Xiao and Mei [57] recommended the use of coconut-shell fiber in conjunction with biochar to reduce the air-entry value for effective stormwater management. As compared to fine particles, larger particles are more resistant to biochar loss caused by wind and water [59]. Medium to large biochar particles or heavy biochar (processed biochar) were suggested to be used to limit the biochar loss [60,65,76].

Based on the observational data in this research, medium biochar particles applied at the bottom of the GR-7.5B-M substrate are highly recommended as an optimal biochar-amended GR system. GR-7.5B-M was able to have a higher retention and a longer outflow delay than 7.5% and 15% *v*/*v* medium biochar particles thoroughly mixed into the substrates of GR-7.5M-M and GR-15M-M. While the hydrological performance of GR-7.5B-M was not the most optimal, it still exhibited remarkable retention of rainfall, acceptable delay in runoff outflow, and facilitated fast drainage to prevent waterlogging. Although the drainage speed of GR-7.5M-F was slow, GR-7.5B-M proved to be more advantageous in quickly replenishing the water storage for upcoming events during the wet seasons. Using medium particle sizes of biochar at the bottom of the GR substrates also helped to minimize the biochar loss to the environment. On the other hand, in projects restoring/improving the functions of failed/well-established GRs when other application methods are inappropriate, the application of fine biochar particles through the top-dressing method is an efficient solution. Noteworthy results regarding the comparison between processed and unprocessed biochar have been documented, providing motivation for future research endeavors. Further simultaneous investigations into the different forms of processed biochar, amendment rates, particle sizes, and application methods are necessary to identify the optimal biochar-amended GR design. Moreover, several biochar benefits should all be considered in a study to find the best strategy to address stormwater management as well as other global concerns.

4.2. The Influences of Rainfall Depth, Climate Conditions, and Other Factors

A strong relationship between rainfall depth and the retention capacity of GRs was detected in this study. The impact of rainfall depth was more pronounced when comparing medium/high events with extreme events. The bar charts presented in Figure 8 illustrate the different retention performance of GRs under medium, high, and extreme rainfall events. Although the differences between medium and high events were negligible, the retention rates of the GR test beds in extreme events were significantly lower. When a GR substrate reaches a saturation point during a heavy event, it cannot absorb more water, and then all remaining rainwater becomes runoff. This finding is in agreement with other published results. For example, the retention rate of only 11.9% in the study of Wong and Jim [19] was due to heavy rainfall events with more than 300 mm in depth. The notably low cumulative rainfall retention values in [14,23,30], that were lower than the average reported by others, were indicated by significant cumulative rainfall depths of 1256.3 mm (1 year), 1892.2 mm (27 months), and 481 mm (5 months), respectively.

water

MDPI

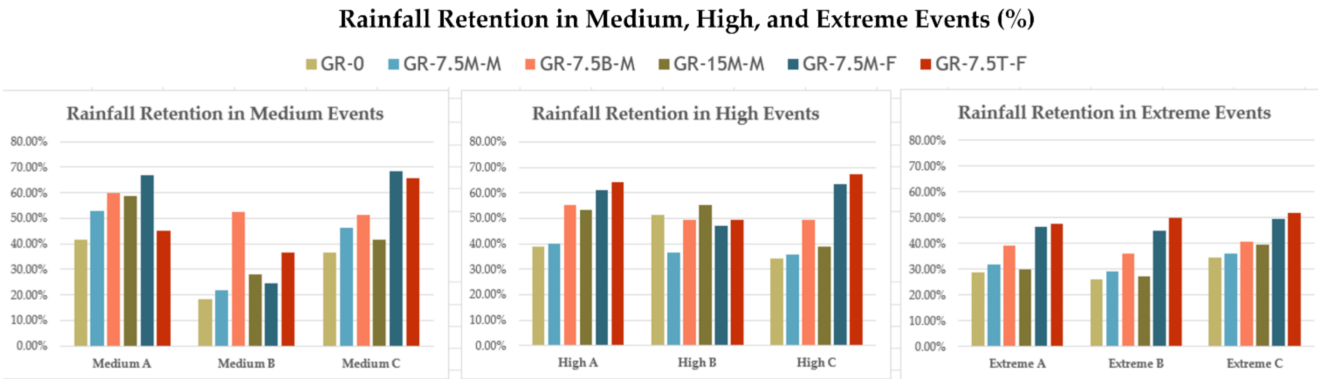


Figure 8. Runoff retention rates of the six green roof test beds under medium, high, and extreme rainfall events.

The influence of the initial soil moisture of the GR substrates on the water retention of GRs has been thoroughly documented [17,29,31]. ADWP has also been considered as a crucial parameter affecting the retention capacity. For instance, the Medium B event was simulated only 5 h after the 8.2 mm Medium A event; hence, the difference in the initial soil moisture of all test beds between these two events was easily recognizable. A substantial reduction in rainfall retention was recorded in all test beds in the Medium B event. Moreover, all test beds in the Extreme C event, having an ADWP of 2 days, performed better than they did in the Extreme B, with zero ADWP in relation to rainfall retention. However, a consistent trend was not observed in other events. With a lower initial soil moisture or longer ADWP, the GRs did not achieve a higher retention or a longer delay in all experiments. Therefore, other parameters such as the available water storage of the drainage layers are likely to play a major role. However, firm conclusions regarding these influential parameters could not be drawn due to insufficient data. A longer monitoring period and a more precise data collection of the initial soil moisture content and ADWP are required to completely understand their impacts.

Most studies examined the effectiveness of biochar by testing small GR test beds, GR modules, and soil columns. Though the establishment of a large experimental site requires intensive effort and investment, future projects are recommended to identify the benefits of biochar-amendment in large-scale GRs.

5. Conclusions

Green roofs (GRs) are widely recognized as one of the optimistic green infrastructures that aim to address various global concerns, including urban flash flooding, water quality degradation, urban heat island effects, energy crises, and air pollution. Though GRs have been studied for decades, more efforts are still required to improve their ecosystem services. One of the innovative strategies is the addition of biochar, a carbon-rich material, to GR substrates to simultaneously enhance several GR benefits. This paper aimed to investigate the impacts of biochar on the hydrological performance of six newly established GR test beds, which included five biochar-amended test beds and one conventional test bed. The study focused on the water retention capacity and the runoff outflow delay of the six GR test beds by using a nozzle-based rainfall simulator. The GR test beds were amended by biochar with different characteristics including particle sizes, application methods, and amendment rates.

The findings and recommendations from this study are summarized below:

(i) Green Roofs (GRs) amended with biochar outperformed conventional GRs in terms of rainfall retention and runoff outflow delays.
(j) This study recommends biochar amendment rate of up to 7.5% *v*/*v*, as an increased biochar amount to 15% *v*/*v* did not lead to a noticeable improvement. The 7.5% *v*/*v* dose is reasonable considering the hydrological performance, biochar costs, and currently limited availability of biochar.
(k) This study suggests the application of bottom-layer biochar as the optimal method due to high water retention, long outflow delay, fast drainage, and less biochar loss.
(l) Applying biochar with water on the surface of GR substrates is the most appropriate method in cases of failed/well-established GRs, where other methods are impractical.
(m) Medium biochar particles are encouraged to be used in future GR systems. While fine particles cause substrate waterlogging and biochar loss to the environment, large particles reduce the rainfall retention rate and runoff outflow delay.
(n) More research is required to properly understand the impacts of initial soil moisture content, antecedent dry weather period (ADWP), and other parameters on the hydrological performance of GRs.
(o) Further investigations are recommended to simultaneously study different biochar variables such as particle sizes and application methods to find out the optimal biochar-amended GR design.

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

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4.2. A field study to assess the impacts of biochar amendment on runoff quality from newly established green roofs.

4.2.1. Introduction

Building upon the findings of the preceding study on runoff quantity, this research investigated the impact of biochar on green roof runoff quality using the same experimental setup. While previous research, including this chapter's initial findings, has demonstrated biochar's efficacy in enhancing runoff retention, its impact on runoff quality remains inconsistent due to factors such as substrate composition, biochar characteristics, and their interactions. Runoff samples were collected from the six biochar-amended green roof test beds for water quality analysis. Parameters assessed included pH, electrical conductivity (EC), total nitrogen (TN), and total phosphorus (TP), which are commonly employed as indicators of urban stormwater quality in Australia. Research methodologies for runoff sampling and water quality analysis aligned with established protocols to ensure data reliability and validity. Runoff samples were collected six times between October and December 2024. To facilitate accurate comparisons, all test beds were exposed to identical experimental conditions, including water source and weather conditions. Experiments were conducted during periods of favorable weather, characterized by dry conditions and minimal wind. Two-month observational data revealed limited positive impacts of biochar on water quality parameters. Specifically, a slight improvement in runoff pH was observed, with effects diminishing over time. A reduction in TN was observed only in test beds with medium biochar particles located at the bottom of green roof substrates. No obvious effects of biochar on other parameters were detected. Despite these mixed results, biochar amendment offers potential benefits for improving green roof runoff quality. The significant reduction in runoff volume achieved through biochar incorporation corresponds to lower pollutant loads compared to non-biochar green roofs. This finding is supported by the current study's runoff volume data and aligns with previous research.

This chapter contains the following journal paper:

- 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. https://doi.org/10.3390/hydrology11080112.

4.2.2. Declaration of co-authorship and co-contribution: papers incorporated in thesis by publication

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DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

Title of Paper/Journal/Book: A Field Study to Assess the Impacts of Biochar Amendment on Runoff Quality from Newly Established Green Roofs

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2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

[redacted] 15/08/2024

Signature **Date**

3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

The undersigned certify that:

1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
2. They take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;

3. There are no other authors of the publication according to these criteria;

4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

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Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Cuong Ngoc Nguyen	80	Conceptual ideas, research, data analysis, experiments, writing.	[redacted]	15/08/2024
Hing-Wah Chau	5	Feedback and discussion on research and writing	[redacted]	21/08/2024
Nitin Muttil	15	Critical comments and discussion on conceptual ideas & research methodologies	[redacted]	22/08/2024

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4.2.3. A field study to assess the impacts of biochar amendment on runoff quality from newly established green roofs

Article

A Field Study to Assess the Impacts of Biochar Amendment on Runoff Quality from Newly Established Green Roofs

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Abstract: Green roofs (GRs) are a widely recognized green infrastructure (GI) strategy that helps reduce runoff volume and runoff pollution caused by the significant increase in impervious urban areas. However, the leaching of several nutrients from GR substrates is a growing concern. Biochar, a carbon-rich material, possesses advantageous properties that can help address such environmental challenges associated with GRs. Therefore, this paper aimed to undertake a field study to investigate the impacts of various biochar application methods, particle sizes, and amendment rates on the quality of runoff from GRs. Observational data of runoff quality were collected over a two-month period from five newly established 1 m × 1 m biochar-amended GR test beds and a control test bed without biochar, with all test beds subjected to artificially simulated rainfall. The results indicated that the addition of biochar did not result in a significant improvement in runoff pH, whereas the electrical conductivity (EC) was higher in runoff from GRs with biochar-amended substrates. When comparing the total nitrogen (TN) concentration in runoff from the non-biochar GR (ranging from 3.7 to 31 mg/L), all biochar test beds exhibited higher TN release (4.8 to 58 mg/L), except for the bed where medium biochar particles were applied at the bottom of the substrate (ranging from 2.2 to 21 mg/L). Additionally, all biochar-amended GRs exhibited higher TP concentrations in runoff (0.81 to 2.41 mg/L) when compared to the control GR (0.35 to 0.67 mg/L). Among the different biochar setups, GR with fine biochar particles applied to the surface of the substrate had the poorest performance in improving runoff water quality. Despite these mixed results, biochar holds significant potential to improve runoff quality by significantly increasing water retention, thereby reducing pollutant loads.

Keywords: green roofs; biochar; green infrastructure; runoff quality; stormwater; runoff retention

1. Introduction

Due to rapid urbanization, the significant increase in impervious surfaces in urban areas not only exacerbates the volume of stormwater runoff but also negatively affects runoff quality [1]. Green roofs (GR) have been recently introduced as an innovative green infrastructure (GI) to reduce runoff volume and mitigate water pollution. However, the leaching of several nutrients from GR substrates is an increasing global concern. Though nutrients are essential for plant development, rainwater or irrigation activities can release them into GR runoff, thereby degrading the water environment. Nevertheless, an agreement regarding the environmental effects of GRs has not been reached, since they significantly vary according to the characteristics of GR substrates [2]. For example, while the GRs in [3] acted as a sink for all examined heavy metal ions in all artificial rainfall events, Beecham and Razzaghmanesh [4] found that a GR was the source of all pollutants. Loads of total phosphorus (TP) and total nitrogen (TN) were lessened by GRs in the study of [5]; however, GR modules in [6] failed to absorb TP, TN, and other pollutants. Runoff quality from GRs is strongly influenced by substrate composition (organic content), substrate depth, GR age, maintenance frequency, and fertilizing methods [7,8]. Runoff from GRs with higher organic content is believed to have higher pollutant concentrations [4]. Zhang, et al. [9] concluded that a nitrogen-rich substrate could result in a high concentration of TN in GR discharge. On the contrary, Gregoire and Clausen [10] observed low concentrations of TP and TN due to the application of a slow-release fertilizer, expanded shale, and biosolids media that had a high sorption rate of pollutants. Additionally, loads of TP and TN from GR runoff were minimal in the study by Gong, Yin, Li, Zhang, Wang, Fang, Shi, and Wang [5] because of the used substrate not containing nitrogen and phosphorus fertilizers. The performance of GRs in terms of runoff quality can be more difficult to deter-mine when the age of GRs, types of GRs, plant performance, temperature of substrates, and other factors are taken into consideration [4,11–14].

Biochar, a carbon-enriched material, is manufactured through "pyrolysis", which is the burning process of biomass in an oxygen-deficient environment [15]. The commonly used feedstocks for producing biochar are organic wastes including wood chips, wood pellets, tree bark, crop residues, and municipal solid wastes [16,17]. As previously dis-cussed, GR substrates play a major role in their serviceability. Biochar, a substrate additive, has numerous advantageous properties to enhance different benefits of GRs, including runoff reduction and runoff quality improvement. The physiochemical characteristics of biochar, such as high porosity, large specific surface area, functional groups, and cation exchange capacity, significantly contribute to its benefits [17]. More particularly, the addition of biochar to GR substrates increases the cation and anion exchange capacities, thereby reducing the leaching of ionic nutrient compounds such as nitrogen due to functional groups on the biochar surface [18]. Biochar, which contains ash residue, is also favorable for use in acidic soils by altering soil pH [19]. An increase in soil pH alleviates the amount of soluble plant-essential nutrients and chemicals that are essential for the development of plants and microbial communities [20,21]. The enhanced runoff quality is also a result of the decrease in runoff volume. The highly porous structure of biochar holds a considerable amount of rainwater [22]. The high water retention capacity limits the availability of GR runoff for nutrient leaching [23]. Different approaches have been taken to investigate this capability of biochar, and positive results were reported in previous studies. For example, Kuoppamäki, et al. [24] found positive impacts of biochar on GR runoff volume when biochar was either applied at the substrate bottom or on the substrate surface. Runoff retention rates from field experiments were shown to increase by up to 10% due to the addition of biochar in the summer. Another finding from D'Ambrosio et al. [25] was observed by applying a hydrological simulation model called "CHEMFLO-2000", which also supported the benefits of biochar in GRs. GRs with biochar added to substrates of expanded clay and loam were compared with GRs without biochar. The modelling results indicated that 3 cm and 5 cm depths of biochar enhanced GR runoff retention from 55.05–65.29% to 66.9 and 69.15%, respectively. A soil test column was used in the study of Huang et al. [26]. Similarly, a considerable improvement in runoff retention in bio-char-amended substrates from 45.5% to 69.3% was observed. Furthermore, biochar indirectly improves runoff quality by enhancing plant performance followed by increased plant uptake of water and nutrients [2,27].

The performance of GR in terms of runoff quality has been inconsistently reported in the literature [28]. Similarly, different concentrations and loads of pollutants were also observed in runoff from biochar-amended GRs. The characteristics of biochar, depending on feedstocks and pyrolysis conditions, affect the efficiency of biochar in capturing pollutants [29]. For example, GRs with biochar either as the top substrate layer or as the bottom substrate layer [24] had lower loads of TP and TN in GR discharge as compared to non-biochar GRs. A similar finding was found in studies by [30,31]. Loads of TP and heavy metals such as potassium (K+), calcium (Ca2+), iron (Fe), zinc (Zn), and Mg (Magnesium) were lessened after the application of biochar in the studies of [27,32]. Oppositely, loads of TP in runoff from biochar-amended GRs were higher than that from non-biochar GRs in experiments carried out by [1,32,33]. In line with the loads of pollutants, concentrations of pollutants in runoff from GRs modified with biochar were mostly lower than those from conventional GRs. The biochar in [34] improved the retention of TP and TN, thereby reducing the concentrations of TP and TN in GR discharge. Wood biochar and olive husk biochar in [35] were both able to significantly adsorb different heavy metals, including Cd (Cadmium), Cu (Copper), Cr (Chromium), Ni (Nickel), Pb (Lead), and Zn. However, opposite findings were observed in some studies. Event mean concentrations (EMC) of TP were from 0.05 to 1.47 mg/L and from 0.18 to 2.09 mg/L in runoff from non-biochar and biochar-amended GRs, respectively. Additionally, concentrations of TN, chemical oxygen demand (COD), and biochemical oxygen demand (BOD) were reported as increased after the application of biochar in the study of Petreje et al. [36].

The primary aim of this research was to investigate how runoff quality from a GR was impacted by (1) amending GR substrates with biochar, and (2) different biochar-GR setups (with varying biochar-related variables). The work presented in this study is a continuation of previous work by Nguyen et al. [37], wherein the water retention capacity and runoff outflow delay of biochar-amended GRs were studied. In this study undertaken at the same experimental site, the authors examined GR runoff quality to further understand the effectiveness of biochar in GRs. Most previous studies only focused on investigating the influence of biochar amendment rates and particle size [27,33,38–41]. Research investigating various biochar-GR setups has not been undertaken previously and hence this research aimed to study all existing biochar variables to find an optimal biochar–GR system in terms of improving runoff quality. To achieve this, the observational data of runoff quality from six 1 m2 GR test beds were analyzed using a pressurized nozzle-based rain-fall simulator. More specifically, there were five biochar-amended test beds that were different from each other in application methods, particle sizes, and amendment rates of biochar. One test bed without biochar was used as the control test bed. During the observational period, the differences in plant conditions of each test bed were minimal, thereby restricting the influence of vegetation on the research outcomes. While there are a significant number of important water quality indicators, the measured water quality parameters in this research were narrowed down to the following parameters: pH, EC, TP, and TN. TP and TN are important parameters to evaluate the quality of water bodies and they are used as primary criteria in urban stormwater guidelines and standards across Australia [42,43]. pH was also measured to understand the GR's benefit in neutralizing acid rain, whereas EC provides general information about the leaching of pollutants into runoff in the form of nutrient ions. In the present study, tap water was used in the rainfall simulator. Given that the chemical properties of tap water affect the results of GR runoff quality, this study attempted to evaluate the capabilities of different GR test beds in mitigating the release of nutrients from GR substrates. The performance of various GR test beds in retaining nutrients in the substrates was reasonably compared under the same experimental conditions, including the tap water source and atmospheric conditions. Nevertheless, factors such as the properties of tap water and weather conditions can significantly influence runoff characteristics and are recommended for examination in future studies. Consequently, the suitability of light expanded clay aggregate (LECA)-based GR substrates with biochar and the optimal biochar–GR systems in terms of runoff quality could be evaluated.

The following outlines the structure of this paper. The information about the research site; experimental design, including GR materials, the GR test beds, biochar types, rainfall simulation device; and methods of collecting and analyzing data is described in Section 2. The subsequent two sections present and discuss the results of the runoff quality performance of various biochar-amended green roof (GR) systems. The conclusions regarding the effectiveness of biochar in improving GR leachate are presented in Section 5.

2. Materials and Methods

2.1. Experimental Setup

Runoff samples were collected from six GR test beds on the roof of Building M at the Footscray Park campus of Victoria University (VU), Victoria, Australia. The six GR test beds were identically made from galvanized steel with dimensions of 1 m × 1 m (Figure 1). They were then elevated 0.3 m above the roof tiles by steel frames underneath, to conveniently collect GR runoff. An extensive GR (EGR) system was chosen with a 150 mm substrate depth. The substrate was dominated by light expanded clay aggregate (LECA)—80% *v*/*v*, whereas hardwood mulch and coir chips made up 15% *v*/*v* and 5% *v*/*v* of the substrate mix, respectively. Other components included a non-woven geo-textile membrane (which acts as the filter layer) and a drainage layer made up of trays of Atlantis 20 mm Flo-cell and VersiDrain® 30 manufactured by Atlantis Corporation, Chatwood, NSW 2067, Australia and Elmich, Newington, NSW 2127, Australia, respectively.

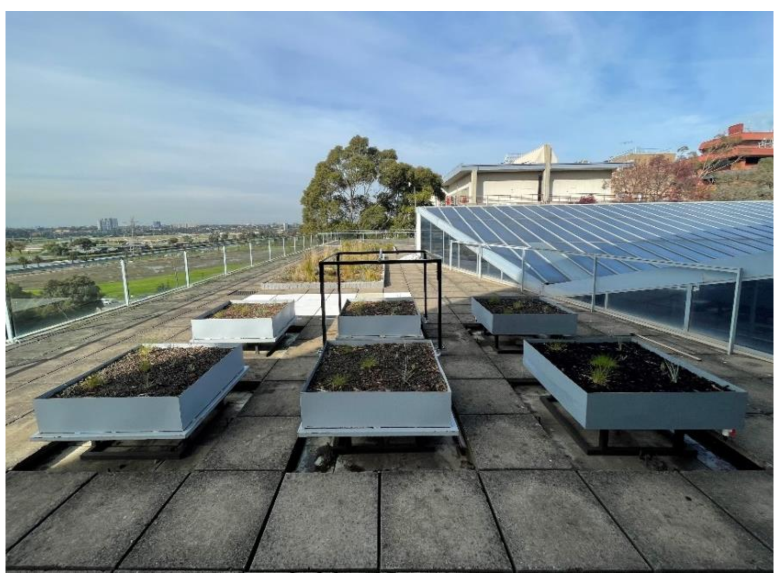

Figure 1. The six green roof test beds on Building M at Victoria University's Footscray Park Campus.

Biochar was added to five out of the six GR test beds using different application methods, particle sizes, and amendment rates. The configurations of the biochar-amended GRs are illustrated in Table 1. The two selected amendment rates were 7.5% *v*/*v* and 15% *v*/*v* in this study, and 1–3 mm and less than 1 mm particles were studied as medium and fine biochar particles, respectively. Biochar was thoroughly mixed with other substrate components in most test beds. Additionally, one test bed applied biochar as a bottom layer of the substrate and one test bed mixed biochar with water and then spread it on the substrate surface. The abovementioned biochar application methods, particle sizes, and amendment rates were found to affect the quality of GR runoff in previous studies [24,27,33,38].

Table 1. Characteristics of the six green roof test beds developed as part of this study.

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	Mixed	Medium
GR-7.5B-M	7.5	Bottom Layer	Medium
GR-15M-M	15	Mixed	Medium
GR-7.5M-F	7.5	Mixed	Fine
GR-7.5T-F	7.5	Top Dressing with Water	Fine

A rainfall simulation system (Figure 2) was utilized to uniformly produce rainfall events for each GR test bed. This nozzle-based rainfall simulator uses the pressure from tap water to create numerous droplet sizes [44]. By contrast, the application of an unpressurized system requires a 9.1 m fall height to obtain the actual kinetic energy of rainfall [45]. A pressurized simulator is more advantageous to apply and can better simulate rainfall compared to an unpressurized simulator [46]. The MPL 0.21M-B spray nozzle was supplied by Spray Nozzle Engineering Company–Melbourne. A pressure reducer was also used to maintain a pressure of 3 bars during the experiments. At that pressure, the nozzle produced 0.82 L/min of large droplets with a full-cone spray pattern to entirely cover the 1 m2 area of the GR test beds. Additionally, it needed to be installed 600 mm above the top surface of the test beds. More information about the experimental setup was provided in the previous research of Nguyen, Chau, and Muttil [37].

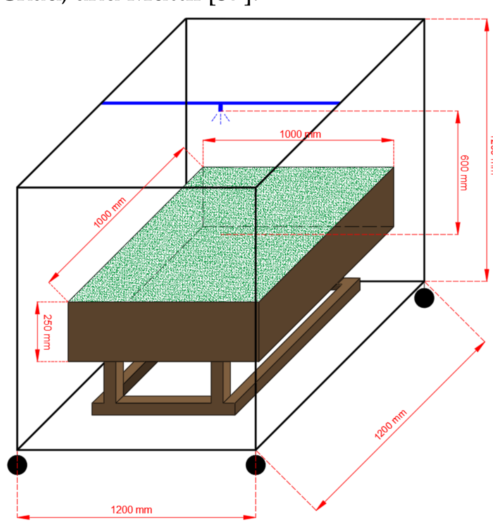

Figure 2. Design of the rainfall simulation device above a GR test bed.

2.2. Data Collection and Analysis

Water quality sampling commenced on 2 October 2023 and concluded on 8 December 2023. Five sets of runoff quality samples were collected on 2 October, 9 October, 23 October, 6 November, 20 November, and 8 December. There was a gap of 2 to 3 weeks between runoff sampling to allow noticeable changes in the amount of nutrients in the GR substrate/runoff. A smaller gap may not have led to any differences in the water quality of the collected runoff samples between experiments. Additionally, the selection of date/time of runoff sampling depended on favorable weather conditions. Experiments were carried out during dry weather and there were no strong winds that could have potentially affected the GR runoff quality results. Other climatic factors such as antecedent dry weather periods could also have had an impact on the chemical properties of GR runoff. However, all test beds were subjected to the same atmospheric conditions, thus supporting a reliable basis for comparing their performance.

A 10 min artificial rainfall was identically simulated for each test bed to produce adequate runoff for the water quality analysis. The rainfall simulation device used the same source of tap water to prevent the chemical properties of the tap water from affecting the comparison of runoff quality between the test beds. The analyzed water quality parameters consisted of pH, EC, TP, and TN. Then, 5 L plastic containers were pre-cleaned and placed under the drainage outlet of each test bed to collect runoff. Immediately after the collection, pH and EC were measured using portable pH and TDS/EC meters. Successively, runoff samples were moved into pre-cleaned 500 mm plastic bottles and then transported to the laboratory and prepared for the measurements of TP and TN on the same day of collection. Concentrations of TP and TN were spectrophotometrically analyzed by using a HACH DR 5000™ instrument manufactured by Hach Pacific, Dandenong South, VIC 3175, Australia. While TN was measured in the range of 2 to 150 mg/L and/or 0.5 to 25 mg/L using the persulfate digestion method, TP was measured in the range of 0.06 to 3.50 mg/L using the acid persulfate digestion method. The selection of these two methods was in accordance with the concentration range of TP and TN that has been frequently reported by previous studies. The observation data were illustrated using bar graphs, not only to determine the differences in quality of runoff from non-biochar and biochar test beds in an event, but also to assess the influence of GR aging on runoff quality. Single factor ANOVA analysis was also utilized to examine the statistical significance of difference between specific groups of test beds. Accordingly, conclusions about the impacts of biochar on the GR runoff quality and the ideal biochar–GR design could be drawn.

3. Results

The materials used in the GR substrate mixture in this study only included LECA, mulch, and coir chips. Since nutrition from the substrate was sufficient for the chosen GR plants, no fertilizer was applied at the time of constructing the test beds. Therefore, the concentration of TN in all runoff samples was below the minimum detection range of the selected HACH methods in the first sampling on 2 October 2023. The two selected HACH methods for measuring TN concentration have a wide detection range from 0.5 to 150 mg/L. However, the amount of runoff TN from all test beds in the first sampling was nearly zero, which could not be used for data analysis. To achieve the research objective, an identical amount of nitrogen fertilizer (nitrogen as blood and feather meal 14% *w*/*w*) was added to each GR test bed through well top-dressing with water on 3 October 2023 prior to the second sampling on 9 October 2023. Consequently, the results of TP and TN concentrations were only available from the second sampling, whereas the measurements of runoff pH, TDS, and EC started recordings from the first sampling itself.

3.1. pH

Natural processes and anthropogenic activities have led to serious acid rain globally, causing numerous negative impacts on ecology and human health [22,23]. Therefore, the solution of constructing GRs on building rooftops has huge potential to mitigate acid rain in urban areas, since rainwater passing through GR substrates becomes more alkaline [18]. Modifying GR substrates with biochar is expected to further enhance this ecological service (of mitigating acid rain) provided by GRs. Figure 3 reveals pH values of runoff from six GR test beds, including one without biochar and five differently modified by biochar. The effectiveness of biochar on runoff pH was more pronounced in the first three rainfall events when all biochar-amended GRs had higher runoff pH than the conventional GR. After that, the runoff pH of the biochar test beds gradually decreased, whereas the non-biochar test bed remained stable. More particularly, the pH of runoff from GR-7.5M-M, GR-15M-M, and GR-7.5M-F was lower than that from the zero-biochar test bed for the last three events. On the other hand, GR-7.5B-M and GR-7.5T-F had the highest runoff pH during the monitoring period. However, the differences in pH, ranging from 7 to 7.5, between all test beds were negligible (p-value = 0.1 > 0.05).

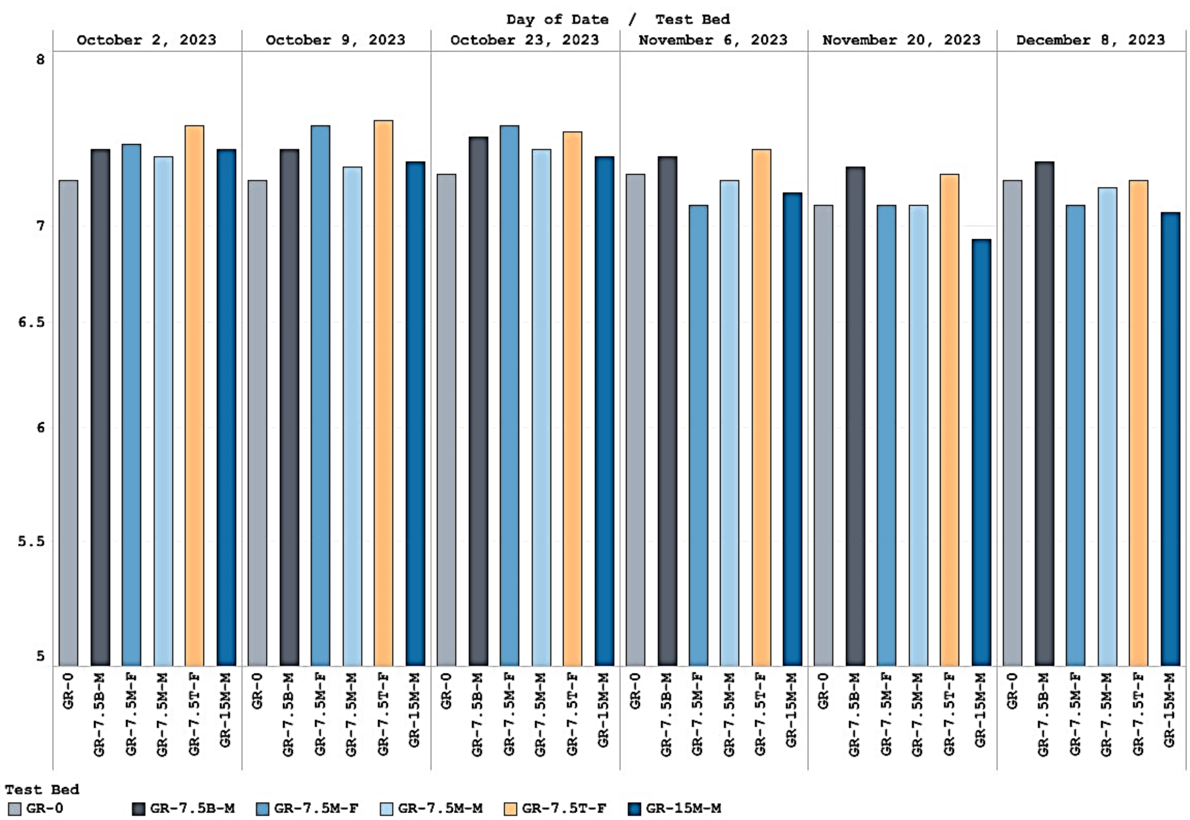

Figure 3. pH values of runoff from different biochar–green roof test beds.

hydrology

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3.2. Electrical Conductivity (EC)

Electrical conductivity (EC) is a useful representative of the amount of total dissolved solids (TDS) in water and is a good water quality indicator for estimating salinity level [24,25]. Runoff with a high EC value contains a high number of nutrient ions leached out from GR substrates. Observations from this study showed that biochar-amended GRs tended to increase EC in runoff as compared to the control GR (Figure 4). In addition, substrates amended with fine biochar particles (GR-7.5T-F and GR-7.5M-F) released more nutrient ions into the runoff than medium particles. However, no significant impact of biochar application method was found between these two GRs (p-value = 1 > 0.05). In addition, a negligible impact of biochar amendment rates on EC was detected when comparing GR-7.5M-M and GR-15M-M (p-value = 0.67 > 0.05). Among the biochar-amended test beds, the EC in runoff of GR-7.5B-M was the lowest. Moreover, this GR with medium biochar particles applied at the bottom of the substrate had a lower EC in runoff than the non-biochar GR for the last sampling (8 December 2023). An increasing pattern of EC for all test beds over the study period was identified, which has a strong relationship with the increasing trend of TN concentration that will be discussed in the Discussion section.

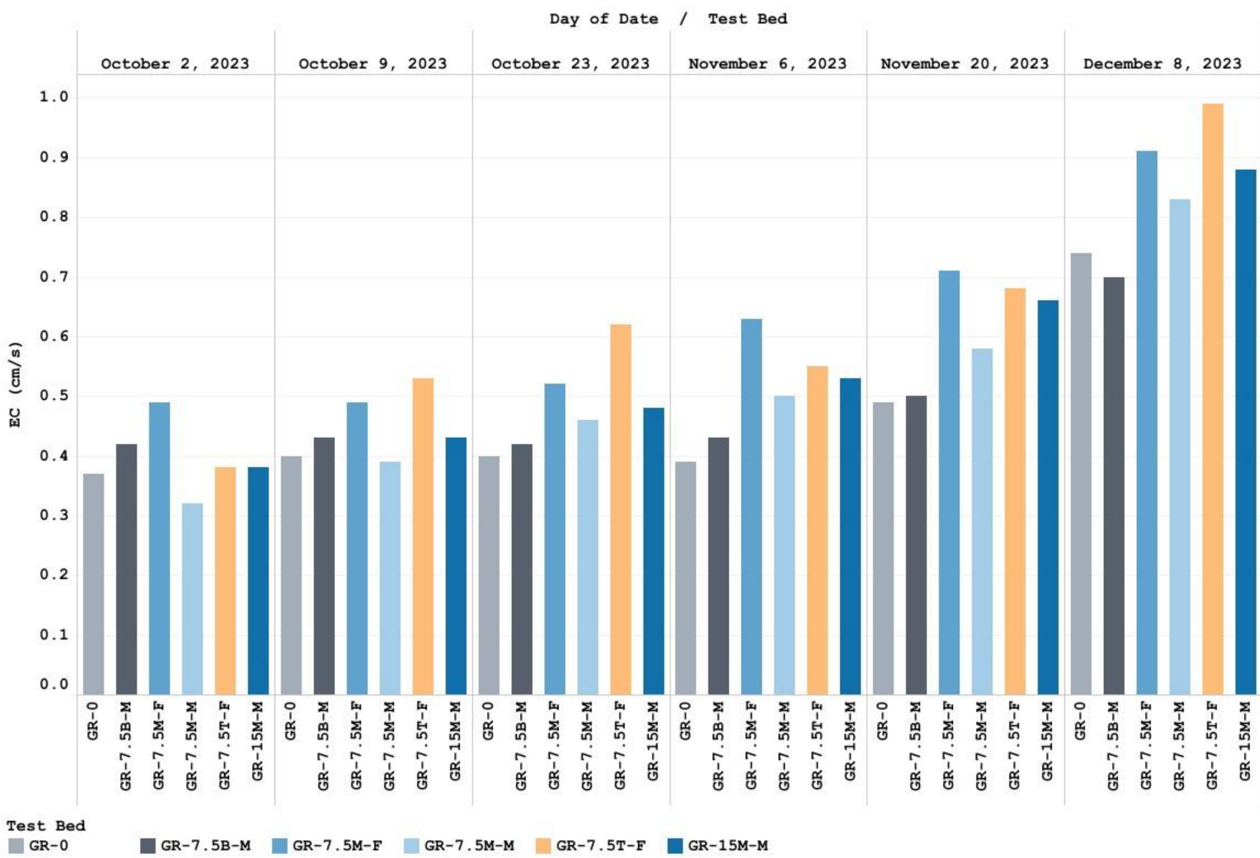

Figure 4. Electrical conductivity (EC) values of runoff from different biochar–green roof test beds.

3.3. Concentration of Total Nitrogen (TN)

Figure 5 illustrates that the TN concentrations in runoff of most biochar test beds were higher than that of the test bed containing no biochar. The only exception was the test bed with medium biochar particles placed at the bottom of the substrate (GR-7.5B-M). For 5 out of 6 rainfall events, GR-7.5B-M released less TN in runoff than the control test bed (GR-0). TN concentrations in runoff of GR-7.5B-M and GR-0 were twice as low as those of the other test beds. More specifically, the TN concentration of runoff from GR-7.5B-M was 2.2 to 21 mg/L, whereas the other biochar test beds (4.8 to 58 mg/L) released a higher amount of TN in runoff when compared to the non-biochar test bed (3.7 to 31 mg/L). An increasing trend in TN concentration in GR runoff was observed, from 2.2–9.5 mg/L in the first sampling to 21–58 mg/L in the last sampling. Fine biochar particles on the top surface of GR-7.5T-F tended to have the weakest impact on mitigating TN release in runoff. Runoff from GR-7.5T-F had the highest TN concentration under all simulated rainfall events. With the same fine particle size, the application method of thoroughly mixing in GR-7.5M-F performed slightly better than the top-dressing application method in GR-7.5T-F (p-value = 0.62 > 0.05). Medium biochar particles in GR-7.5M-M and GR-15M-M tended to have a higher TN retention when compared to fine particles. However, there was no significant difference between these two test beds when increasing the amendment rates from 7.5% to 15% (p-value = 0.87 > 0.05).

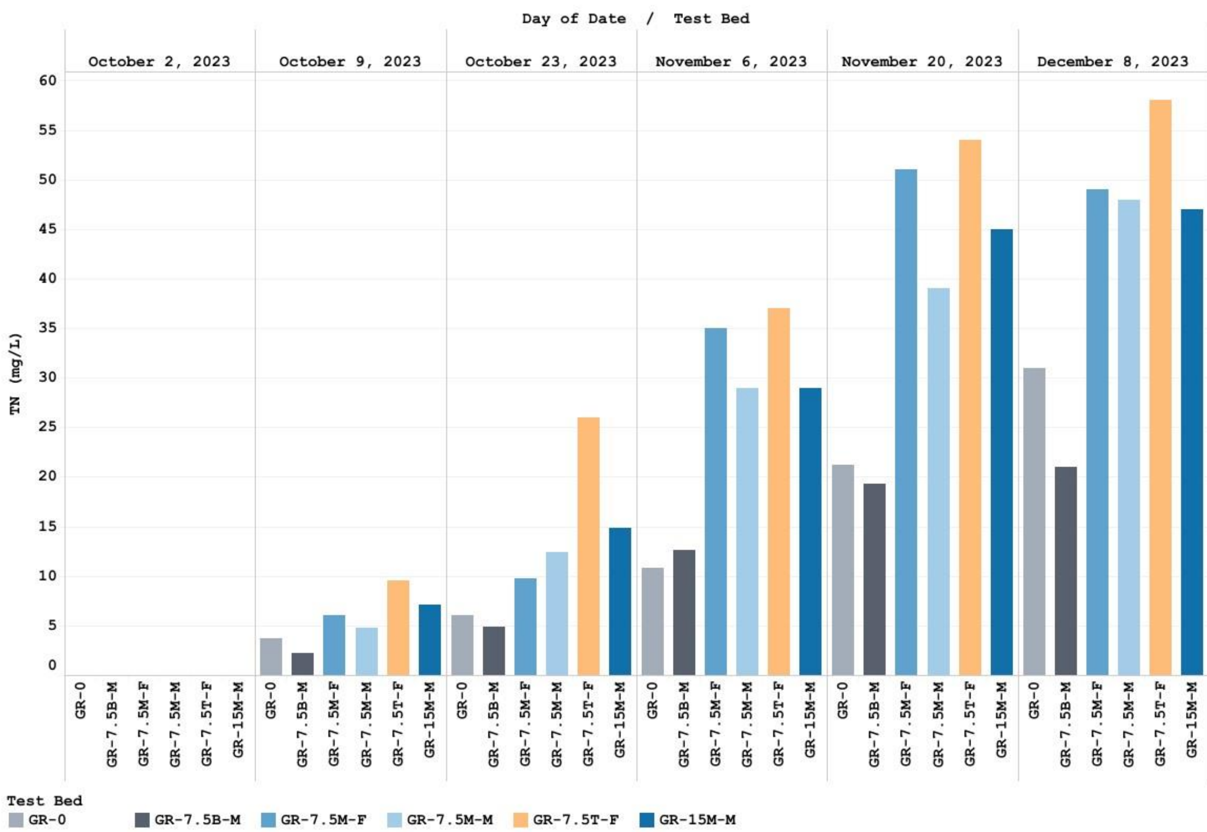

Figure 5. Total nitrogen (TN) concentration of runoff from different biochar–green roof test beds.

3.4. Concentration of Total Phosphorus (TP)

The addition of biochar to GR substrates did not have a reducing impact on TP concentration as compared to GR without biochar (Figure 6). All biochar-amended GRs (0.81 to 2.41 mg/L) had higher TP concentration in runoff than the control GR (0.35 to 0.67 mg/L). GR-7.5T-F with fine biochar particles on the top of the substrate continued to have the poorest performance in retaining TP (0.98–2.41 mg/L). Furthermore, the top-dressing method of biochar in GR-7.5T-F significantly increased the runoff TP concentration as compared to the mixing method in GR-7.5M-F (p-value = 0.048 < 0.05). The fine biochar particles in GR-7.5M-F were also found to be significantly more effective in retaining TP than the medium biochar particles in GR-7.5M-M (p-value = 0.05). With the same mixing biochar method and particle size, the lower amount of biochar (7.5% v/v) performed significantly better than 15% v/v biochar in the first two experiments. However, a similar trend was not observed in the other experiments. Similarly, an inconsistent trend was observed when comparing the impact of biochar application methods (mixing and bottomed layer) on TP retention between GR-7.5B-M and GR-7.5M-M. A decreasing pattern of runoff TP concentration was observed. Runoff TP concentrations decreased quickly in a short monitoring period of about 2 months.

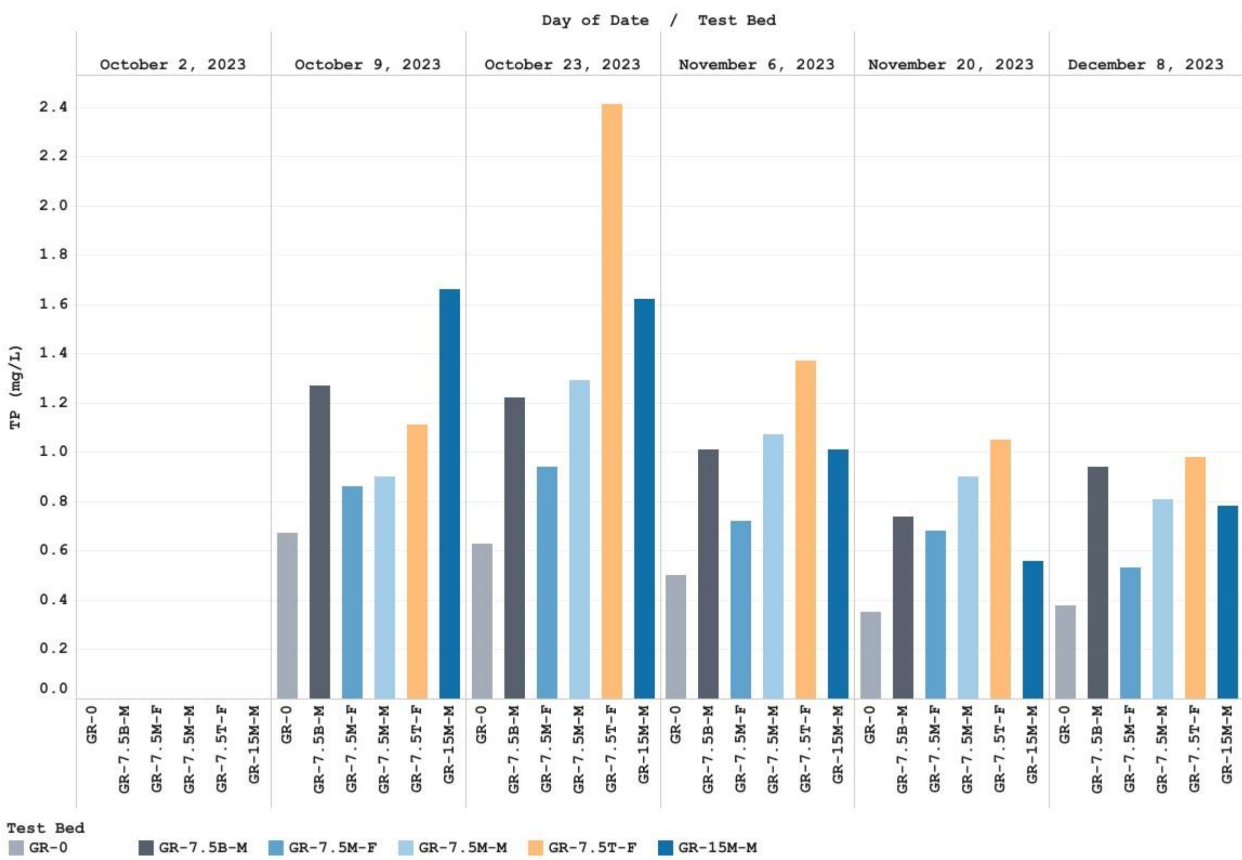

Figure 6. Total phosphorus (TP) concentration of runoff from different biochar–green roof test beds.

4. Discussion

4.1. pH

Though GR-7.5B-M and GR-7.5T-F had the highest runoff pH during the monitoring period, the benefit of biochar in increasing GR runoff pH could not be confidently concluded. Moreover, the differences between the test beds and the influences of biochar particle sizes, amendment rates, and application methods on runoff pH were negligible. The results obtained from this study are comparable with those from the study of Xiong, Li, Wang, Wu, Li, and Xue [33]. The runoff pH of the GR treatment without biochar was lower than that of the GR treatments with different biochar types and biochar addition rates in the first month of monitoring. In the next 2 months, the runoff pH slightly decreased and became constant, and no significant difference was found between the biochar and non-biochar GRs. Similar observations were reported by Liao, Drake, and Thomas [27] when analyzing runoff quality of pilot-scale GRs (71 cm2) amended with different types and particle sizes of biochar. In the first flush at the beginning of the experiment, the run-off pH of non-biochar GR was lower than that of biochar GRs. In the second flush (115 days after the 1st flush), the effect of biochar decreased, and no significant difference was found between non-biochar and biochar GRs. Opposite findings were reported in the study of Qianqian, Liping, Huiwei, and Long [1]. The authors also measured the pH of runoff from modular GRs (50 × 33 cm) using artificial rainfall. Under different rainfall depths over 6 months, the substrates modified with biochar produced higher runoff pHs. No impacts of biochar on runoff pH were observed when Kuoppamäki, Hagner, Lehvävirta, and Setälä [24] investigated three GR treatments, including one without biochar and two with two different biochar types using plastic boxes (18 × 18 cm) in a 6-week laboratory experiment. Additionally, Meng, Zhang, Li, and Wang [32] recorded the runoff pH of 18 extensive GR test beds (1 × 1 m) for 25 runoff samples from 93 actual rainfall events. The mean pH values from a 1.5-year monitoring period indicated that the addition of biochar resulted in a slight increase in runoff pH as compared to non-biochar GRs and rainwater. It is worth noting that the influence of different biochar amendment rates (5, 10, 15, and 20%) on runoff pH was inconsiderable. Similarly, Goldschmidt [38] reported a higher runoff from biochar GR substrates in a full-scale experiment over two growing seasons. The increase in biochar amendment rate from 2.5% to 10% also did not lead to a remarkable difference. Runoff pH values from three simulated rainfalls reported by Novotný et al. [51] were also slightly higher due to the addition of three types of biochar. Wood biochar, food waste biochar, and sewage sludge biochar retained positive effects on runoff pH after 10 months. In general, biochar substrates tend to neutralize pH and pro-duce runoff that is more alkaline than non-biochar substrates, due to the presence of alkaline metals in biochar [7]. Similar results were found in numerous papers using either tap water (artificial rainfall) or actual acidic rainwater. However, the addition of biochar does not result in a significant improvement and the impact decreases over time.

4.2. Electrical Conductivity (EC)

The effects of biochar on the EC of biochar-GR runoff have been inconsistently re-ported. Similarly to the findings of the present study, Kuoppamäki, Hagner, Lehvävirta, and Setälä [24] concluded that biochar tended to increase EC when they measured EC in runoff from pilot-scale GRs amended with two different biochar types in the 6th week of a lab experiment. Goldschmidt [38] conducted a full-scale experiment including various GRs in plastic trays (60 × 20 cm). They found that the average EC during two growing seasons was also higher in runoff from biochar substrates than that from non-biochar substrates. However, the differences were not significant and higher biochar amendment rates (2.5, 5, and 10%) slightly increased the EC in runoff, which is consistent with the present study. In the study of Liao, Drake, and Thomas [27], all particle sizes of processed biochar had positive impacts on EC in runoff, especially in the second flush (115 days after the 1st flush), whereas the runoff EC was higher with all particle sizes of unprocessed biochar in both flushes, except for 2.8–4 mm biochar particles. Moreover, particle sizes for both processed and unprocessed biochar had a negative relationship with runoff EC. Those findings were also observed in the present study. Runoff EC was much lower in the second flush than in the first flush, which was different from the increase in EC over time in the present study. This could be explained by the low amount of nutrients in GR substrates 115 days after the substrate preparation as compared to nutrient-rich substrates, due to the shorter monitoring period of only about 60 days in the present study. On the other hand, biochar was also found to have positive effects on runoff EC. For example, Qianqian, Liping, Huiwei, and Long [1] measured the EC of runoff from commercial substrates and biochar substrates. Under all simulated rainfalls with different rainfall depths, the runoff EC of biochar substrates was slightly lower. Another similar result was record-ed by Meng, Zhang, Li, and Wang [32]. The average runoff EC from 1 m2 extensive GRs by analyzing 25 runoff samples over more than one year indicated that biochar succeeded in reducing runoff EC. However, the effect of biochar did not become significantly greater by adding more biochar (5, 10, 15, and 20%). Biochar type affected the runoff EC in the study by [51]. While GRs added with biochar from food waste and wood increased the runoff EC, GRs with sewage sludge released significantly lower levels of ions in runoff. To conclude, biochar performs inconsistently in terms of runoff EC according to the time of sampling, substrate type, and biochar type. Biochar particle sizes have a more pronounced in-fluence on runoff EC, which is reported in the present study and others.

4.3. Concentration of Total Nitrogen (TN)

Biochar failed to alleviate the TN concentration in this study, except for the GR-7.5B-M test bed. Therefore, medium biochar particles are recommended to be amended at the bottom of LECA-based GR substrates to reduce TN concentrations. The application methods of mixing and top-dressing with medium and fine biochar at two amendment rates (7.5 and 15%) in the other biochar test beds did not effectively improve the TN retention. However, some consistent trends were found. As compared to the top-dressing method, thoroughly mixing fine biochar particles was a more effective solution to decrease TN concentration in runoff. Medium biochar particles tended to perform better than fine particles in TN retention. Nevertheless, the differences between those test beds were inconsiderable. An increasing trend in TN concentration in GR runoff was observed, which could be explained by more and more dissolved nutrients being released over time from the nitrogen-rich fertilizer added to the GR substrates before the second sampling (9 October 2023) through rainfall and irrigation. Accordingly, the release of increased fertilizer salt ions was the reason for the increasing trend in EC in runoff.

Negative impacts of biochar on TN concentration in GR runoff were also observed by Liao, Drake, and Thomas [27]. Two biochar types (unprocessed and processed) with four different particle sizes thoroughly mixed into substrates of GRs in growth containers (71 cm2) also released higher levels of TN in runoff. Only 2.8–4 mm unprocessed biochar was lower in concentration of TN than non-biochar GRs in both samplings. There was a considerable decrease in runoff TN in the second sampling (115 days after the 1st sampling), and non-biochar and biochar GRs were not significantly different from each other in run-off TN concentration. Furthermore, Novotný, Šipka, Miino, Raček, Chorazy, Petreje, Tošić, Hlavínek, and Marković [51] could not find a TN-reducing effect of biochar by testing three different types of biochar. Those GR test beds (0.5 × 1.0 m) only produced runoff that was close to the no-biochar test bed in TN concentration for the last simulated rainfall (10 months after GR installation). On the other hand, the TN concentrations in runoff from biochar GRs reported in the present study are inconsistent with most previous studies. For example, the mean TN concentration of runoff from the biochar substrate in the study of Qianqian, Liping, Huiwei, and Long [1] was significantly lower than that from commercial substrate (9.85 and 16.14 mg/L, respectively). Those results were collected from 50 × 33 cm modular GRs under eight simulated rainfalls with different rainfall depths. Xiong, Li, Wang, Wu, Li, and Xue [33] investigated two types of biochar, including rice husk (RH) biochar and maize straw (MS) biochar. They found that both biochars successfully reduced TN leaching in runoff in all six studied rainfall events in three months. The TN-reducing effects of these two types of biochar were significantly different at the same amendment rates. Moreover, neither biochar type had a better performance at higher amendment rates. Runoff TN concentration also quickly decreased in roughly two months. Biochar added to stabilized sludge-based pilot-scale GRs effectively improved runoff quality by reducing the runoff TN concentration from 3.27 to 2.16 mg/L [52]. A longer observation of 18 extensive 1 m2 GR test beds in 1.5 years under real rainfall also indicated that coconut shell biochar mixed with peat, vermiculite, sawdust, and perlite as GR substrates succeeded in decreasing TN concentrations [32]. Average TN concentrations in runoff from non-biochar GRs were twice as high as those from biochar GRs. The increase in biochar addition rates also did not significantly affect the concentration of TN in the runoff in this study. In another study by Beck, Johnson, and Spolek [30], the performance of two GR metal trays (61 × 61 cm) planted with two different plants, sedum and ryegrass, under artificial rainfall was positive in terms of TN concentration. TN concentrations of the ryegrass trays were 10.1 mg/L, compared to 79.2 mg/L for the control trays. It is noted that only two rainfall simulations were run, and the second simulation started 2 h after starting the first simulation. The performance of biochar in TN retention depends on many factors, such as the suitability of biochar within the GR system. While amendment rates tend to have less effect, biochar types, application methods, and particle sizes were found to influence the release of TN in runoff in this study and others. Therefore, further research on biochar variables should be conducted, and biochar–GR systems need to be tested before large-scale applications.

4.4. Concentration of Total Phosphorus (TP)

The addition of biochar to GRs in the present study did not positively affect the concentration of TP in runoff. Biochar substrates act as a potential source of TP, since they might release part of the P into the runoff [1]. A review by Li et al. [53] found that the addition of biochar to soil could result in either an increase or decrease in runoff P concentrations. Soil P availability was increased by adding biochar, and P in soil became available P, leading to higher P levels in runoff [33,54]. Fine biochar particles evenly spread on the GR surface released the most TP into runoff. Oppositely, the mixing application method of fine biochar particles released significantly less TN into runoff. In contrast to TN retention, higher TP retention was recorded with fine biochar particles. These findings are consistent with previously conducted studies. For instance, a long-term observation of several 1 m2 GR test beds found that all biochar substrates did not reduce the TP concentration in run-off [32]. Various biochar addition rates (5, 10, 15, and 20%) also did not result in a significant difference. Additionally, the use of two types of biochar by Xiong, Li, Wang, Wu, Li, and Xue [33] did not lead to lower TP concentrations in runoff. However, the performance of rice husk biochar substrates was closer to that of non-biochar substrates. The impacts of biochar amendment rates on runoff TP concentration were significant in this study. A higher amount of biochar released more TP, especially for maize straw biochar, into runoff and the trends were consistent during the study period. Biochar produced from three different feedstocks, including wood, sewage sludge, and food waster, in the study of Novotný, Šipka, Miino, Raček, Chorazy, Petreje, Tošić, Hlavínek, and Marković [51] could also not alleviate TP levels in runoff during the experimental period of 10 months. Biochar type also significantly affected the TP release, with the best performance by food waste biochar. One possible explanation for the low effects of biochar was the low initial concentration of TP in GR substrates, limiting the TP adsorption ability of biochar. The GR substrates used in the present study were also low in TP. Moreover, the studies of both Qianqian, Liping, Huiwei, and Long [1] and Meng, Zhang, Li, and Wang [32] used the same substrate with a low initial TN concentration. Under both artificial rainfall and natural rainfall, their biochar-amended GRs did not succeed in reducing TP release in runoff. Opposite findings were found in the study of Beck, Johnson, and Spolek [30] when their initial GR substrates were higher in TP concentration. There were still positive results. For instance, the TP concentration in runoff was lower with biochar substrates (8.3–8.4 mg/L) than with non-biochar substrates (10.3–17.4 mg/L) [30]. However, only two rainfall events were simulated. The decreasing trend in TP in the present study was also observed in the studies by [29,33]. Observation data illustrated that phosphorus was significantly washed out from GR substrates at the initial stage and then gradually decreased over time [29]. Xiong, Li, Wang, Wu, Li, and Xue [33] stated that biochar made from different feedstocks could possibly be responsible for the different results regarding runoff quality. Therefore, the compatibility of biochar with a GR system needs to be evaluated before a field-scale implementation. The use of a batch or column test is suggested [29].

4.5. Long-Term Impacts of Biochar on Green Roof Runoff Quality

Most studies reported a decreasing trend in nutrient concentrations in runoff, which could be explained by newly established GR substrates containing several nutrients that are gradually released into runoff over time. This indicates that GR acts as a source of pollutants, especially at the early stage [33,55]. The results of runoff EC, nutrients, and heavy metal concentrations in the study by Novotný, Šipka, Miino, Raček, Chorazy, Petreje, Tošić, Hlavínek, and Marković [51] also supported this conclusion. The pollution of runoff was more severe one month after installation, which gradually decreased over time. Conversely, the TN concentration and EC in runoff were not observed to decrease in the present study. One possible reason for this was the high application of nitrogen fertilizer in the substrates. The number of dissolved fertilizer nutrients kept increasing, so de-creasing trends in TN concentration and EC could not be detected in the short monitoring period of about two months. Therefore, results of GR runoff quality strongly depend on sampling time, and future studies are recommended to investigate runoff quality at different stages of a GR's lifetime. Since the availability of nutrients in GR substrates changes and tends to decrease over time, long-term observations are necessary to understand the performance of biochar as the age of the GR increases.

Despite mixed findings regarding nutrient concentrations, biochar still has huge potential to improve runoff quality due to its significant water retention capacity, leading to lower pollutant loads in runoff. Numerous papers have highlighted the effects of biochar in reducing TP loadings in runoff, regardless of higher TP concentrations. For example, Kuoppamäki, Hagner, Lehvävirta, and Setälä [24] found higher TP and TN concentrations in runoff from biochar GRs than those from non-biochar GRs. By contrast, loadings of TP and

TN were reported as lower with both application methods of biochar, due to a higher water retention. The results of Cheng, Vaccari, Johannesson, and Fassman-Beck [29] extracted from observations and modelling also supported the long-term positive impacts of biochar on GR runoff quality. The reduction in annual cumulative TP loading when compared to an un-greened reference roof could have been largely due to the reduction in runoff volume. Similarly, the LECA-based substrates amended with biochar in the present study did not effectively reduce nutrient concentrations in GR runoff during the short study period. However, the benefits of these GR systems regarding runoff quality could not be concluded early and require a long-term monitoring period. The potential for im-proving the GR runoff quality by increasing runoff retention and decreasing pollutant loads from the test beds could be supported by the runoff volume data reported in the previous study of Nguyen, Chau, and Muttil [37]. At the same experimental site with the same GR test beds, the runoff retention capacities of the biochar-amended GRs were ap-apparently higher than those of non-biochar GRs under different rainfall scenarios. With a total rainfall of 110.7 L, the maximum volume of rainfall retained by biochar-amended GRs was 58.9 L, while the non-biochar GRs retained 37.9 L of rainfall. Nevertheless, selection of correct biochar types for GR substrates is still necessary. The suitability of biochar with GR substrates plays a major role in determining the efficiency of biochar in improving GR runoff quality [33].

5. Conclusions

Green roofs (GRs) provide a wide range of ecological services, consisting of runoff retention, urban thermal reduction, energy saving, and air purification. However, GRs tend to act as a potential source of pollutants, especially immediately after the establishment of GRs. Nutrient loss to runoff causes water pollution, while insufficient nutrients in GR substrates can hinder the growth of plants and subsequently diminish the effectiveness of GR services. The addition of biochar to GR substrates has huge potential to reduce the release of nutrients into GR runoff. Therefore, this paper aimed to investigate the effects of biochar on GR runoff quality by measuring pH, electrical conductivity (EC), and TN and TP concentrations in newly established GR test beds. Furthermore, the influence of biochar amendment rates, application methods, and particle sizes on GR runoff quality was also evaluated. The quality of runoff from six 1 m^2 GR test beds, which included five biochar-amended test beds and one control test bed (without biochar), was analyzed using six artificial rainfall events within a two-month period.

The following is a summary of the key conclusions and recommendations based on this study:

(a) GRs tended to neutralize rainwater by producing alkaline runoff (pH ranging from 6.93 to 7.59). The impacts of biochar on runoff pH were insignificant and more pronounced at the beginning of the experiment.

(b) All GR substrates were a source of EC, and runoff EC was higher with biochar-amended substrates. Small biochar particles tended to produce runoff with higher EC. Among the biochar-amended test beds, the EC in runoff from the test bed with medium biochar particles applied at the bottom of the substrate was the lowest.

(c) TN concentrations of runoff from most biochar GRs were significantly higher than from non-biochar GR. The only exception was the test bed with medium biochar particles applied at the bottom of the substrate. Compared to medium biochar particles, fine particles exhibited a slightly weaker capacity to reduce TN in GR runoff.

(d) The addition of biochar resulted in an increase in TP concentration in GR runoff due to a higher P content in substrates, which is also consistent with previous findings. In contrast to TN retention, fine biochar particles were observed to be more effective for TP retention than medium biochar particles.
(e) When compared to the other biochar test beds, the test bed with biochar applied to the surface of the substrate (GR-7.5T-F) exhibited the poorest performance in terms of runoff quality.
(f) Despite mixed findings regarding nutrient concentrations, biochar still holds huge potential to enhance runoff quality, due to the considerable reduction in runoff volume that it can achieve.
(g) A pronounced relationship between runoff quality and GR aging was also recognized. The availability of nutrients in GR substrates tends to decrease over time and long-term observations are necessary to understand the performance of biochar as GRs age.
(h) The compatibility of biochar with a GR system significantly influences the effectiveness of biochar in improving GR runoff quality.

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Chapter 5

Assessing the performance of biochar-amended green roofs in terms of plant growth

5.1. Addition of biochar to enhance plant performance in green roofs: A long-term field study

5.1.1. Introduction

As a continuation of the works presented in Chapter 4, this chapter further investigates the impact of biochar on green roof (GR) plant performance. While previous research has suggested that biochar can enhance substrate fertility and plant performance, a comprehensive understanding of plant responses to varying biochar parameters under long-term conditions remains limited. This study investigated the performance of different plant species across a range of biochar-amended GR configurations, considering biochar amendment rates (7.5% and 15% *v/v*), particle sizes (less than 1 mm and 1-3 mm), and application methods (mixing, top layer, and bottom layer). Plant growth was monitored across six 1 m^2 green roof test beds established at the same study site, with three plant species (wallaby grass, common everlasting, and billy buttons) evaluated over a one-year period. Plant height was recorded fortnightly, while plant dry weight and coverage area were assessed at the end of the monitoring period. Although plant responses varied, consistent evidence of improved plant growth indicators was observed across all test beds, suggesting the potential of biochar to enhance green roof vegetation. Optimal plant growth was achieved in GRs amended with medium biochar particles at a rate of 15% *v/v*. The observed enhancement in plant growth is attributed to improved substrate temperature and moisture conditions, as well as increased nutrient availability. Nutrient availability within the GR substrates was inferred from runoff quantity and quality data presented in Chapter 4. Additionally, substrate temperature measurements at a 10 cm depth on consecutive hot and cold days support these conclusions. Given the critical role of vegetation in green roof function, careful plant selection and maintenance are essential for system optimization. This study provides preliminary recommendations for developing optimal biochar-green roof systems to enhance plant growth for specific plant species.

This chapter contains the following journal paper:

- Nguyen, C.N.; Chau, H.-W.; Muttil, N. Addition of Biochar to Green Roof Substrate to Enhance Plant Performance: A Long-Term Field Study. *Buildings* **2024**, 14, 2775. https://doi.org/10.3390/ buildings14092775.

5.1.2. Declaration of co-authorship and co-contribution: papers incorporated in thesis by publication

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DECLARATION OF CO-AUTHORSHIP AND CO-CONTRIBUTION: PAPERS INCORPORATED IN THESIS

This declaration is to be completed for each conjointly authored publication and placed at the beginning of the thesis chapter in which the publication appears.

1. PUBLICATION DETAILS (to be completed by the candidate)

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2. CANDIDATE DECLARATION

I declare that the publication above meets the requirements to be included in the thesis as outlined in the HDR Policy and related Procedures – policy.vu.edu.au.

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3. CO-AUTHOR(S) DECLARATION

In the case of the above publication, the following authors contributed to the work as follows:

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Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Cuong Ngoc Nguyen	80	Conceptual ideas, research, data analysis, experiments, writing.	[redacted]	23/08/2024
Hing-Wah Chau	5	Feedback and discussion on research and writing		23/08/2024
Nitin Muttil	15	Critical comments and discussion on conceptual ideas & research methodologies		23/08/2024

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5.1.3. Addition of biochar to enhance plant performance in green roofs: A long-term field study

Article

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, there remains a necessity for long-term observational studies focusing on the impacts of various bio-char-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 the 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 eco-system 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, re-store 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 com-prehensive 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 pay-back 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] high-lighted 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 im-prove 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 drain-age layer. Biochar, a carbon-rich substrate additive, has been investigated in different fields, including agriculture and geotechnical structures, due to its advantageous physio-chemical 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 thick-ness 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 per-formed 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 bio-char-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. How-ever, 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 effective-ness 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.

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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.

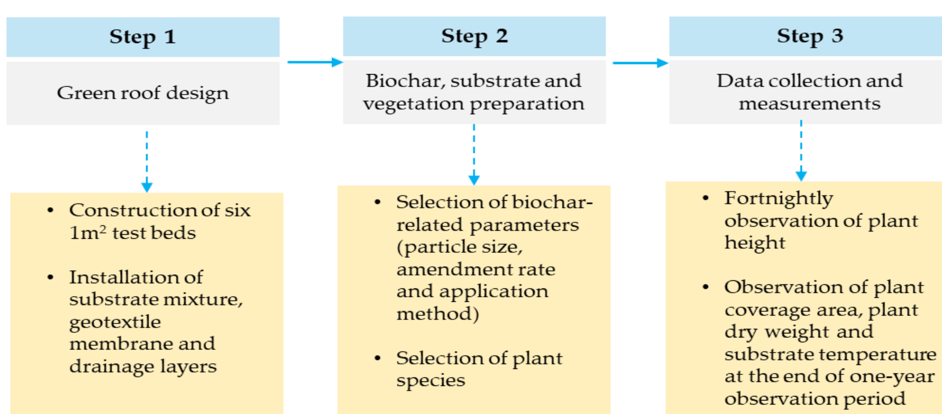

Figure 1. A flow chart depicting the methodological framework. used in this study.

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, a 50 m² 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 m² GR was not suitable for the investigation of the benefits of biochar to plant growth and hence six 1 m² GR test beds were installed on the same rooftop (Figure 2b). Six 1m × 1m 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 20mm 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 light weight, flexible and affordable design, easy installation and expansion, and low maintenance [56,57]. However, the experimental setup in this study aimed to utilize 1m² 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.

(a) (b)

Figure 2. The green roofs on the rooftop of Building M at the Footscray Park campus of Victoria University (a) The 50 m² GR system and (b) The six GR test beds.

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.

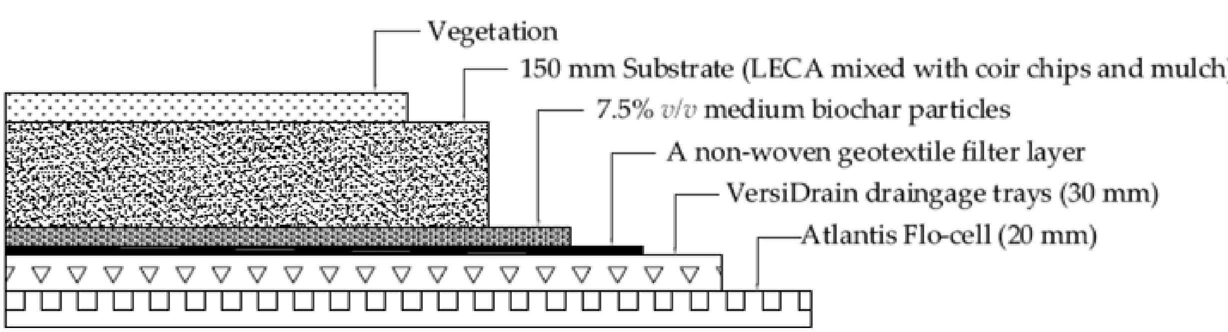

Figure 3. The cross-section of a green roof test bed with 7.5% *v/v* medium biochar particles applied at the bottom of the substrate.

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 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.

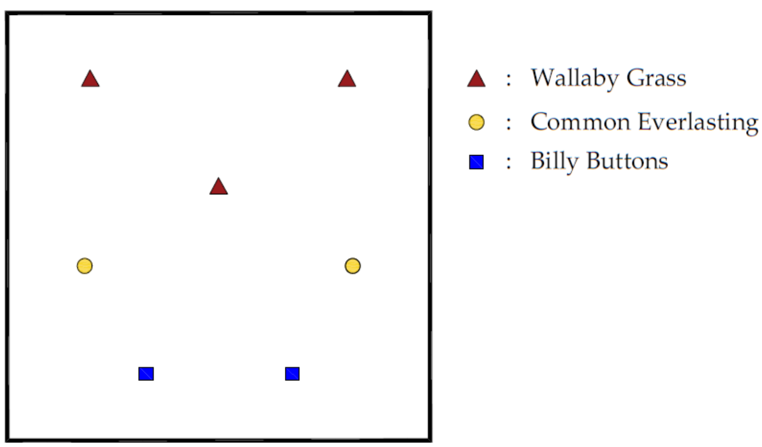

Figure 4. The distribution of plants in each test bed.

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. Afterwards, they were gently washed before they were dried in a forced-air oven at 60⁰C for 48 hours. Eventually, the dried samples were weighed to measure the plant dry weights. Similar methodologies were adopted in previous studies [51,52].

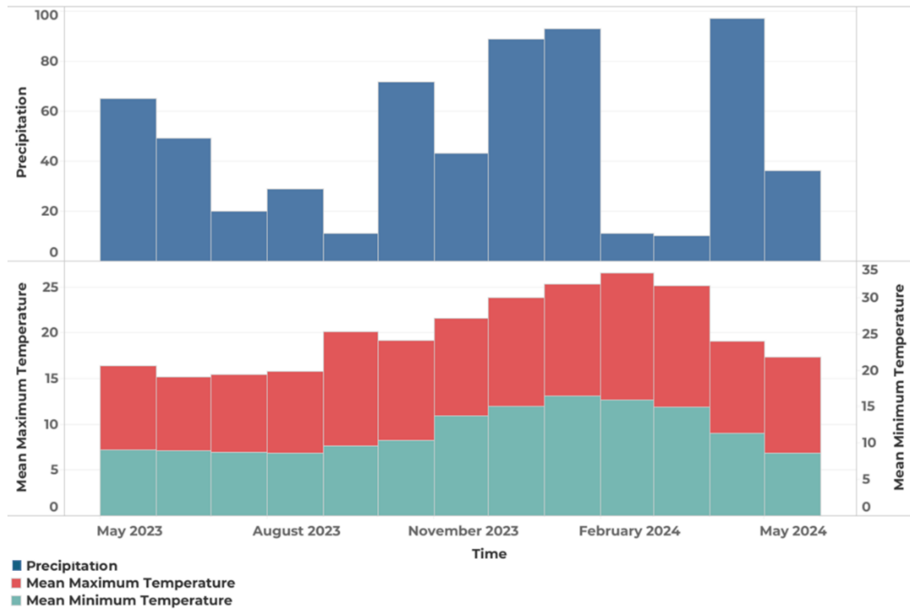

Figure 5. Weather characteristics at the study area during the observation period from May 2023 to May 2024.

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-minute 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.

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

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 of biochar in the last two observation periods.

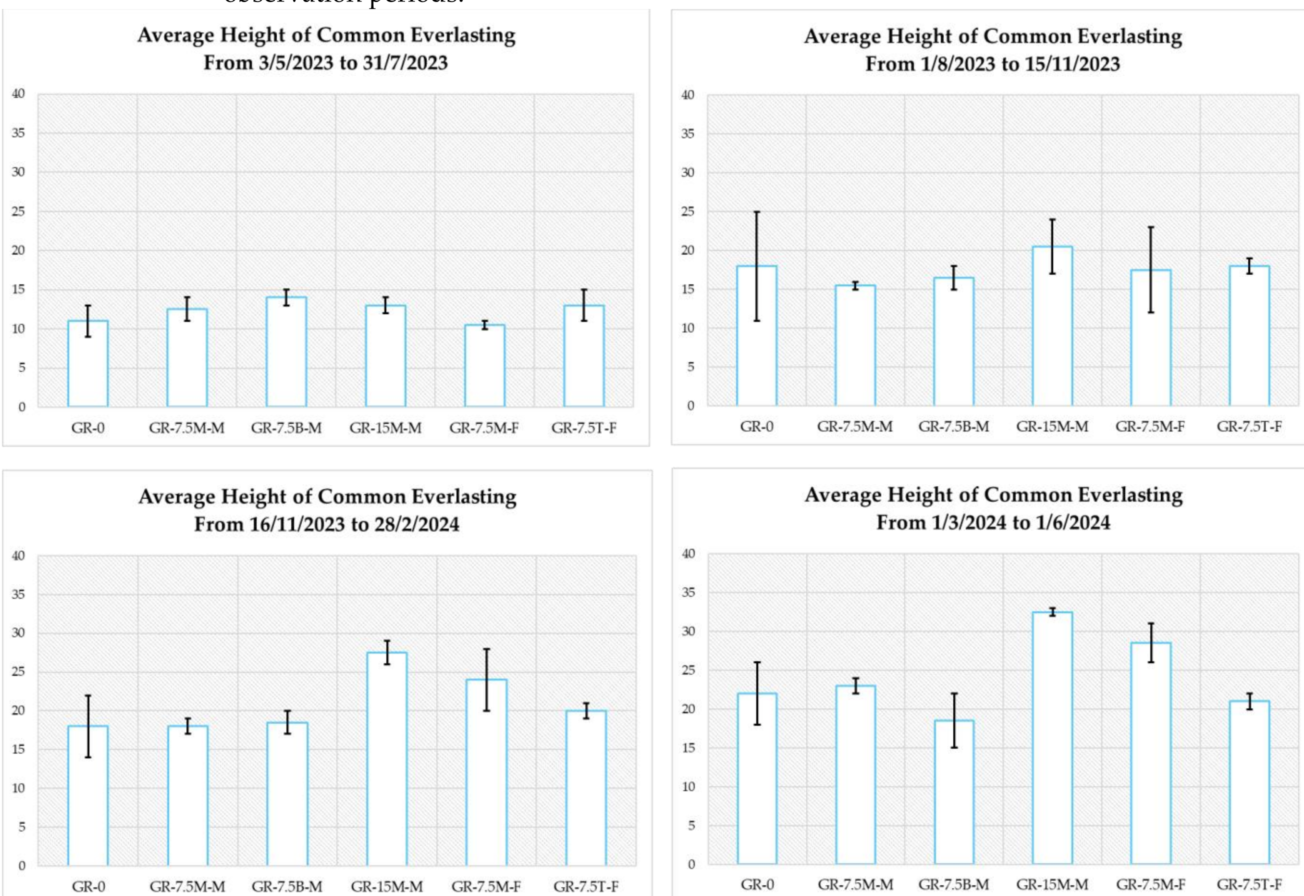

Figure 7. Average height of two common everlasting plants with standard error in the six green roof test beds during the monitoring period.

Figure 8 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 the 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 buttons 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.

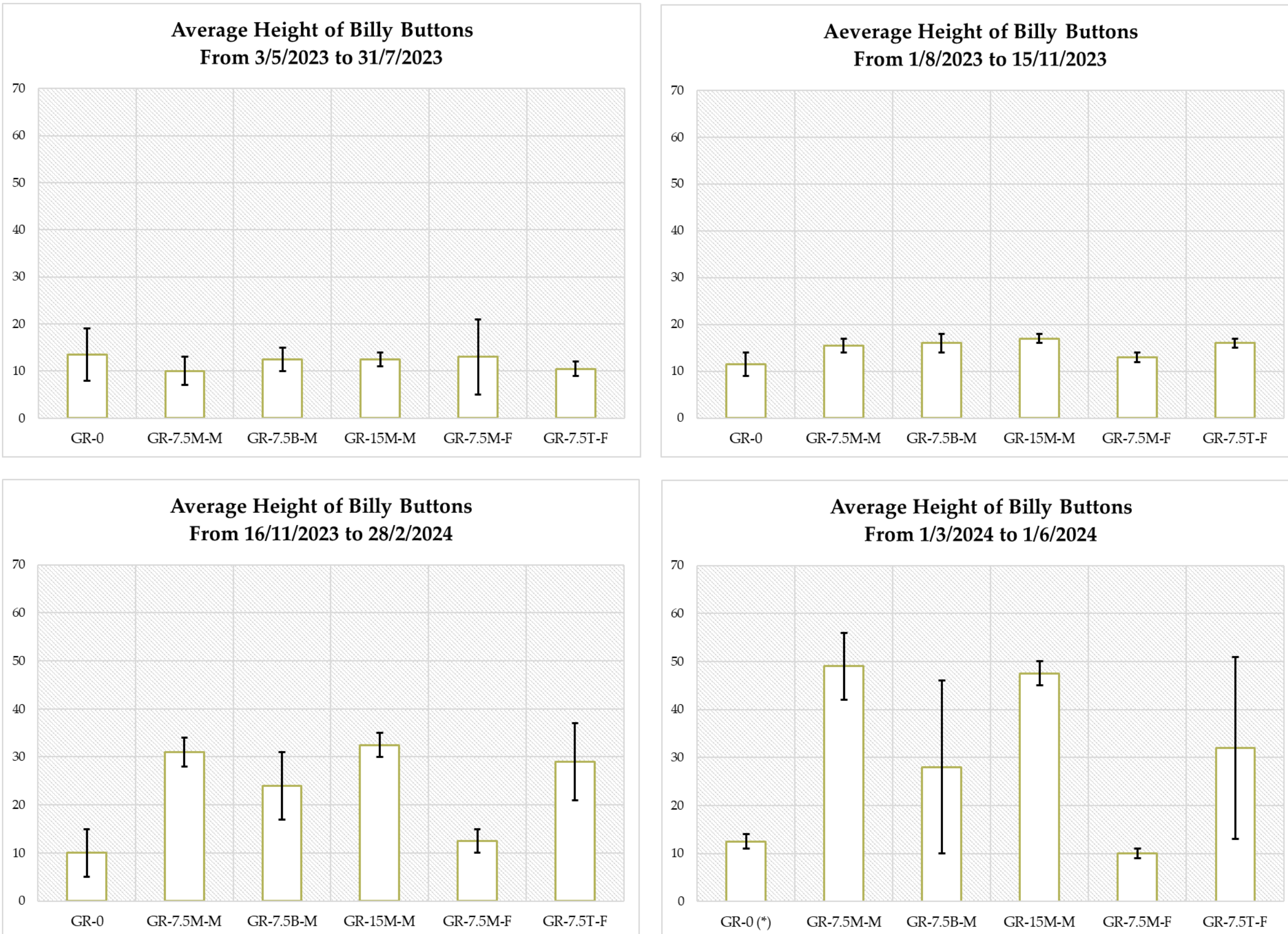

Figure 8. Average height of two billy button plants with standard error in the six green roof test beds during the monitoring period. (*) one plant died, the average height was measured from one plant only.

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.

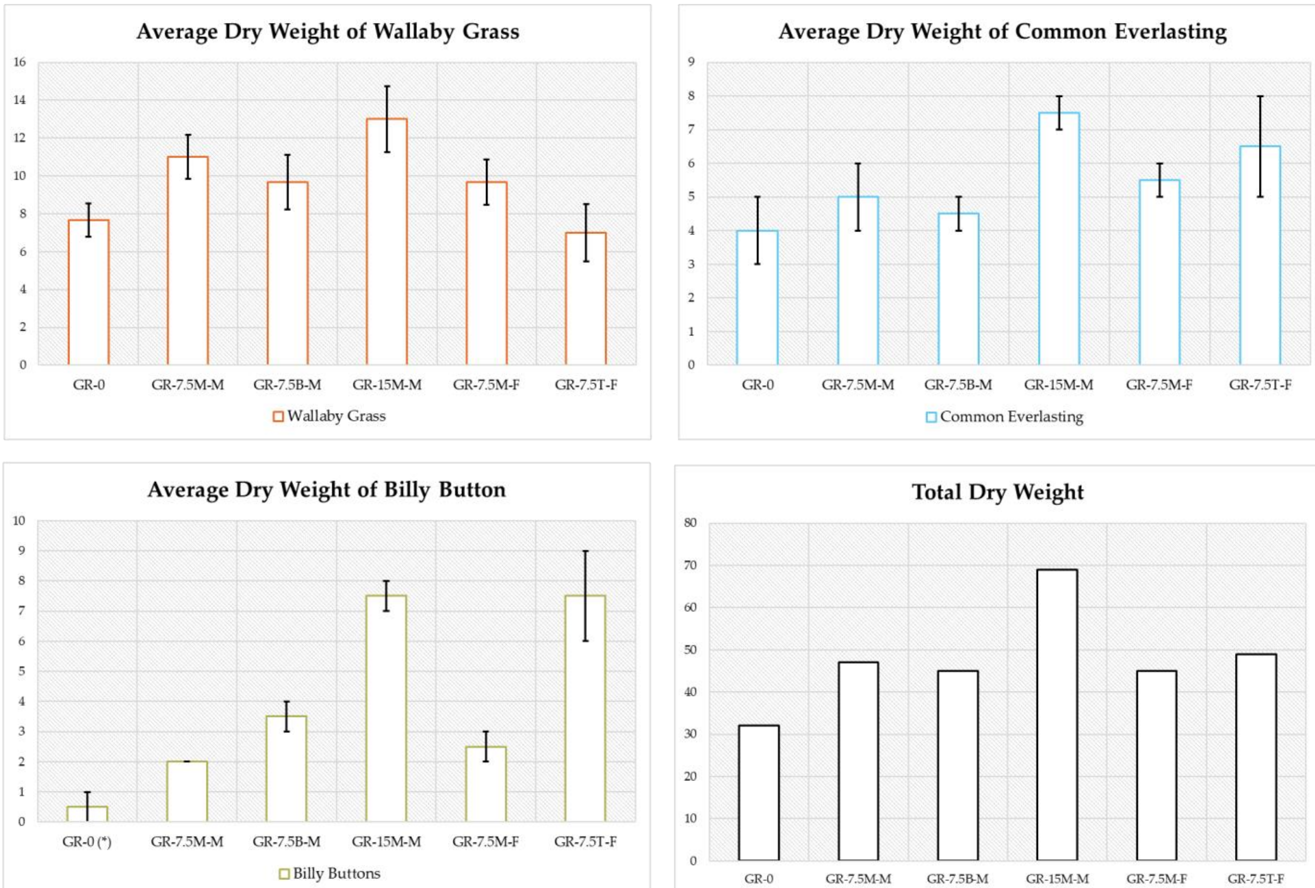

Figure 9. Average dry weight of plants with standard error in six green roof test beds at the end of the monitoring period. (*) one plant died, the average dry weight was measured from one plant only.

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.

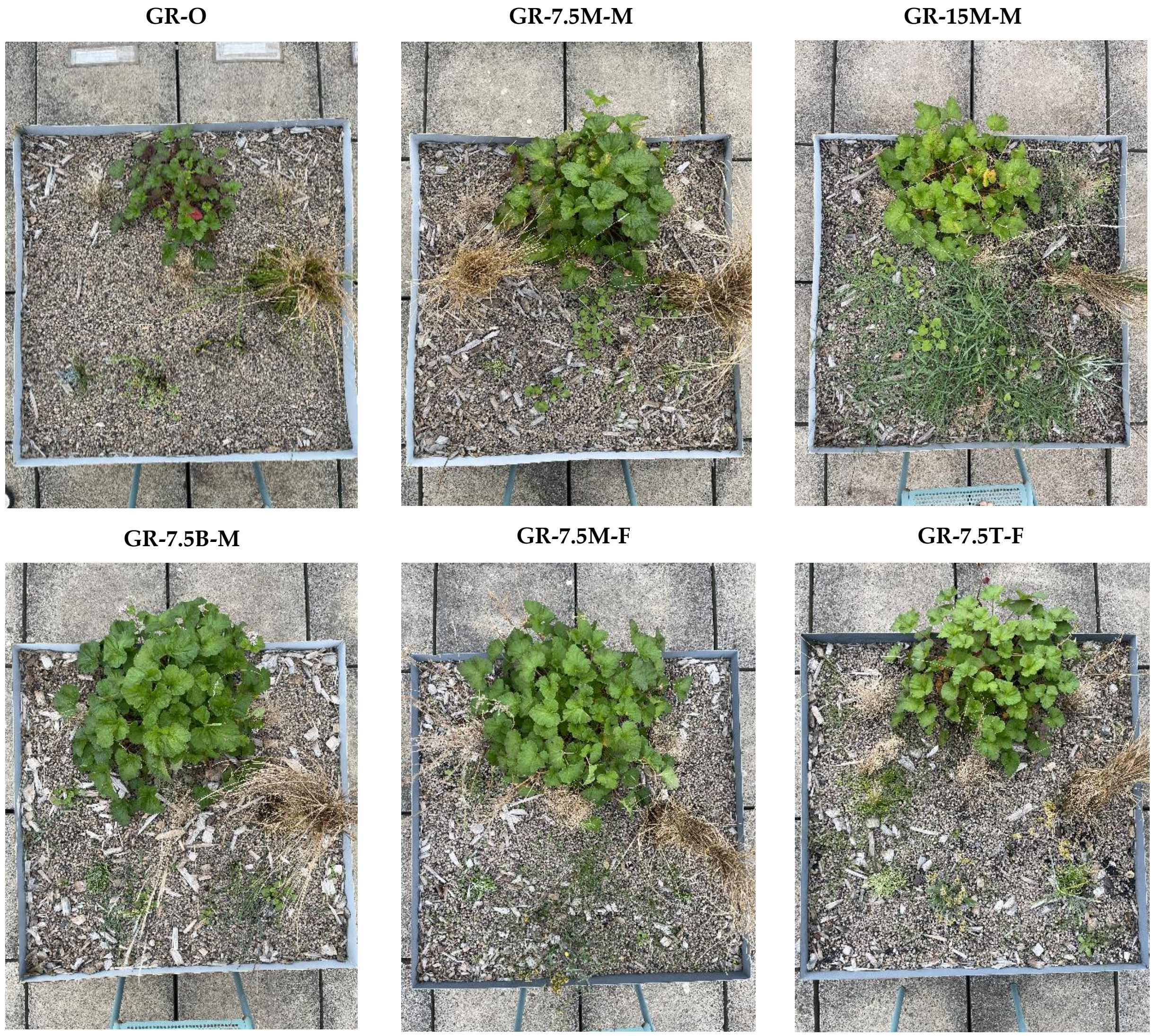

Figure 10. Plant coverage area in the six green roof test beds at the end of the monitoring period.

3.3. Substrate Temperature

Figure 11 and Figure 12 illustrate temperature data at 5-minute 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^{0}C and 3.5^{0}C for GR-7.5M-M and GR-15M-M, respectively. They were reduced to 2^{0}C during the cold days.

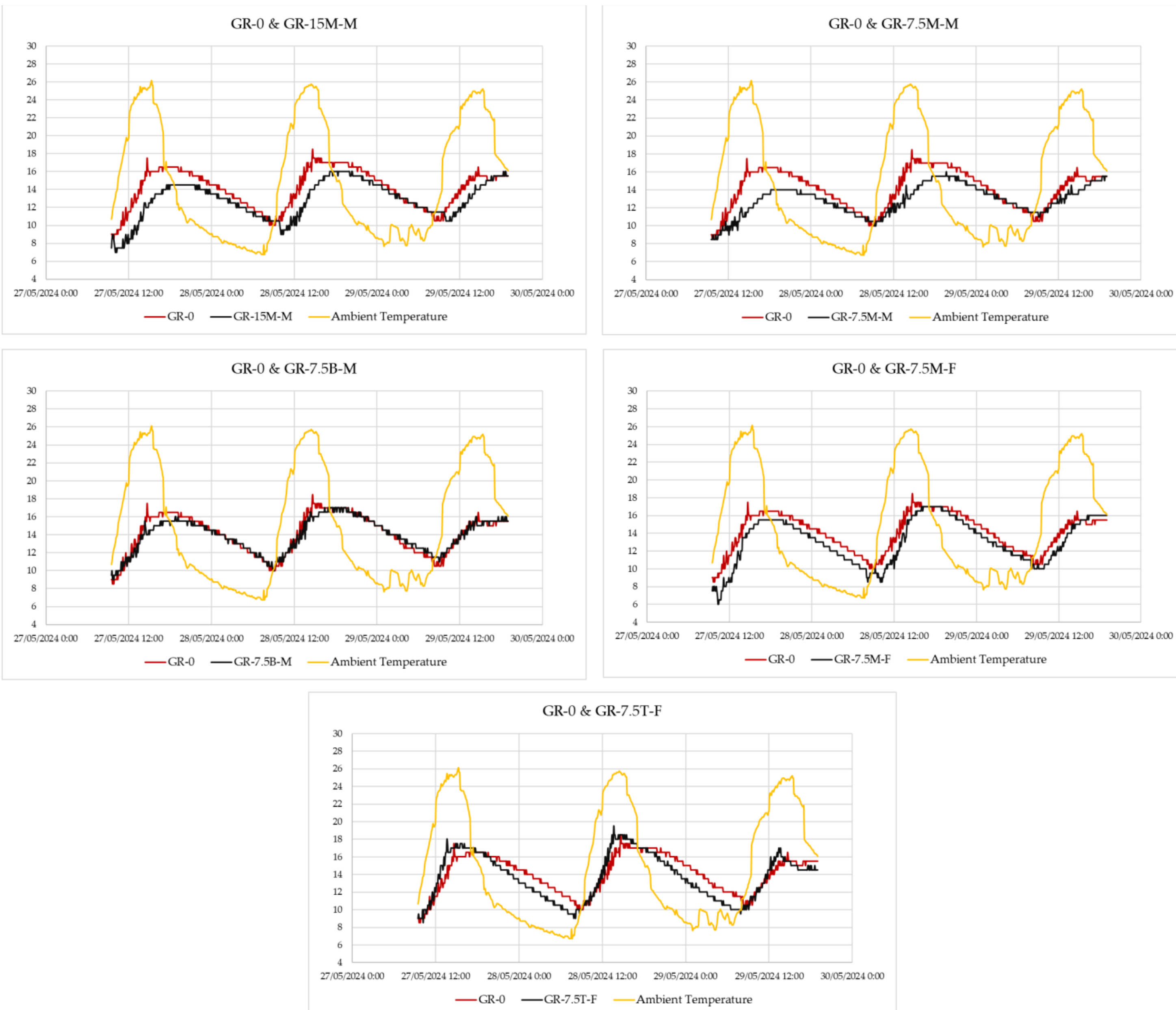

Figure 11. Temperature at 10 cm substrate depth in the six green roof test beds from 9:30 to 19:00 over three consecutive hot days (from 27 May 2024 to 29 May 2024).

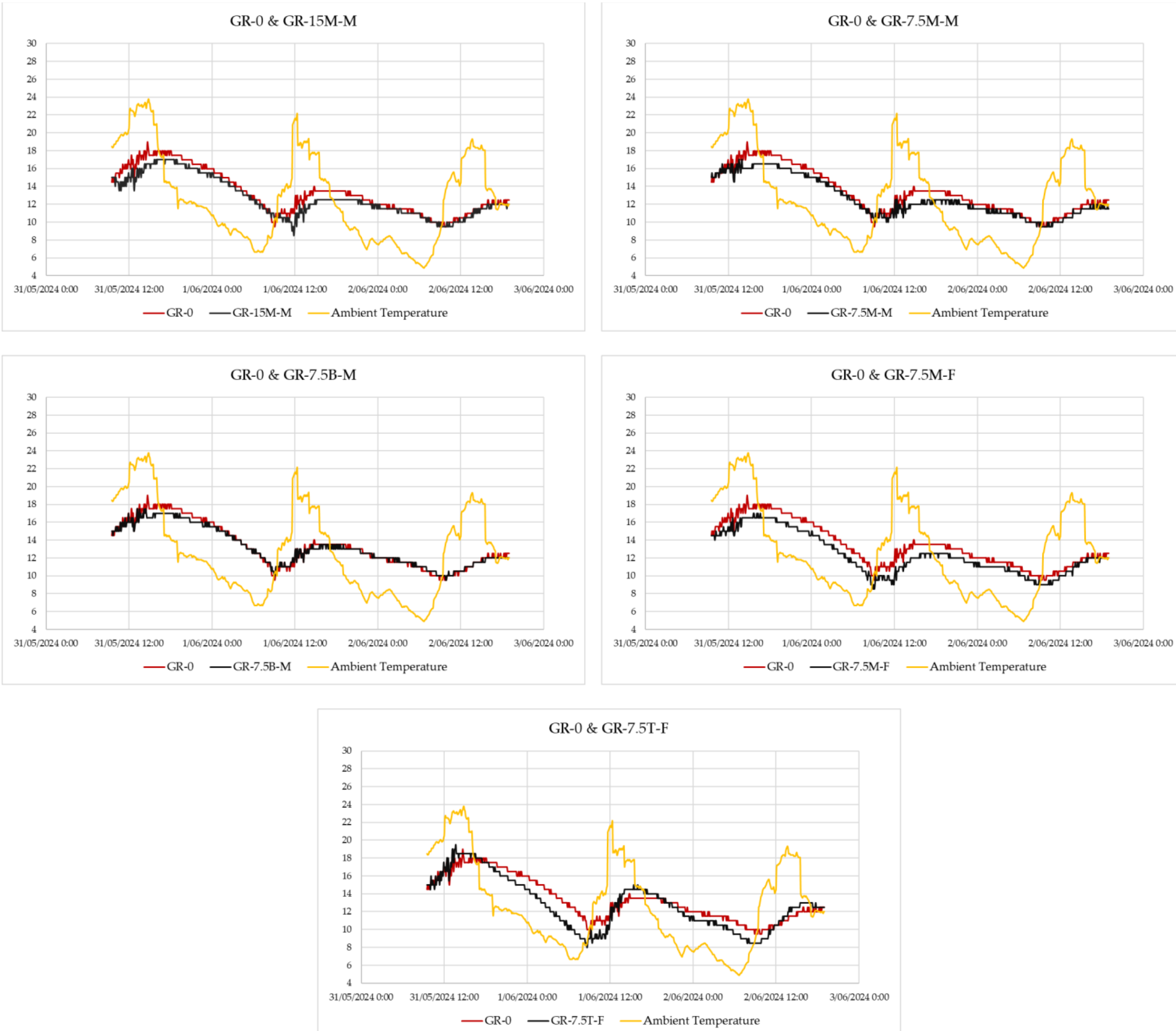

Figure 12. Temperature at 10 cm substrate depth in the six green roof test beds from 9:30 to 19:00 over three consecutive cold days (from 31 May 2024 to 2 June 2024).

4. Discussion

4.1. Impacts of Biochar on Green Roof Plant Performance

Six 1m² GR test beds were constructed on the building roof top 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 x 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 x 9 cm), and by Goldschmidt [39], which featured five replications per treatment and 45 plastic trays (60 cm x 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 multi-year 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 biochar 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 the substrate moisture and substrate temperature in hot summer (up to 45^0C). 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 thermafl 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 as 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 including substrate temperature and runoff quantity/quality was based on their direct impacts on GR plant performance. The importance of these parameters in explaining 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 2^0C relative to the reference concrete roof. A numerical approach using ENVI-met and a DesignBuilder model was adopted by Aboelata [82]. The simulation results indicated that intensive GRs reduced the energy consumption of buildings by 4%, 2.4%, and 1.4% for heights of 12m, 18m, and 30m, 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^{0}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 put 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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Chapter 6

Summary, Conclusions and Recommendations

6.1. Summary

Rapid urbanization has caused a multitude of environmental and socio-economic challenges. A primary consequence is the substantial conversion of green spaces into impervious surfaces, leading to an increase in the frequency and intensity of urban flash flooding due to reduced rainwater infiltration. Additionally, impervious surfaces contribute to the urban heat island (UHI) effect, negatively impacting human thermal comfort (HTC) and increasing energy consumption for heating and cooling. From an environmental perspective, urbanization has resulted in biodiversity loss, water pollution, and air pollution, which adversely affect human health. To address these pressing issues, numerous solutions have been introduced and implemented in recent decades. One such solution is green roofs (GRs), a water-sensitive urban design (WSUD) practice that offers a sustainable approach to transforming urban rooftop areas into green spaces. Despite extensive research, the widespread adoption of GRs remains hindered by several factors. These include the high initial costs with uncertain return on investment (ROI) and the variability in GR performance across different climatic conditions. A comprehensive understanding of GR performance and its influencing parameters is therefore essential. This PhD thesis presents a series of studies investigating various aspects of GRs, with a particular focus on stormwater management and the application of biochar.

To acquire a comprehensive understanding of the green roof (GR) concept, Chapter 2 presents two in-depth literature reviews. The first review focused on identifying current research trends and knowledge gaps to inform the development of subsequent thesis chapters. A quantitative approach was employed to collect data from over 100 published works, providing a broad overview of GR performance across various geographical locations and considering diverse GR benefits. The second review paper investigated the potential of biochar to enhance GR performance. Based on the first literature review, biochar, an innovative GR material, was identified as an area with limited research. The physicochemical properties of biochar contribute to improved GR ecosystem services, including runoff retention, runoff quality, temperature reduction, plant performance, and others. A comprehensive review of over 75 research papers published between 2010 and 2023 was conducted to summarize the performance of established biochar-amended GRs and provide recommendations for future research directions within Chapters 4 and 5. In addition to identifying research opportunities, this chapter offers insights into successful research methodologies and experimental setups to ensure the effective fulfilment of the subsequent thesis chapters.

Chapter 3 presents a conceptual stormwater model designed to simulate the hydrological performance of GRs at a catchment scale. The development of such models can contribute to increased awareness and recognition of GR benefits among authorities and the community. Data on 50-year precipitation at 6-minute intervals, flat roof areas suitable for GR installation, and impervious/pervious surface areas within the Footscray Park campus of Victoria University, Melbourne, Australia, were collected. This data was subsequently input into MUSICX eWater, an Australian-based stormwater modeling software, to assess the impact of large-scale GRs on runoff quantity and quality. The simulated GR system featured a 15-cm thick substrate composed of light-expanded clay aggregate (LECA), mulch, and coir chips. As GRs are not a built-in component of MUSICX, they were modeled using either a bioretention node, which shares similarities with GR systems, or a land-use node with hydraulic properties representative of the LECA-based substrate. The model compared runoff volume and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) between these two modeling approaches and a baseline scenario without GR implementation. The paper presented in this chapter aims to provide a simplified and reliable modeling framework that can be readily applied by non-modelers, such as urban planners, to facilitate the widespread adoption of GRs. Additionally, this research addresses the knowledge gap regarding large-scale GRs identified in Chapter 1 and presents opportunities for further research to enhance the accuracy of GR models.

In contrast to the computer modeling approach presented in Chapter 3, Chapter 4 employs field experiments to investigate green roof (GR) performance. While previous research has explored GR benefits in terms of runoff reduction, the influence of innovative materials like biochar and other factors on GR hydrological performance remains relatively limited. To address this knowledge gap, six 1 m^2 GR test beds were established on the rooftop of Building M at Victoria University's Footscray Park Campus. These test beds were elevated above the roof tiles to facilitate runoff data collection. Biochar was incorporated into five test beds using varying amendment rates (7.5% and 15% *v/v*), particle sizes (less than 1 mm and 1-3 mm), and application methods (top, mixing, bottom). The sixth test bed served as a control. A rainfall simulation device was utilized to replicate identical rainfall conditions across all test beds. The experimental design aimed to assess the impact of different biochar parameters on the runoff quantity and quality of newly established GRs. The first part of Chapter 4 focused on runoff reduction, with nine simulated rainfall events representing medium, heavy, and extreme intensities. Runoff retention and outflow delay data were collected, and the influence of GR substrate moisture and the antecedent dry weather period (ADWP) were considered. The second part of Chapter 4 investigated runoff quality. Using the same simulated rainfall depth of 10 mm, runoff samples were collected over a two-month period for water quality analysis. The selected water quality indicators, total phosphorus (TP) and total nitrogen (TN), are commonly used to assess urban stormwater quality in Australia. To ensure data accuracy, runoff samples were collected and analyzed using established protocols. While the chemical properties of the tap water used for rainfall simulation differed from those of natural rainwater, the study effectively assessed the influence of biochar on nutrient leaching in both biochar-amended and non-biochar GRs. The findings presented in Chapter 4 contribute to promoting the widespread adoption of GRs by highlighting the benefits of biochar incorporation. By considering various biochar-GR configurations, this research provides valuable insights for optimizing future biochar-GR system designs.

While previous research has investigated the influence of biochar on GR plant performance, a comprehensive understanding remains limited. To address this knowledge gap, Chapter 5 conducted a long-term field study examining plant growth within various biochar-amended GR configurations. As vegetation is a critical component of GR systems, ensuring its performance is essential for optimal GR serviceability. Building upon the experimental setup established in Chapter 4, this study monitored the performance of three plant species: wallaby grass, common everlasting, and billy buttons. Plant height was recorded fortnightly throughout a one-year period, and plant dry weight was measured at the end of the study period. To accurately determine dry weight, plants were carefully removed from the test beds using established research methods and subsequently dried in a forced-air oven at 60°C for 48 hours. To support the findings, substrate temperature was measured at a 10 cm depth. Substrate temperature is closely correlated with substrate moisture, plant water availability, and the permanent wilting point. The addition of biochar to GR substrates enhances porosity, improving plant drought resistance. Additionally, nutrient availability within the biochar-amended GRs contributed to plant performance. Data on runoff quantity and quality from Chapter 4 was used to support these findings. This chapter concludes with a discussion of biochar-related parameters and future research directions.

6.2. Conclusions

All aims identified through the cohesive framework outlined in Section 1.2 were successfully achieved. This framework helps to bridge the theoretical and practical components of the research. Key conclusions derived from this PhD study are summarized as follows:

- Extensive GRs (EGRs) remain more widely adopted than intensive GRs (IGRs) due to factors such as affordability, moderate maintenance, and reduced structural requirements. Furthermore, there is a growing trend towards integrating GRs with other systems, including green walls, blue roofs, and solar PV systems, to enhance their overall effectiveness;
- Despite positive research outcomes, the widespread implementation of GRs continues to be hindered by incomplete understanding of their performance and influencing parameters, inadequate local research, a lack of supportive regulations, and substantial investment costs;
- While current GR research primarily focuses on runoff retention and indoor/outdoor temperature reduction, other benefits, such as runoff quality improvement, air purification, noise reduction, biodiversity restoration, and socioeconomic impacts, have been insufficiently investigated;
- The performance of GRs has been reported inconsistently, particularly regarding runoff quality. This variability can be attributed to factors such as GR components (plant species, substrate mixtures, and drainage layers) and climatic characteristics;
- To attract broader attention from authorities and the community, GR benefits must be more prominently highlighted through innovative and environment friendly construction techniques and materials. This research demonstrates the potential of biochar to enhance GR ecosystem services.
- Researchers have employed a diverse range of methodologies to study GRs, including different test bed sizes, greenhouses, and modular systems. However, a

knowledge gap persists in the application of computer modeling software to understand the impacts of GRs at a catchment scale;

- While biochar has been explored in GR systems, its application remains limited, with insufficient research on biochar-amended GRs and the influence of various biochar parameters. While research indicates the significant potential of biochar to enhance runoff retention, runoff quality, plant growth, and other GR benefits, further investigation is needed to optimize its application;
- The MUSICX-based model developed in Chapter 3 simulated the performance of large-scale GRs at Victoria University's Footscray Park campus. The model demonstrated annual reductions in runoff volume, total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) loads. While significant reductions of approximately 30% were achieved for runoff volume and TN load, achieving local stormwater quality guidelines required a combination of GRs and other water-sensitive urban design (WSUD) devices;
- The field experiments conducted on biochar-amended GR test beds at the Footscray Park campus demonstrated positive hydrological performance. Biochar effectively improved water retention capacity and delayed runoff outflow under various rainfall intensities. The GR test bed incorporating 7.5% *v/v* medium biochar particles applied at the bottom of the substrate exhibited optimal stormwater management performance;
- Analysis of runoff quality from the same test beds revealed variations in performance across different biochar-GR configurations and water quality indicators. While biochar slightly increased runoff pH and reduced TN in specific configurations, its influence on other parameters was limited. Despite these mixed results, biochar's ability to improve runoff quality through enhanced water retention and subsequent reduction in pollutant loads is evident;
- The study also investigated the impact of biochar on plant performance within the GR test beds. Findings indicate that biochar positively influenced plant health, with the most favorable results observed in GRs amended with 15% *v/v* medium biochar particles. Substrate temperature, moisture, and nutrient availability were identified as key factors influencing plant performance.

6.3. Recommendations for Future Studies

Despite comprehensive investigations of green roofs (GRs) in this PhD thesis and prior studies, numerous knowledge gaps persist. To address these limitations, future research opportunities are identified and discussed in the following:

- While GRs have demonstrated effectiveness in reducing stormwater runoff and indoor/outdoor temperatures, further research on other benefits, including runoff quality, energy savings, noise insulation, air pollution, biodiversity, and socioeconomic impacts, is required. Moreover, the inconsistent reporting of GR performance highlights the need for research on influential parameters such as GR size, age, climatic conditions, and hydraulic characteristics;
- Despite positive findings, further research is required to fully understand the integration of GRs with other systems, such as green walls and solar panels;
- The knowledge gap regarding large-scale GRs identified in this thesis underscores the need for future research utilizing modeling tools to assess their performance and facilitate widespread implementation;
- The MUSICX-based model presented in Chapter 3 can be further refined by researchers and modelers to enhance its accuracy. Incorporating irrigation into future simulations is crucial, as it significantly contributes to GR runoff. Additionally, investigating the combined effects of GRs with other water-sensitive urban design (WSUD) practices, such as bioretention and wetlands, is recommended to achieve local stormwater objectives;
- The limited research on biochar-amended GRs necessitates further investigation. Future studies should focus on evaluating the impact of various biochar parameters (amendment rates, particle sizes, and application methods) on GR performance;
- Although this study demonstrated the positive influence of biochar on GR performance, additional research is required to understand the effects of initial soil moisture content, antecedent dry weather periods (ADWP), and other factors. A comprehensive understanding of biochar-related parameters is essential for optimizing biochar-GR configurations;

- The observed aging effects on GR performance in this study highlight the importance of long-term field observations. Additionally, researchers are suggested to evaluate the compatibility of biochar with different GR substrates to understand its influence on runoff quality;
- While this study demonstrated the positive impact of biochar on plant performance, variations in plant responses to biochar have been reported in other studies. Future research is encouraged to investigate the influence of biochar parameters on plant performance through multi-year field observations of diverse plant species within various biochar-GR configurations, considering specific climatic conditions to identify optimal system designs.

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