CHALMERS
UNIVERSITY OF TECHNOLOGY

Biochar as a Substrate Amendment in Green Roofs

A Comparative Analysis of Nutrient Retention, Water Management and Application Techniques

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

ALBIN NORDLANDER

DEPARTMENT OF ARCHITECHTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

MASTER’S THESIS ACEX30

Biochar as a Substrate Amendment in Green Roofs

A Comparative Analysis on Nutrient Retention, Water Management, and Application Techniques

Master’s Thesis in the Master’s Programme Infrastructure and Environmental Engineering

ALBIN NORDLANDER

Department of Architecture and Civil Engineering
Division of Water Environment Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2023

Biochar as a Substrate Amendment in Green Roofs
A Comparative on Nutrient Retention, Water Management, and Application Techniques

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

ALBIN NORDLANDER

Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2023

Department of Architecture and Civil Engineering
Division of Water Environment Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2023

Biochar as a Substrate Amendment in Green Roofs

A Comparative Analysis on Nutrient Retention, Water Management, and Application Techniques

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

ALBIN NORDLANDER

Department of Architecture and Civil Engineering
Division of Water Environment Technology
Chalmers University of Technology

ABSTRACT

Incorporating green roofs offers sustainable solutions to various urban problems, but they also present challenges such as nutrient leaching, which can impact the environment and cause eutrophication. Biochar, a carbon-rich by-product of pyrolyzed biomass, emerges as a potential solution to this problem. This carbon-negative technology can enhance soil fertility, water retention, and mitigate nutrient loss. However, the properties and subsequent performance of biochar are heavily influenced by its feedstock and pyrolysis temperature, resulting in significant variability.

This thesis compared the effectiveness of two types of biochar, conventional wood-chip biochar and granulated crop-based biochar, in improving the performance of green roofs. Initial investigations suggested superior adsorption properties in wood-chip biochar, owing to its high surface area and porosity. However, considering the application rate based on volume, revealed the granulated biochar to be more beneficial for adsorption. Granulated biochar, characterized by higher oxygen, nutrients, and ash content, demonstrated better chemical affinity which was pivotal for adsorption, outweighing surface area and porosity. No significant differences in water retention between the two biochars or the unamended substrate were observed, contradicting the expected behavior of biochar. The long-term effects of different biochars, considering aging and the impacts of microbial activity, were not analyzed in this study. For short-term adsorption efficiency, the optimal technique was to apply biochar as a layer at the bottom of the substrate. Scientific literature, however, indicated that plants benefited the most when biochar could interact with the roots. Combining both options was thus suggested as a solution for maximizing plant benefits, nutrient retention, and carbon sequestration. The literature review suggested that more studies on biochar addition to green roofs in the 10-15% (v/v) range are needed, and both plant health and nutrient retention should be addressed. The thesis concluded with the proposition that better understanding of biochar could enhance green roofs, offering an environmentally beneficial solution to the issue of nutrient leaching.

Key words: Adsorption, nutrient retention, water retention, carbon sequestration, pyrolysis temperature, feedstock.

Biokol som ett substrattillskott i gröna tak

En jämförande analys av näringshållning, vattenhantering, och appliceringstekniker

Examensarbete inom masterprogrammet Infrastruktur och miljöteknik

ALBIN NORDLANDER

Institutionen för arkitektur och samhällsbyggnadsteknik
Avdelningen för Vattenmiljöteknik
Chalmers tekniska högskola

SAMMANFATTNING

Gröna tak erbjuder hållbara lösningar för en mängd urbana problem, men de innebär också utmaningar såsom näringsläckage, vilket kan påverka miljön och orsaka övergödning. Biokol är en potentiell lösning till detta problem. Biokol är en restprodukt från pyrolyserad biomassa, och denna koldioxidnegativa teknik kan förbättra jordens fruktbarhet och vattenhållning, samt minska näringsläckage. Men dess egenskaper och prestanda påverkas starkt av råmaterial och pyrolyseringstemperaturer, vilket resulterar i betydande variationer mellan olika sorters biokol.

I detta arbete jämfördes effektiviteten hos två typer av biokol, konventionellt biokol från träflis och granulerat biokol från frörens, för att förbättra prestandan hos gröna tak. Inledande undersökningar indikerade att biokolet från träflis hade bättre adsorptionsegenskaper tack vare dess porositet och stora specifika yta. Det sig dock att det granulerade biokolet, med högre syre-, närings- och askinnehåll, hade bättre kemiska ytförhållanden vilket var avgörande för adsorptionen och överträffade specifik yta samt porositet. Ingen nämnvärd skillnad i vattenhållning mellan de två biokolen eller det omodifierade substratet observerades, vilket skiljde sig från den förväntade effekten av biokol. De långsiktiga effekterna av olika biokol, avseende åldring och påverkan från mikrobiell aktivitet, försvårade jämförelsen. För adsorptionseffektivitet på kort sikt var det optimalt att applicera biokol som ett lager i botten av substratet. Vetenskaplig litteratur föreslog dock att växter gynnades mest när biokol kunde interagera med rötterna. Att kombinera båda alternativen föreslogs därför som en lösning för att maximera fördelarna för växtliv, näringshållning, samt lagring av koldioxid. En bristande aspekt i litteraturen avseende forskning om biokol kunde identifieras, och framtida studier uppmanas anpassa sig till branschstandarder och ta hänsyn till både näringshållning och påverkan på växtliv. Avhandlingen avslutades med slutsatsen att en bättre förståelse för biokol kan förbättra gröna tak, och erbjuda en hållbar lösning till problemet med näringsläckage.

Nyckelord: Adsorption, näringshållning, vattenhållning, kolinlagring, pyrolystemperatur, råmaterial.

Contents

Preface

This study constitutes my master's thesis and it was done in collaboration with the Advanced Green Roofs research project at Chalmers University of Technology. The aim was to help with improving green roofs, and to provide data for the research project whose goal is to develop modelling tools for the transport of nutrients in biochar amended green roofs. The work of this thesis was carried out during the spring of 2023, and it concludes my studies at Chalmers University of Technology. Researching this topic has been very rewarding and educational, and I want to express gratitude to several people for helping me with this thesis; my supervisor Oskar Modin at the division of Water Environment Technology, for always being there to answer all of my questions quickly and in depth, and helping me set up the experiments; Amir Saeid Mohammadi at the division of Water Environment Technology, for all the help in the lab as well as keeping it in good shape, along with everyone's moods; Angela Sasic Kalagasidis at the division of Building Technology, as well as Dario Maggiolo and Kaj Pettersson at the division of Fluid Dynamics, for the interesting, productive and enjoyable meetings for the Advanced Green Roofs research project.

I also want to thank my examiner Britt-Marie Wilen at the division of Water Environment Technology, as well as my opponents and all the other people that were present in the lab and during the spring. You all helped with constructive questions and discussions, while making this a pleasant experience.

Göteborg, June 2023
Albin Nordlander

Abbreviations

CH_4	Methane
PFAS	Per- and polyfluoroalkyl substances
C	Carbon
O	Oxygen
H	Hydrogen
CEC	Cation exchange capacity
PAHs	Polycyclic aromatic hydrocarbons
N	Nitrogen
P	Phosphorus
GHG	Greenhouse gas
PV	Photovoltaic
v/v	Volume-to-volume
w/w	Weight-to-weight
TP	Total phosphorus
TN	Total nitrogen
COD	Chemical oxygen demand
K	Potassium
Ca	Calcium
Mg	Magnesium
PRB	Permeable reactive barrier
EMC	Event mean concentration
MB	Methylene blue
rpm	Revolutions per minute
UV	Ultraviolet

Notations

C_{ads}	Adsorbed concentration
C_{135}	Concentration after 135 minutes
C_0	Initial concentration
$C_{ads,control}$	Adsorbed concentration of the control
m_{ads}	Adsorbed mass
$m_{biochar}$	Mass of biochar
V_{liquid}	Volume of the liquid
$A_{biochar}$	Surface area of the biochar
$V_{biochar}$	Volume of the biochar

1 Introduction

The urbanization process has brought a set of environmental challenges, such as the urban heat island effect, increased stormwater runoff, reduced biodiversity, and poor air quality (Beninde et al., 2015; Lehmann, 2014; Manso et al., 2021). The Urban heat island effect is caused by the absorption of heat by excessive impervious and hard surfaces in urban areas, who also result in scarcity of vegetation and increased stormwater runoff, causing flooding and water pollution (Chithra et al., 2015). These aspects can be linked to habitat destruction, the disappearance of green spaces, and emissions of pollutants.

A strategy for addressing these issues is through the use of green roofs. Green roofs, which are essentially vegetated roofs, can assist in mitigating the urban heat island effect, reducing stormwater runoff, increasing biodiversity, and improving air quality (Liu et al., 2021). Research has shown that green roofs can have a positive effect on the microclimate, energy consumption, and even acoustics of buildings (Berardi, 2016; Manso et al., 2021). However, one challenge with green roofs is nutrient leaching (Kuoppamäki & Lehvävirta, 2016), which can lead to decreased stormwater quality, eutrophication, and costly local treatment of nutrients from the stormwater. These issues are a barrier to the widespread adoption of green roofs.

In chapter 2, The Swedish Environmental Code (1998:808) states:

Section 3 - Persons who pursue an activity or take a measure, or intend to do so, shall implement protective measures, comply with restrictions and take any other precautions that are necessary in order to prevent, hinder or combat damage or detriment to human health or the environment as a result of the activity or measure. For the same reason, the best possible technology shall be used in connection with professional activities. Such precautions shall be taken as soon as there is cause to assume that an activity or measure may cause damage or detriment to human health or the environment.

So, if local water agencies decide that green roofs cannot be constructed in a way that is safe for sensitive water bodies, they will not be permitted. A potential solution to the problem of nutrient leaching is mixing biochar into the substrate of green roofs. Biochar is a carbon rich material that is produced by heating biomass, such as wood or plant material, in the absence of oxygen (Ippolito et al., 2020). Biochar has been found to have excellent adsorption properties, which can be used to adsorb nutrients in water treatment applications (Xiang et al., 2020). The use of biochar in green roofs can not only improve the retention of nutrients, but also improve the water retention capacity of the substrate, and the survival rate of plants (Cao et al., 2014). There is a growing body of literature on the use of biochar in soils and green roofs substrates. Studies have shown that biochar can effectively adsorb a variety of compounds, including nutrients such as nitrogen and phosphorus (Dai et al., 2019, 2020). Biochar is also famous for its sustainability, as it is a carbon negative technology, and is mostly created from waste products (Allohverdi et al., 2021).

However, the properties of biochar can vary significantly depending on choice of feedstock and production method, sometimes generating vastly different results in separate studies (Ippolito et al., 2020; Pandey et al., 2020; Weber & Quicker, 2018). There are also discrepancies in experimental conditions between studies, making comparisons between different biochars challenging. As a quite novel technology within green roof systems, more clarity on its effects is needed before biochar implementation can become more widespread.

1.1 Aim

The aim of this study was to further examine the effects of mixing biochar into substrates in order to provide useful information for the future application of biochar into green roofs. Two different biochars were compared with regards to their adsorption and water retention capacity. Various mixing methods were investigated, such as mixing biochar into the substrate entirely, applying it as a layer in the bottom, or as a layer on the surface, which is how biochar would most easily be incorporated into existing green roofs. The two biochars were also compared with regards to their water retention capacity in a commercial substrate. Furthermore, the project was conducted in collaboration with a research team that uses the test results to calibrate mathematical models describing the transport of compounds within green roofs. In summary, the ambition was that this master's thesis would contribute to making a positive impact, provide useful information, and drive research forward within the green roof industry. To enable a good discussion, circumvent the limitations as well as possible, and to provide a quality collection of current knowledge in the subject in one place, a literature review was also conducted. Research questions for this thesis included:

- How do the two different biochars in this study compare to one another with regards to adsorption capacity and water retention?
- What is the optimal mixing method and application rate for incorporating biochar into the substrate of green roofs, to improve adsorption capacity, nutrient retention, and plant growth?
- How does the water retention in a commercial green roof substrate change when either of the two types of biochar is incorporated, compared to the same substrate without any biochar?
- What is the release rate of nutrients from fertilizer pellets added to green roofs?

1.2 Scope and Limitations

One experiment included the use of a real green roof substrate, pouring water onto the soil and measuring the difference in water retention between a substrate with and without biochar. However, most of the laboratory experiments were not conducted with real green roof soils, but with a substrate consisting of small transparent glass beads mixed with biochar. As such, the impact of biochar on green roof plants was not investigated, nor was the interplay between biochar and soil with regards to nutrient retention. Only the adsorption properties of biochar on a dissolved organic substance, and to some extent water, were analyzed in the laboratory. The data from the laboratory experiments were then compared and used in conjunction with data from scientific literature to discuss the effects, such plant growth, as well as nutrient and water retention, that biochar can have on real green roofs. Furthermore, the properties of biochar are dependent on feedstock and production temperatures (Zhao et al., 2013). In this project, only two different batches and types of biochar were used. Although the different effects and properties between these two types of biochar were compared and analyzed, it is not certain how well the results would correspond with other types of biochar.

2 Literature Review

The literature study was conducted to gather knowledge about the production, properties, and uses of biochar, as well as its effects on soils and plants. Information about green roofs, including their problems and limitations, was also gathered. Finally, literature covering the combination of green roofs and biochar was reviewed. Particularly the studies that included experimental setups.

In the literature study, all 63 scientific articles on Scopus that appeared when searching "(biochar) AND (green roof) OR (green roofs)" were manually scanned. Apart from Scopus, Google Scholar was widely used for finding relevant literature. For sections about biochar and green roofs on their own, meta reviews and analyses were prioritized. Sometimes sources from these articles were reviewed further. Articles that received close examination were mainly chosen based on their publishing dates and the general impressions from their abstracts. The journal that published the article and number of citations also mattered. Mainly though, articles and literature that received close examination were included based on their quality and relevance. This was determined by qualitative judgement. Some industry recommendations, reports and manuals for green roofs and biochar were also included, such as those published by the Swedish biochar research project Rest till Bäst (rough translation - from waste product to "best" product). A vast majority of publications included in the literature study were in English, but some Swedish publications were also used.

2.1 Biochar – Production, Properties, and Uses

The increasing curiosity and enthusiasm for biochar among scholars and professionals stem from its unique characteristics, which provide solutions for environmental, agricultural, and industrial challenges (Atkinson et al., 2010; Jeffery et al., 2011; Woolf et al., 2010). Biochar, a carbon-rich and porous substance, is created by breaking down organic materials in low-oxygen environments through a thermal process, called pyrolysis. This process results in a material high in carbon content and with a large surface area due to its porosity. Thanks to these characteristics, biochar showcases versatility across a wide array of potential uses. Notable examples are flue gas treatment, water treatment, serving as an alternative to coal and coke in metallurgical procedures, enhancing agricultural practices and animal husbandry, contributing to building materials, and even being utilized for medical applications (Weber & Quicker, 2018). Many professionals are against using biochar for energy production, as stated by the European Biochar Certificate (Fransson et al., 2020). This is probably due to the energy inefficiency of first sending material through a sometimes energy intensive pyrolysis process during production only to burn it afterwards, and because biochar in other applications instead act as a carbon sink (Allohverdi et al., 2021; Lehmann et al., 2006; Woolf et al., 2010). Biochar is a stable material perhaps most famous for its carbon sequestering abilities, as it can bind carbon for thousands of years. If biochar is used without being burned, for example as a soil amendment, it can both improve the soil and act as a carbon sink simultaneously (Kamali et al., 2020).

The use of biochar dates back thousands of years to populations native to the Amazon. European colonisers and settlers in the 1800s found fertile black soils on some places in the lowlands of the Amazon that were excellent for agricultural use, as opposed to the regular soils in the rainforest (Fransson et al., 2020). The properties and origins of the soil sparked interest among researchers. While many ancient remains and traces of settlements were found in the area, nobody knew if the soils were naturally occurring or not. At the end of the 20th century however, most scientists agreed that the black soils were a result of human activities (Glaser et al., 2001). The native population used a low-intensive carbonisation method that was more controlled than regular slash-and-burn agriculture, which resulted in the carbon-rich soil. The Terra Preta nova (the new black soil) as it is now called, contains several orders of magnitude more bioavailable phosphorus, as well as more healthy and helpful microorganisms, and it results in slower nutrient cycling compared to regular amazon soil (Fransson et al., 2020).

The pyrolysis process includes heating organic materials in an atmosphere with little to no oxygen in temperatures usually ranging from around 300 degrees Celsius, up to as much as 900 degrees Celsius or more (Joseph et al., 2021). In modern pyrolysis facilities, the temperature is controlled and often quite high, the residence time is long (>15 min), and the volatile gaseous compounds are extracted and taken away from the pyrolysis chamber (Fransson et al., 2020). The volatile compounds from the feedstock create gases like CO_2 and methane (CH_4) among others, which can be captured and used as renewable energy product (Azzi et al., 2019; Matuštík et al., 2020). The gases can also be filtered and released into the atmosphere, as concentrations are usually below permitted limits (Paulsson, 2020). Even though some CO_2 and CH_4 is formed during pyrolysis, less CO_2 equivalents are generated during pyrolysis than during natural decomposition, as it otherwise would not result in carbon sequestration. Recent studies have also found the pyrolysis process to be efficient in breaking up organic contaminants such as per- and polyfluoroalkyl substances (PFAS), known as “forever chemicals”, should they be present in the feedstock (Bamdad et al., 2022; Thoma et al., 2022).

Feedstock and temperature during production largely impacts the properties of the final biochar (Hassan et al., 2020). Feedstocks are often waste products, typically from crops, woody materials, animal manure, or sewage sludge, although any biogenic material could theoretically be used (Weber & Quicker, 2018). Since there is an abundance of organic wastes being produced all over the world, using some of it for biochar production can be a sound strategy for improving environmental sustainability. With proper knowledge, biochar from different feedstocks could be applied for different purposes best suited for their properties. The race towards a sustainable society has likely contributed to the high interest in biochar, and research about this material is still increasing (Wu et al., 2019).

2.1.1 Production and Feedstock Effects on Biochar Properties

Biochar's physiochemical properties are significantly influenced by production conditions such as temperature, heating rate, retention time, and air conditions (Pandey et al., 2020). Most researchers emphasize pyrolysis temperature and feedstock as the most important aspects (Ippolito et al., 2020; Weber & Quicker, 2018). Heating rate and residence time also plays a big role, but it is generally agreed that a longer residence time with a bit lower heating rate (slow pyrolysis) is preferable for the high yield production of stable, high-quality biochar to be used in soils (Ameloot et al., 2013; Brown et al., 2011; Leng & Huang, 2018; Pandey et al., 2020; Tan et al., 2021). Therefore, the aspects of heating-rate and residence time will not be covered deeply in this section.

Biomass for biochar production primarily consists of cellulose, hemicellulose, and lignin (Kim et al., 2020). Lignin is the most stable and contributes to the highest biochar yield, while cellulose and hemicellulose are more volatile (Weber & Quicker, 2018). Most volatile compounds are converted into gases during pyrolysis, while much of the stable carbon (C) and some nutrients remain. Particularly phosphorus, but also nitrogen to a lesser extent (Fransson et al., 2020). The characteristic high specific surface area and porous structures are formed when some compounds decompose, and others do not (Li et al., 2019). Higher pyrolysis temperatures generally lead to more porous structures with increased specific surface area, and higher concentrations of fixed C (Hossain et al., 2020; Weber & Quicker, 2018). Since the volatile compounds contain acidic functional groups, the pH of biochar increases at higher pyrolysis temperatures as these compounds detach (Zhang et al., 2015). The functional groups largely consist of Oxygen (O) and Hydrogen (H) which also decreases, as these elements more readily decompose than C during pyrolysis (Janu et al., 2021). Consequently, functional groups and Cation Exchange Capacity (CEC) are less prominent in high-temperature biochar, as functional groups contribute to higher CEC (Joseph et al., 2021). Low temperature biochars can also contain more polycyclic aromatic hydrocarbons (PAHs), which are harmful substances that are created during partial decomposition.

Various biomasses can be used as feedstock for biochar production, most of which contain some moisture in the form of water vapor, free liquid, or chemically bound water (Tomczyk et al., 2020). It is recommended to use dry feedstock, as water content increases energy requirements during pyrolysis. Woody feedstock, commonly used for biochar production, is rich in lignin and cellulose (J.-Y. Kim et al., 2020; L. Li et al., 2023). The degradation of cellulose and hemicellulose, along with the partial degradation of lignin, creates porous structures and high specific surface area in biochar (Tomczyk et al., 2020). Consequently, woody feedstocks generate biochar where these characteristics are more prominent, compared to other feedstocks (Joseph et al., 2021). However, woody biochar contains fewer plant-available nutrients than manure-based biochar and biochar from sewage sludge, with crop- and grass-based biochar falling somewhere in between (Joseph et al., 2021). The CEC of biochar is correlated with the nutrient content and, to some extent, the ash content (Gai et al., 2014), which are more prevalent in the non-woody feedstocks. Nonetheless, it is crucial to avoid excessive ash and inorganic materials in the feedstock, as they can negatively affect the pyrolysis process (Paulsson, 2020). Robust analysis and quality assurance of the feedstock is needed to produce a biochar of high quality. For example, if the feedstock contains a lot of Cadmium, a pyrolysis temperature of 700 degrees or more is needed for removal. Other metals can be present as well, but they are generally not found in harmful quantities.

To summarize, higher pyrolysis temperatures correlate positively with higher pH, specific surface area, more pores, and fixed C concentrations (Joseph et al., 2021). Pyrolysis temperature correlate negatively with CEC, as well as presence of functional groups and PAHs (Tomczyk et al., 2020). N is removed to some extent with higher temperatures, while P and other nutrients and minerals are not as affected (Naeem et al., 2016). Meanwhile, woody feedstock results in a high yield of biochar, with a lot of fixed C, pores and specific surface area, with a lower nutrient content and CEC (Joseph et al., 2021). Biochar from sewage sludge and animal manure results in more nutritious biochar, with low specific surface area and less pores, but with high CEC and more functional groups. Grass- and crop-based biochar usually fall somewhere between these in terms of properties. With temperature adjustment though, it is possible to significantly alter the properties of the biochar regardless of feedstock.

2.1.2 Effect on Soil and Nutrient Retention Mechanisms

Apart from its carbon sequestering properties, biochar might be most famous for its use a soil amendment. Biochar can cause profound changes to soil properties and functions, such as increase soil pH, CEC, porosity and aeration, soil stability and bioavailable nutrients, water retention, provide habitat for helpful microorganisms and fungi, while decreasing nutrient leaching (Joseph et al., 2021). Nonetheless, careful application and thorough understanding are necessary when using biochar, given that not all changes it induces are instantly beneficial to all soil types. As mentioned, different biochars can also have very different properties.

When first applied, fresh biochar can temporarily immobilize nitrogen (N) in the soil, partly via adsorption (Dai et al., 2020). Biochar may initially also exhibit a low CEC due to the reduction of oxygen containing functional groups during pyrolysis (Weber & Quicker, 2018). When the CEC of biochar is low initially, the exchanging of ions and interaction with nutrients is also low, even if the nutrients are adsorbed on the surface and pores of the biochar. This fixes the nutrients in place and decreases their availability to plants. Biochar also quickly increases the number of microorganisms in the soil when applied who also start competing for N initially (Phillips et al., 2022). However, over the course of a few months, the CEC of biochar increases as it ages and becomes more integrated with the soil. In the long run, biochar increases the CEC of soils by a lot compared to unamended soils, allowing the retention of more nutrients while enhancing their availability to plants (Joseph et al., 2021). To address the initial limitation in N availability, priming biochar with N can be beneficial and is usually recommended. If priming biochar with N is not done, the Swedish biochar research project Rest till Bäst recommends using 1.5-2 times the normal amount of N fertilizer in conjunction with the application of biochar (Fransson et al., 2020).

Another significant effect of biochar on soil is its ability to increase the pH. While this can be advantageous in acidic soils, where it can help neutralize the pH and improve nutrient availability, it may not be suitable for all soils. In some cases, a high pH may lead to nutrient imbalances or reduced nutrient availability, highlighting the importance of considering the specific soil conditions and properties of particular types of biochar (Odutola Oshunsanya, 2019). Introducing biochar to organic soils such as peat moss, can lead the increased microbial activity that follows to contribute to the digestion and decomposition of the organic materials in the soil, increasing greenhouse gas (GHG) emissions (Fransson et al., 2020). While peat moss provides a good soil structure, and excellent water retention, it is not renewable. Biochar has thus been suggested as a sustainable alternative, as it offers some similar benefits, such as water retention, but also additional advantages (Głodowska et al., 2016). As stated previously though, applying biochar in already functioning organic soils might not be constructive. Some sources however claim that biochar on the contrary can reduce GHG emissions and the decomposing of already present soil C (Joseph et al., 2021), but this is disputed in other sources. For example, biochar has been shown to increase methane production in anaerobic digestion (Wang & Wang, 2019), and increase the rate of composting (Akdeniz, 2019), indicating more rapid C decomposition and increasing GHG emissions. The interplay between biochar and digestion of other present organic materials in soils is likely quite complicated, and Jeffery et al. (2016) claims it varies from case to case.

Biochar provides most of its benefits a while after application, when it has aged and become integrated into the soil (Joseph et al., 2021). The integration of biochar with soil over time is a complex process that involves physical, chemical, and biological interactions. The porous structure of biochar provides habitat for soil microorganisms, which in turn break down organic matter and release nutrients (Fransson et al., 2020). Additionally, biochar particles can aggregate with other soil components, enhancing soil structure and water-holding capacity (Blanco-Canqui, 2019). Biochar may also become slightly oxidized. All these aspects increase the formation of functional groups on the surface of biochar, increasing its CEC, which retains nutrients in the soil while synchronously making them more available to plants (Joseph et al., 2021). Biochar has various effects on plant health, including impacts on seed germination, plant growth, flowering, the ability to resist diseases, and adaptation to environmental stresses. A meta-analysis found that applying biochar with fertilizer can lead to increased plant productivity with an average improvement in crop yields of 15% over one year in various climates, compared with only applying fertilizer (Ye et al., 2020). Another

meta-analysis showed that biochar reduces N leaching by an average of 26%, as well as improves phosphorus (P) availability for plants (Joseph et al., 2021). While plant benefits are often attributed to biochars with high CEC, those types of biochar have some disadvantages. These include the incomplete breakdown and phytotoxicity of some materials from low pyrolysis temperatures, as well as lower long-term stability, surface area, and porosity, of sludge, compost, and animal manure based biochars (Weber & Quicker, 2018). As such, a medium high to high pyrolysis temperature used on nutrient rich crop feedstock can perhaps create a versatile biochar, that provides most of the benefits suitable for many soils. However, it is important to remember that biochar preferably should be produced from waste materials, and that all biochar can have functions and benefits at the right place. Sticking to only one type of biochar is not taking advantage of the abundance of organic waste materials that are being produced everywhere, and it might not be viable in the long run.
The long-term effects of biochar on soil are generally positive. This is evidenced by the ancient Terra Preta soils found in the Amazon Basin. These soils, enriched with biochar, have remained fertile for centuries, suggesting that biochar can contribute to sustainable agricultural practices (Joseph et al., 2021). Crop yields from Terra Preta soils are approximately twice as high compared to nearby unamended soils. Several studies show that just a single application of biochar in varying conditions combined with fertilizer can increase crop yields for several years, in some cases combined with an increased resistance to pests (Kumar et al., 2018; Rafiq et al., 2020; Ye et al., 2020). Biochar also has potential for soil remediation purposes, as it can help immobilize heavy metals and other contaminants, reducing their bioavailability and mitigating their impacts on plants and ecosystems (Wang & Wang, 2019).

In summary, biochar offers significant potential for improving soil properties and nutrient retention mechanisms, but its effects can be highly dependent on the feedstock and production conditions. To optimize the benefits of biochar, it is essential to consider factors such as feedstock type, production temperature, and appropriate application rates for the specific soil conditions. By tailoring biochar applications to these factors, it is possible to harness its full potential in enhancing soil health and promoting sustainability.

2.2 Green roofs: Types, Benefits, and Limitations

Green roofs offer a wide array of benefits in urban areas, contributing in multiple ways by managing stormwater and neutralizing acid rain, reducing the urban heat island effect, extending roof life, and providing habitats for plants and wildlife (Francis & Jensen, 2017; Y. Li & Babcock, 2014; Shafique et al., 2018). Additionally, they can improve the quality of life for residents by decreasing energy consumption of buildings, reducing air and noise pollution, increasing aesthetic value, providing recreational opportunities, and offering space for food production. As such, these vegetated rooftops generate ecosystem services that provide environmental, economic, and social benefits for residents in cities. With roofs accounting for around 40-50% of total paved areas, and 20-25% of the total urban area (Besir & Cuce, 2018), utilizing green roofs is an opportunity that can create substantial positive impacts. Although green roofs and photovoltaic (PV) cells may seem like competitors, they can both be utilized effectively for different purposes in the right places. There is still ample unexploited roof space for both solutions individually, but limited studies have shown that co-constructing them can offer benefits for both. Green roofs can be protected by the solar panels from the elements, while PV cell efficiency can be enhanced through cooling from the green roofs (Shafique et al., 2020).

There are three main types of green roofs: intensive, extensive, and semi-intensive (Vijayaraghavan, 2016). Intensive green roofs feature a thick substrate layer (usually 200-2000 mm), a wide variety of plants, and higher maintenance and capital costs due to their weight affecting the building structure. They can support diverse plant life, such as shrubs and small trees, but require regular upkeep, including fertilizing, weeding, and watering. Extensive green roofs, on the other hand, have a thinner substrate layer (often less than 150 mm) and are characterized by lower capital costs, weight, and maintenance requirements. In practice though, the most common extensive roofs, sedum roofs, usually have substrate layers of ranging between 30-80 mm thick (Pettersson Skog et al., 2021). Extensive roofs can support limited vegetation types, such as grasses, mosses, and some succulents, making them suitable for situations where no additional structural support is needed. Semi-intensive green roofs fall between the two, offering a balance of features. The classifications are based on the types of vegetation they can support, as well as their maintenance requirements, rather than their substrate thickness.

The foremost obstacle in implementing green roofs is the cost, as installation requires substantial investment depending on factors like the type of green roof, location, labor, and equipment (Vijayaraghavan, 2016). Moreover, operation, maintenance, and disposal add to the overall expense. Many cost-benefit analyses overlook certain aspects, leading to biased observations. Benefits such as air quality improvement, urban heat island reduction, aesthetics, ecological preservation, and noise reduction are difficult to quantify and may not directly translate to savings for building owners, making it challenging to justify green roof costs.

Urban environments subject plants to harsh conditions, such as low humidity and limited access to water and nutrients (Paulsson, 2020). Ensuring the long-term survival of green roofs requires maintenance like fertilization and, in some cases, irrigation, which can deter some developers, owners, and managers of real estate. Commercial developers may seek unrealistic assurances, such as green roofs without irrigation, fertilization, or weed growth (Vijayaraghavan, 2016). To minimize irrigation intervals, plant selection is often limited to a few succulent species, which can compromise aesthetic appeal and discourage customers. In the early stages, green roofs may require significant fertilization, which can lead to considerable nutrient leaching. Stakeholders may need to take measures to address this issue, with Grönatakhandboken (the Green

Roof Manual) even suggesting redirecting the runoff to other vegetated surfaces for the first few years (Pettersson Skog et al., 2021). Concerns also arise around the additional work required to repair green roofs in case of sealing issues. While some may believe green roof installation increases the likelihood of leaks, research has shown that green roofs can actually extend roof life by protecting the waterproof membrane from ultraviolet (UV) exposure, heat, cold waves, and mechanical damage (Vijayaraghavan, 2016).

In retrofitting existing buildings with green roofs, the main concerns involve the additional loads and potential structural failure (Shafique et al., 2018). Green roofs require growth media with low bulk density to prevent structural collapse, especially in older buildings with load restrictions. An optimal substrate should be lightweight, stable, and capable of supporting a wide range of vegetation while helping plants withstand extreme climatic conditions. It is also essential for the substrate to have high water holding capacity and minimal leaching for better performance.

2.2.1 Nutrient Cycling and Mechanisms of Leaching in Green Roofs

The release of nitrogen and phosphorus contribute to eutrophication, which is one of the largest environmental problems globally, leading to oxygen depletion in shallow waters and potential reductions in certain fish and biotic populations (Khan & Mohammad, 2014). As stated previously, nutrient leaching from green roofs can be particularly high in the early stages of its lifetime. This is probably because the more readily available nutrients have been washed away later on, and because older roofs have more substantial root systems that can bind nutrients more efficiently (Pettersson Skog et al., 2021). New green roofs also often require more fertilization in order for plants and roots to become alive and well after installation. Studies have found that nutrient discharge from green roofs is closely linked to fertilizer use (Shafique et al., 2018). Conventional fertilizers in particular can cause high nutrient concentrations in runoff. Therefore, using slow-release fertilizers is recommended, and has been proven to efficiently reduce nutrient leaching. Apart from fertilization and maintenance practices, as well as the age of the green roof, leaching is also influenced by various other factors. These include the type of growth medium, green roof type (extensive or intensive), substrate depth, vegetation, rainfall size, and the type of drainage (Vijayaraghavan, 2016).

It is generally agreed that intensive green roofs leach more nutrients than extensive green roofs, owing to their usually deeper substrate but also due to the type of vegetation found on these roofs (Vijayaraghavan, 2016). The sedum species which are common on extensive green roofs are very resilient to climate conditions much thanks to their water- and nutrient retaining capabilities, resulting in less leaching (Shafique et al., 2018). The same properties of sedum also result in lower maintenance requirements, which is probably why they are so popular globally. Maintenance of sedum roofs are usually required only once every two to three years (Pettersson Skog et al., 2021), and experts are constantly trying to find ways for decreasing the required maintenance. It's important to remember though, that while sedum roofs are cheap and low maintenance, they don't provide the same ecosystem services as intensive green roofs.

Rainfall intensity highly affects the leaching of nutrients. Nitrogen is very mobile in water, and several studies have shown that both nitrogen and phosphorus leaching is higher during more heavy rainfall (Y. Li & Babcock, 2014). Both nutrients, but particularly phosphorus, were often higher in concentration than the U.S EPA guideline values. Those studies were from some time ago, but Grönatakhandboken confirms the same trend (Pettersson Skog et al., 2021). Besides using slow-release fertilizer, ways to mitigate leaching due to heavy rain include not irrigating before heavy precipitation, as well as avoiding fertilization during wet seasons. With proper knowledge it is possible to create a balance between nutrient availability in the substrate, and nutrient requirements of the green roof vegetation. Substrate type also plays a big role in the amount of nutrients that can be retained in green roofs. Preferably it should have a high water-holding capacity, as nutrients leach with the infiltrated runoff. Recently, biochar incorporation into green roof substrates has emerged as solution for decreasing the leaching of nutrients even further, as it can retain nutrients with its physiochemical properties.

2.3 Biochar in Green Roofs Substrates – Previous Studies and Knowledge

Given the extreme habitats that green roofs present, characterized by drought, nutrient deficiency, extreme temperatures, and high wind speeds, strategies for enhancing their resilience and promoting plant growth are essential (Chen et al., 2018; Kuoppamäki et al., 2021; Liao, Drake, et al., 2022a). The tendency for green roofs to leach nutrients in its early age or when fertilized, is an additional challenge that needs to be managed. In this context, biochar emerges as a potentially advantageous solution. This lightweight and recalcitrant substrate amendment offers high nutrient and water retention capacities, acting as a buffer against these harsh conditions. Introducing biochar into green roof systems can thus lead to substantial weight reductions, improvements in plant performance, and reduced maintenance needs. As the incorporation of green roofs in urban areas is often done to improve sustainability, the carbon sequestering properties of biochar should also be well-received by stakeholders. Therefore, the synergistic combination of biochar and green roofs presents a promising avenue for optimizing the function and sustainability of these urban ecosystems.

The recommended quantity of biochar to integrate into any vegetated soil should ideally not exceed the 20-25% range, calculated on a volume-to-volume (v/v) basis. Several studies, either reported by or conducted by Rest till Bäst, have demonstrated that surpassing this threshold can detrimentally affect plant performance (Chen et al., 2018; Fransson et al., 2020; Paulsson, 2020). Common rates of biochar incorporation typically fall within the 10-15% (v/v) range, with the same studies showing this range to yield the most optimal results for plant health and growth.

Numerous considerations support the use of volume, rather than weight, as the guiding metric for incorporating biochar into green roof substrates. The most compelling of these reasons is that plants primarily interact with their substrate through the volume and the spatial distribution it offers, not its weight. Key factors of the substrate that directly impact plant growth, such as water retention, nutrient retention, air space, and the CEC of the biochar, are primarily influenced by elements such as porosity and surface features, which have less to do with density. Different biochars exhibit a wide range of densities, from 80-320 kg/m^3 (Brewer & Levine, 2015), and thus using a fixed weight-to-weight ratio (w/w) may lead to inconsistencies. For instance, incorporating 5% biochar by weight could translate to a 10% (v/v) for one type of biochar, and over 30% (v/v) for another. Some biochars are also quenched with water after pyrolysis, which increases their weight without affecting their volume or other properties (Fransson et al., 2020). Therefore, using volume as a guide when integrating biochar into green roof substrates offers a more reliable and consistent approach.

Considering the information listed above, and from previous sections, many of the studies conducted on the topic of biochar in green roofs had some room for improvement. For example, both the volume fraction (v/v) and the weight fraction (w/w) are relevant to report when biochar is added to green roof soil; however, many studies only provide information about the weight fraction (Gan et al., 2021, 2022; Goldschmidt & Buffam, 2023; Haeldermans et al., 2023). Liao et al. (2022) compared two biochars that were applied on a w/w basis, but also provided the bulk densities of all materials which made a translation into v/v possible (see Appendix 1). This showed that 12% biochar was added for one type, and 21% for the other type, based on a v/v ratio. This kind of discrepancy makes it difficult to make a fair comparison between the two, as the impact of different types of biochar depends heavily on the volume that was applied. In some studies, the addition of up to 40% (v/v) biochar was used (Cao et al., 2014; Werdin et al., 2021), while perhaps there could have been more focus on the 10-15% range. In other studies, local soil was used without the addition of any fertilizer, instead of commercial green roof soil with fertilizer (Chen et al., 2021; Gan et al., 2021). In one study, the biochar pyrolysis temperature was reported to be within a large span of several hundred degrees Celsius (Xiong et al., 2023). Olszewski & Eisenman (2017) compared plant performance for substrates with biochar, versus a control substrate with no biochar. However, the control had an entirely different substrate composition than the biochar-amended ones. Very few studies included experiments where the biochar had been primed with nutrients before application, even though initial biochar immobilization of N is reported by several authors (Dai et al., 2020; Fransson et al., 2020; Joseph et al., 2021; Paulsson, 2020; Phillips et al., 2022; Weber & Quicker, 2018). There is a large variety in experimental conditions and data provided in scientific studies of biochar amendment in green roofs, which makes it difficult to compare studies and provide design recommendations.

2.3.1 Effects on Nutrient Leaching and Plant Well-being

Kuoppamäki et al. (2016) used a <2 mm sieved birch biochar pyrolyzed for 2 hours at 380-420˚C in several green roof systems totalling 26 modules. The substrate consisted of 85% recycled and crushed brick, 5% compost, 5% crushed bark and 5% sphagnum moss. 7% biochar (w/w) was applied either as bottom layer in the substrate (buried biochar) or mixed with water and spread as evenly as possible on the top (surface biochar). Buried biochar modules reduced Total Phosphorus (TP) leaching by 25-35%, while surface biochar resulted in a 10% reduction. Looking at their provided graph, the trends and percentages were in the same range for Total Nitrogen (TN) leaching reduction, however not explicitly stated in numbers. However, TP and TN concentrations in runoff were not that different to the control. It seems that the reduction in runoff quantity had the biggest effect on the leaching. In a laboratory experiment from the same article, they compared another type of biochar with their first, main type. This new biochar was pyrolyzed at 450˚C for 23 hours by another company, and the feedstock type was not stated. There were however substantial differences in surface area and pH between the two biochars. 7 m^2/g and a pH of 7.6 for the main biochar, and 140 m^2/g and a pH of 9.2 for the other type. Compared to the control, the main biochar reduced TN and TP load by 24% and 27%, while the new biochar actually increased TN and TP load by 5% and 21%, respectively.

Kuoppamäki & Lehvävirta (2016) published a study using the same, main biochar, and similar substrate as above (with 5% peat instead of 5% sphagnum moss). In this study, the biochar was applied as a 10% (v/v) layer in the middle of the substrate. Total annual reductions were seen for both TN and TP leaching. The concentrations of nutrients were also mostly reduced, but results were indecisive. Some modules contained no vegetation. Interestingly, biochar had bigger effects for reducing nutrient leaching in modules with vegetation, than in modules without vegetation. This suggests that biochar increased the plants uptake of nutrients. Yet another team lead by Kouppamäki published a similar, but 7-year study, where a 10% (v/v) layer of biochar was again added as a layer in the middle of the substrate (Kuoppamäki et al., 2021). They used two kinds of vegetation. One kind of green roof used pre-grown mats, while the other used plantings that had deeper roots, being able to reach the biochar in the middle of the substrate. Plant cover for the green roof with plantings were increased, while plant cover for the mats were reduced, compared to controls with no biochar. This again indicated that while biochar may adsorb nutrients, if the roots can interact with the biochar, it can benefit plants and increase nutrient availability. In these experiments, reductions in TP leaching were significant for the first few years. After 6 years however, light fertilizations were conducted where biochar had a negligible effect on leaching.

Qianqian et al. (2019) added coconut shell biochar pyrolyzed at 600˚C, at a 10.5% (v/v) rate to a commercial green roof substrate. Before biochar incorporation, the commercial substrate green roof consisted of peat, vermiculite, perlite, and sawdust with a volume ratio of 2:3:3:0.5, respectively. Differences in water retention between the biochar substrate and the control were negligible, probably due to the already high water-holding capacity of the commercial substrate. The chemical oxygen demand (COD) and concentrations of TN were nearly halved in runoff from the biochar substrate. TP concentrations though, were a little bit higher from the biochar substrate during this 6-month experiment. These findings thus differed from the ones made by Kuoppamäki et al. (2016) as they only found small differences in TN and TP concentrations, but reduced leaching due to increased water retention.

Chen et al. (2018) used a natural alluvial soil from the local area, without the addition of any nutrients. The biochar used in the experiment was derived from sewage sludge, and was applied in 5%, 10%, 15%, and 20% (v/v). The best effect for plant growth was found in the range of 10-15%. For 10% incorporation, plant growth for different vegetation was increased by 32.7%, 44.8% and 57.3% in the three different modules. It should be noted though, that sludge biochar can be rich in nutrients. This aspect probably exaggerated the good effects on the plants, as no other fertilizer was reported to have been added. However, even though the biochar provided nutrients, an amendment rate of 10-15% (v/v) was still the most beneficial.

In a study previously mentioned, Liao et al. (2022) undertook a comparative analysis of two distinct biochars, both added on the same weight-to-weight (w/w) basis, which translated to 12% and 21% on a volume-to-volume (v/v) basis. Both biochars were produced from sawdust, subjected to pyrolysis at approximately 625˚C. However, one of the biochars was granulated. This granulated variant contained elevated levels of N, P, Potassium (K), Calcium (Ca), and Magnesium (Mg), but with a C content of 60% in contrast to the 80% C content of the conventional biochar. Both biochars were evenly mixed with a commercial green roof substrate enriched with compost for nutrient provision. The experiment ran for 115 days. In comparison to the control group, 12% granulated biochar increased the plant leaf area by an average of 66%, whereas 21% conventional biochar reduced the plant leaf area by an average of 41%. This pattern was also reflected in the final biomass measurements. *Agastache foeniculum* plants grown with 12% granulated biochar showed a 53% increase in total biomass, and conversely, a 47% decrease in total biomass when grown with 21% conventional biochar. In a companion study by the same team, they found that 21% conventional biochar had a big impact on reducing the leaching of nutrients, while 12% granulated biochar did not have much effect (Liao, Drake, et al., 2022b). The main impact on nutrient leaching long-term from the granulated biochar was suggested to mainly be attributed to the increased plant uptake of nutrients.

In a study by Cheng et al. (2022), the P discharge from extensive green roofs was examined. The green roofs were constructed using nonproprietary base substrates, composed of 90% lightweight aggregate (either pumice or expanded clay) and 10% compost, and were planted with a variety of Sedum species. The research included TP testing of the event mean concentrations (EMCs) in the discharge from these experimental extensive green roofs, as well as a reference roof. Two types of biochars - wood-derived, and oat hull-derived, were installed in used as permeable reactive barriers (PRBs). As such, they were not incorporated into the substrate itself. The volume of each PRB material constituted 10% of the total substrate volume. The study did not provide any information regarding the pyrolysis temperatures used for the biochars. Furthermore, it was discovered that neither the wood biochar nor the oat hull biochar achieved any phosphorus reduction. Contrarily, the oat hull biochar appeared to increase the TP EMCs in the runoff.

Several field tests were also conducted by different actors within the Swedish research project Rest till Bäst (Fransson et al., 2020; Paulsson, 2020). In Augustenborg, Malmö, 674 g/m^2 of granulated crop-based biochar was added to already installed extensive sedum roofs. Pyrolysis temperature of the biochar was not stated. The nutrient-primed biochar was to be compared with conventional slow-release mineral fertilizer pellets (the control). One biochar was primed with similar amounts of nutrients as the control, while another, identical biochar was primed with twice the amount. The fertilizer used for priming was organic. All three amendments were probably spread on top of the roof surface, as is practice when applying fertilizer pellets. However, this was not explicitly stated. During the three-year study period, the plant growth was best for the biochar primed with twice the amount of nutrients. No noteworthy differences were measured in the runoff quality between the different setups. The main takeaway from the experiment was that biochar primed with organic fertilizer could be used as a replacement for inorganic mineral fertilizers. More tests were conducted within the Rest till Bäst project, but they did not examine the impact on leaching of biochar. In those tests, plant growth was usually best when biochar was applied at a rate of 10-15% (v/v). Biochar amendment did not always produce noteworthy improvements in plant performance but was highlighted as being able to sequester carbon, without causing any harm to plants.

2.3.2 Challenges and Limitations of Biochar in Green Roofs

The main challenge for the evolution of biochar use in green roofs is probably the many diverging and difficult to interpret results from research within the topic. Uncertainty makes investors uncomfortable (Bird & Yeung, 2012), which can hinder implementation. As was seen in the previous chapter, biochars of different origins and production methods produced vastly different results. To increase knowledge and drive research forward, there needs to be more uniformity in scientific literature. A notable aspect of many previous studies were the discrepancies in units for biochar application, as well as the exclusion of vital information such as pyrolysis temperature. Many studies were not included in this thesis for that purpose. There is a need for more research on biochar where authors make use of commercial green roof substrates, adding biochar in a range of around 10-15% (v/v), with recommended amounts of fertilizer. The 10-15% volumetric application rate is recommended by Rest till Bäst, which has 27 partners ranging from universities, small and large businesses as well as municipal agencies. This application rate also seemed to produce the best effects or plant growth in tests. In summary, to make the knowledge gained from research applicable to the industry, more research should adhere to industry standards.

Much research about biochar is readily available, and many of the suggested improvements can easily be applied in future research. However, many recommendations for biochar specific to green roofs are not as readily available internationally. Research about green roofs has been conducted for a long time in Scandinavia, Switzerland and particularly in Germany, which is where modern green roofs were first implemented in the 60s (Shafique et al., 2018). Research as well as industry recommendations about green roofs, is thus not always available in English, hindering progress internationally.

Biochar certification is currently available in Europe via the European Biochar Certificate, it is however only mandatory in Switzerland. Certification requires manufacturers to provide more in-depth information about the origins and production of their biochar. If implemented more widely, biochar certification could probably clear up some uncertainties in research. It could also increase the quality of many biochars. The demand for biochar is increasing, but the supply of high-quality stock does not keep up (Fransson et al., 2020). Sometimes charcoal for barbecuing purposes has been sold branded as biochar. Without proper analysis and control of feedstock and production, the properties of the final product will often be subpar and unknown. Contaminants such as PAHs and heavy metals may also be present in high amounts.

The confusing and contrasting properties of different biochars that hinder wider implementation can, with more knowledge, perhaps instead be exploited. A focal point for Rest till Bäst, as well as other research teams and projects, is currently to find the right biochar for the right place (Haeldermans et al., 2023; Paulsson, 2020).

3 Methodology

The main purpose of employing the methods used in this study was to gather, analyze, and interpret data that is relevant for the topic of biochar and its properties within green roofs. Mainly with regards to its nutrient and water retention capabilities, but when applied at reasonable rates beneficial for plant growth. Another purpose was to provide data for the research team that is developing tools and mathematical models of nutrient adsorption by biochar.

Biochars vary greatly depending on feedstock and production materials, which has already been covered in previous sections. As such, to increase knowledge and further research on the topic, two biochars of different origin were compared on both their organic substance retention, and water retention capabilities. The two biochars varied in production method, feedstock, and properties. To enable a comparison, two different experimental setups were used. One adsorption capacity experiment, which involved applying the biochars in varied amounts in a plastic cylinder, with a mesh in the bottom holding the biochar in place. A solution with organic salt was then circulated through the biochar column over several hours, with samples being taken regularly to measure the organic concentrations. An organic salt was used to replicate nutrients and enable the testing of adsorption capacity for the biochars. In the water retention experiment, the biochars were mixed with a green roof substrate and then applied as columns in the same plastic cylinder. Water was then dripped through the substrate, with a scale underneath catching the excess water in a beaker.

Another experiment was conducted where the adsorption capacity was compared for different mixing methods of biochar into a substrate of glass beads. The biochar was either completely mixed into the substrate, added as a layer on the surface, or as a layer in the bottom. A similar solution as before, containing organic salt, was then forced to travel through the substrate, but without circulating it multiple times. The effluent was then measured over time, enabling the comparison of adsorption based on the application method biochar. The hypothesis was that applying the biochar at the surface would be the least efficient, while applying it as a layer in the bottom would be most efficient. This would be in line with the results from the study by Kuoppamäki et al. (2016) that was described in *2.3.1 Effects on Nutrient Leaching and Plant Well-being*. They found that surface biochar reduced TN and TP leaching by around 10%, while a layer in the bottom reduced the leaching by around 25-35%. Although, it was argued that the leaching may have been reduced mainly because the biochar decreased the effluent quantities.

A fourth experiment was set up to measure the time it took for quick-release and slow-release fertilizer pellets to dissolve into distilled water. This was mainly done to assist the research team with data for their modelling tool.

Further sections list the materials that were used, provide more in-depth descriptions of the experiments and analytical methods, and show the calculations used to interpret the results.

3.1 Materials

Wood-chip biochar from Hjelmsäter Fastigheter. Made from woodchips of European Spruce (Picea Abies). The wood chips were waste products from damaged trees, for example due to spruce bark beetles. Certified by the European Biochar Certificate. See Figure 1 below.

Figure 1. Wood-chip biochar from Hjelmsäter Fastigheter. Sieved, 0.5-2 mm.

Pyrolysis temperature: ~750˚C
Retention time: ~1.5 hours
Specific surface area (BET): 369.51 m^2/g
Bulk density (<3 mm): 155 kg/m^3
pH (in $CaCl_2$): 8.3
Carbon (w/w): 94%
Oxygen (w/w): 2.0%
Hydrogen (w/w): 1.8%
Total Nitrogen (w/w): 0.45%
Ash content (550˚C, w/w): 2.5%
Phosphorus: <0.1% (2.8% of ash content)

Granulated biochar from Skånefrö. Made from bioagropellets, consisting mainly of agricultural waste from seeds. Certified by the European Biochar Certificate. See Figure 2 below.

Figure 2. Granulated biochar from Skånefrö. Sieved, >2 mm.

Pyrolysis temperature:	630-650˚C
Retention time:	15 ± 2 min
Specific surface area (BET):	4.7 m^3/g
Bulk density:	291 kg/m^3
pH (in $CaCl_2$):	10.1
Carbon (w/w):	78.3%
Oxygen (w/w):	4.0%
Hydrogen (w/w):	1.6%
Total Nitrogen (w/w):	2.90%
Ash content (550˚C, w/w):	13.6%
Phosphorus:	2.44% (17.5% of ash content)

Glass beads. Mainly 1 mm in diameter, but smaller and bigger diameters were also used for some tests. The glass beads were washed with either acid or ethanol.

Commercial substrate from Bara Mineraler. Consisting of Pumice (40%) with size fractions between 2-8 mm, sand, and organic compost. Good drainage and infiltration capacity while still being able to hold a lot of moisture. Pore volume of 60%, with a water holding pore volume of 50%. See Figure 3 below.

Figure 3. Green roof substrate from Bara Mineraler.

Fertilizer pellets from Veg Tech. Quick-release (Yara Pro Magna), and 4 months slow-release (Multicote 4 mån).

3.2 Setup - Adsorption Capacity

The purpose of this experiment was to measure and compare the adsorption capacities of the different biochars in the short term. The biochar was applied as a column inside a hollow plastic cylinder, with a mesh in the bottom. The mesh held the biochar in place while still allowing liquid to pass through. This cylinder with biochar was then lowered into a slightly wider beaker, that contained a blue liquid solution with dissolved organic content. A peristaltic pump was used to circulate the liquid from the bottom of the beaker, through the pump and then dripped inside the cylinder, on top of the biochar column. Thus, a flow was generated, and the liquid continuously passed through the biochar column that was held up by the mesh. See Figure 4 and Figure 5 below.

Figure 4. The hollow cylinder with biochar (left), is lowered into the beaker holding a buffer solution and Methylene Blue (right).

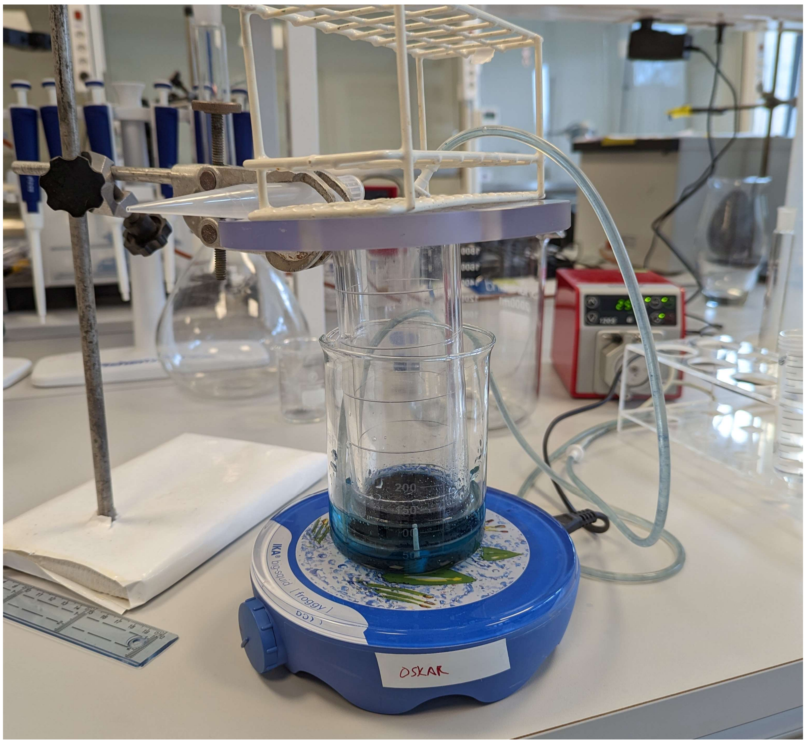

Figure 5. After the hollow cylinder is partially lowered into the beaker, the pump (red) pumps the solution from the beaker and into the hollow cylinder, generating a flow through the biochar column.

Both biochars were applied at a rate of 2 g, 3.5 g, and 5 g. The wood-chip biochar was sieved with size fractions between 0.5-2 mm, for a more reproducible result. Because the other biochar was made from granules of similar size fractions, it was at first not sieved. It became clear however that a lot of ash and smaller particles were present also in the granulated biochar. Like the wood-chip biochar, the granulated variant was then also sieved to create a more reproducible result. When the sample size is very small compared to commercial applications, doing this seems more important. However, to see if the ash content made an impact on the adsorption capacity, it was still included in this study and compared to the sieved version. The granulated biochar was sieved >2 mm, see Figure 6.

Figure 6. Granulated biochar from Skånefrö, after being sieved >2 mm to remove ash content.

The inside diameter of the hollow cylinder measured 50 mm. The liquid that was circulated through the biochar was a 100 ml solution consisting of Milli Q ultra-pure de-ionized water, a buffer (380 mg/L of KH_2PO_4, and 300 mg/L of K_2HPO_4), and Methylene Blue (6 mg/L of $C_{16}H_{18}ClN_3S$). Methylene Blue (MB) is an organic and blue substance. The concentration of MB was measured with regular intervals, as it declined over time due to adsorption. The reason for using a buffer was to lower the impact of biochar pH in the experiment, as the MB-solution was to be circulated through the biochar column continuously. In a real green roof substrate, biochar would surely influence the pH of the water passing through, but it would probably be much more limited. The peristaltic pump was a small Watson Marlow model set to 25 revolutions per minute (rpm), corresponding to a flow rate of 4 ml/min. A syringe with soft plastic tubing was used to extract 5 ml samples with regular intervals. Before extracting samples, the solution was briefly stirred with a magnetic stirrer. Each sample was analyzed quickly and then returned into the beaker. Many samples were taken during each experiment, and the volume would have been affected a lot if samples were not returned after analyzing. During one experiment, 20 g of glass beads were used instead of biochar as a control. The glass beads were 1 mm in diameter.

3.3 Setup - Adsorption Based on Biochar Application Method

This experiment tested the adsorption efficiency for different application methods of biochar into a substrate of glass beads. Much of the equipment, materials, and chemicals that were used in the previous Adsorption Capacity Experiment were also used in this setup. The same hollow cylinder, with a mesh in the bottom, was used to hold up the substrate. The cylinder was lowered into a slightly wider beaker (Beaker 1). This time the beaker contained a similar buffer solution, but with a clear color absent of MB. Instead, an MB-solution (same as previously) was pumped from a second beaker (MB-beaker) and dripped inside the hollow cylinder on top of the substrate. This generated a flow through the substrate, but this liquid was not circulated. Beaker 1 continuously flowed over as more and more liquid flowed through the substrate and through the mesh, into Beaker 1. At the surface of Beaker 1, where the liquid flowed over, was the point where samples were extracted. The organic content of the samples increased over time, as more and more MB-solution was pumped from the MB-beaker into Beaker 1. To understand the setup better, see Figure 7 below.

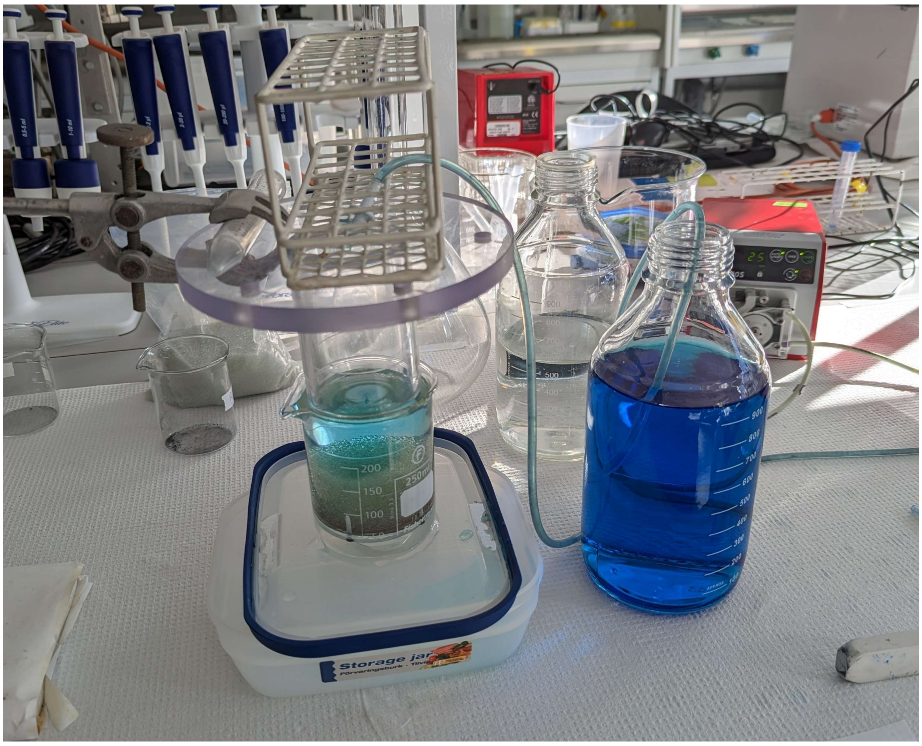

Figure 7. The cylinder carrying the substrate is submerged into Beaker 1 (left), that contains a clear liquid. The dark blue solution from the MB-beaker (right) is discharged inside the hollow cylinder. The MB-solution starts mixing with the clear liquid, eventually passing through the substrate and the mesh in the bottom, into Beaker 1. The samples are extracted from the surface of Beaker 1, and over time, the organic content of the samples increases.

This experiment was thus setup so that the concentration equivalent of the MB-solution would eventually be reached for all tests, as the clear liquid from Beaker 1 would be replaced. As such, a lower concentration at the outflow would mean a higher adsorption efficiency. The main purpose was to compare different application methods of biochar, not the adsorption capacities of the two different biochars. As such, only the wood-chip biochar was used in this experiment. The substrate column measured 32 mm in height and contained glass beads as well as 15% biochar (v/v). Although, a 32 mm column of only glass beads was used as a control. The pump was set to 50 rpm, corresponding to 8 ml/min. The glass beads measured 1 mm in diameter for most experiments. For some experiments though, glass beads in multiple sizes were used according to the Gaussian function (see Appendix 2), resulting bulk volumes of each size fraction as listed below.

Glass bead diameter (mm)	**% of total volume**
0.25-0.5	1
1	77
3	22

According to the targeted Gaussian function, the larger fractions should average 1.9 mm in diameter instead of 3 mm, but that size was not available.

3.4 Setup - Water Retention Capacity

This experiment compared the water retention and drainage of the green roof substrate, when it was mixed with no biochar and with 15% (v/v) of either woodchip-biochar or granulated biochar. The same hollow cylinder as used in previous experiments, was filled with the substrate mix and set up above an empty beaker on a scale. Milli Q ultra-pure de-ionized water was then dripped on top of the substrate. Over time, the water started dripping through the mesh in the bottom of the cylinder, into the beaker underneath. Readings from the scale were written down once every minute as the experiment went on. See Figure 8 below for the experimental setup.

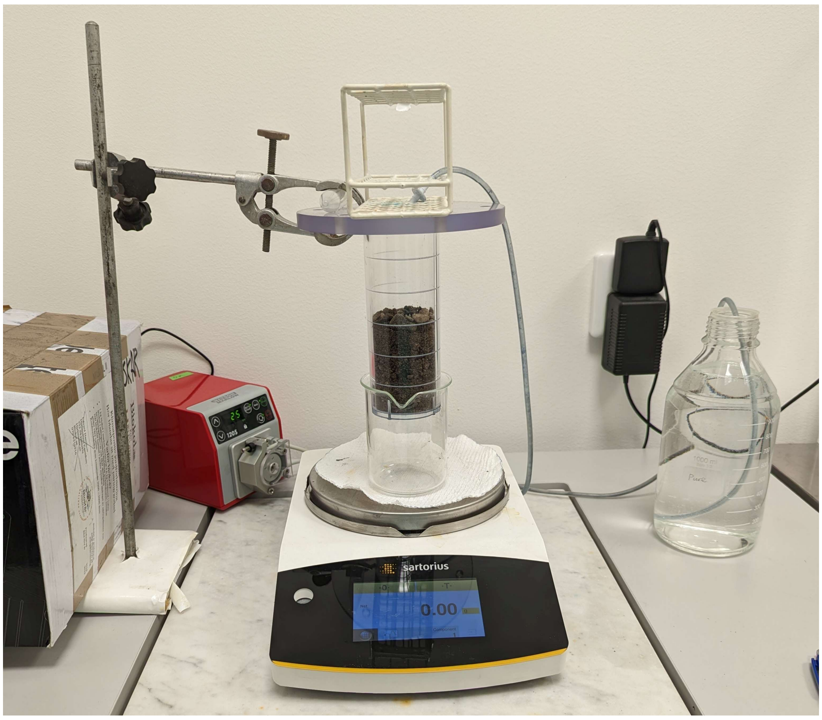

Figure 8. Setup of the water retention experiments. Water from the bottle to the right is pumped and discharged on top of the substrate. Over time, the water falls into the beaker underneath.

The substrate column measured 80 mm in height for all experiments. The reason for using a taller column in these experiments was due to the inhomogeneity and differences in size fractions of the green roof substrate. Using a small 32 mm column like in the previous, Adorption Based on Mixing Method setup, may have led to more inconsistencies between tests. Using a larger sample size decreased the probability of significant variances in conditions between experiments in this setup. The pump was set to 25 rpm, corresponding to 4 ml/min. The experiments ran until 100 g of infiltrated water had fallen into the beaker.

3.5 Setup - Nutrient Pellet Dissolution

In this experiment, the purpose was to measure how much time it would take for pellets of quick-release and slow-release fertilizers to dissolve in Milli Q ultra-pure de-ionized water. 500 mg of pellets of either the quick-release or slow-release variant were submerged in 1 L of Milli Q water. The conditions in the water were either completely calm, lightly stirred, or heavily stirred, using a magnetic stirrer.

3.6 Analytical Methods

Analysis of MB concentrations in the adsorption related experiments was done with a Shimadzu UV-1900i Spectrophotometer. At a wavelength of 680 nm, the absorbance corresponded linearly to the concentration of MB in the liquid solution. 10 mg/L of MB equaled 1.0 in absorbance, 6 mg/L equaled 0.6 in absorbance, and so forth. As such, converting the absorbance into MB concentrations was simple. Before putting the samples in the UV-spectrophotometer, they were centrifuged in a Sigma 4-16 centrifuge at 1500 rpm, for two minutes. This was done to remove trace fragments of biochar that would interfere with the spectrophotometric analysis.

3.7 Calculations

Adsorption Capacity

To calculate how much the MB concentration was reduced via adsorption by each biochar for the duration of an experiment (C_{ads}), the concentration of the last sample (C_{135min}) was subtracted from the initial concentration (C_0). However, even for the control where only glass beads were used, there was a noteworthy decrease in MB concentration over time. This “inherent” adsorption ($C_{ads,control}$) was subtracted when calculating C_{ads} for each biochar. The final equation was thus:

$$C_{ads,biochar} = C_0 - C_{135} - C_{ads,control} \tag{1}$$

The adsorption capacity could then be calculated by multiplying C_{ads} with the volume of the solution (together resulting in the mass of the adsorbate, m_{ads}), and then divided by the mass, surface area, or volume of the biochar:

$$Adsorbed\ mass\ per\ mass\ (m_{ads}/m_{biochar}):\ \frac{C_{ads}*V_{liquid}}{m_{biochar}} \tag{2}$$

$$Adsorbed\ mass\ per\ area\ (m_{ads}/A_{biochar}):\ \frac{C_{ads}*V_{liquid}}{A_{biocha}} \tag{3}$$

$$Adsorbed\ mass\ per\ volume\ (m_{ads}/V_{bioch}\quad):\ \frac{C_{ads}*V_{liquid}}{V_{bioch}} \tag{4}$$

4 Results and Discussion

This section presents the findings from the experiments that were conducted in this study, and covered in section *3 Methodology*. This includes the adsorption capacity of each biochar, adsorption tests for different application methods of biochar, water retention tests, and rate of dissolution for fertilizer pellets. Furthermore, the results were discussed and compared with findings from section *2 Literature Review*.

4.1 Comparison of Adsorption Capacities

The experiments that examined the adsorption rates of the biochars showed that the wood-chip biochar was, by mass applied, slightly more efficient at adsorbing MB from the liquid than the granulated biochar. This was the case for all the different application rates, at least for the final measurements that were conducted at 135 min. Although, the adsorption was quite similar for both biochars, as can be seen in Figure 9 below.

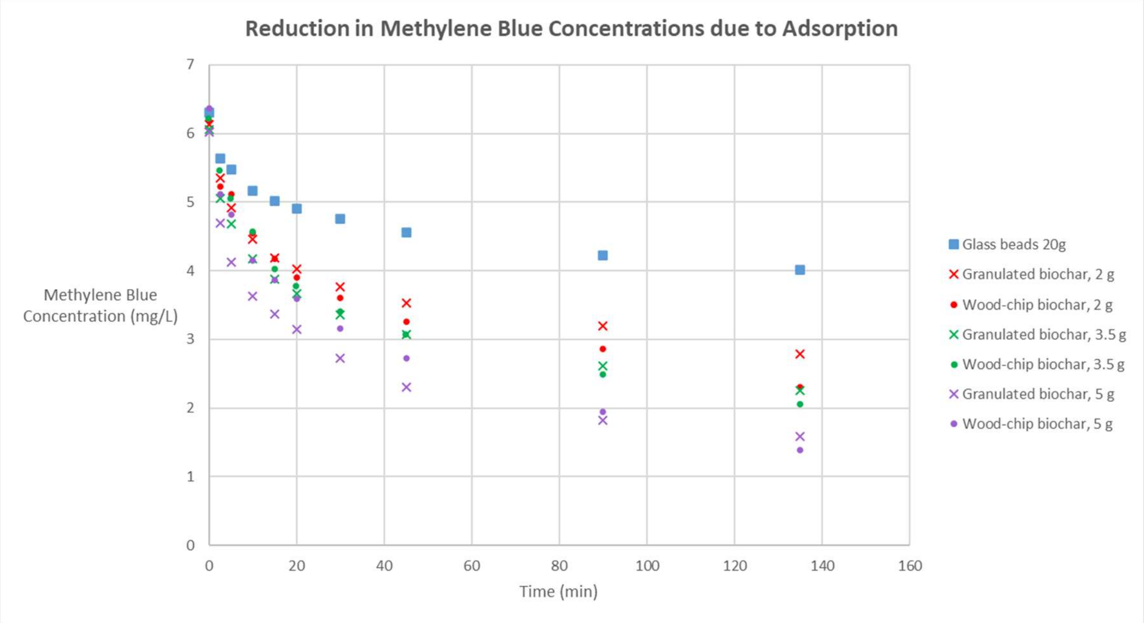

Figure 9. Declining liquid concentrations of MB due to adsorption by granular and wood-chip biochar.

In the early measurements however, granulated biochar was reducing the MB concentration more than the wood-chip biochar. Especially at a 5 g application rate, but that might have been an outlier. There are multiple possible reasons for why the granulated biochar adsorbed better during the early parts of the experiments. The biochar was mostly floating on top of the liquid within the cylinder, but as the granulated biochar had larger fragments and higher density it was more submerged than the wood-chip biochar. It also left more space in between fragments, while the wood-chip biochar covered the surface more comprehensively. These aspects may have resulted in a more even flux through the granulated biochar, so that every fragment contributed to adsorption from early on. Over time though, the wood-chip biochar reduced the concentrations of MB more. It seems that if given more time, the gap in adsorption rates between the two biochars would increase. However, as could be seen in the graph of Figure 9, the concentrations did not change as much in the latter part of the experiments as they were getting closer to the concentration equilibrium (C_{eq}).

In the study by Liao et al. (2022b), they found that the granulated biochar was less efficient at reducing nutrient leaching than conventional biochar, also indicating lower adsorption rates. In that study the difference was way more pronounced. They applied 4.5% on a weight-to-weight (w/w) basis of each biochar in different pots of substrate There were significant reductions in leaching from the conventional, but almost no reduction from the granulated biochar. In their study though, both biochars were derived from woody feedstock, while in the present study, the granulated biochar was made from agricultural seed waste. The tests were also set up quite differently, making comparisons challenging.

There is also the argument that the applied volume of the biochar is more significant than its mass, with regards to adsorption. This was previously discussed with regards to the studies by Liao et al. (2022a, 2022b) as well. Since bulk densities and the specific surface areas for both biochars in this study were known, conversions were possible. Data from the adsorption capacity experiments were tested for retrieving the Freundlich adsorption isotherm for each biochar, but unfortunately the data points did not fit well enough to draw the gradient needed for solving the equation. To enable a comparison between the biochars, the mass of the adsorbate (m_{ads}) was calculated and divided by either the mass, volume, or area of the biochar. Results can be seen below in Table 1.

Table 1 Adsorbed quantities of Methylene blue for different quantities of biochar.

Tests with 2 g	**Granulated biochar**	**Wood-chip biochar**
Mass (g)	2.0	2.0
Surface area (m^2)	9.4	739.0
Volume (cm^3)	6.9	12.9
C_{ads} (mg/L)	1.050	1.590
$m_{ads}/m_{biochar}$ (mg/g)	0.0525	0.0795
$m_{ads}/V_{biochar}$ (mg/m^3)	15 217	12 325
$m_{ads}/A_{biochar}$ (mg/m^2)	0.01117	0.00022
Tests with 3.5 g	**Granulated biochar**	**Wood-chip biochar**
Mass (g)	3.5	3.5
Surface area (m^2)	16.5	1293.3
Volume (cm3)	12.0	22.6
C_{ads} (mg/L)	1.500	1.870
$m_{ads}/m_{biochar}$ (mg/g)	0.04286	0.05343
$m_{ads}/V_{biochar}$ (mg/m^3)	12 500	8 274
$m_{ads}/A_{biochar}$ (mg/m^2)	0.009120	0.0001446
Tests with 5 g	**Granulated biochar**	**Wood-chip biochar**
Mass (g)	5.0	5.0
Surface area (m^2)	23.5	1 847.6
Volume (cm3)	17.2	32.3
C_{ads} (mg/L)	2.140	2.690
$m_{ads}/m_{biochar}$ (mg/g)	0.06114	0.05380
$m_{ads}/V_{biochar}$ (mg/m^3)	12 442	8 328
$m_{ads}/A_{biochar}$ (mg/m^2)	0.01300	0.0001456

As mentioned previously, the wood-chip biochar was a more efficient adsorbent with regards to its mass weight. However, if basing the application rates on volume, granulated biochar was more efficient by a significant margin. On average, the granulated biochar adsorbed 39% more MB per unit of volume, while the wood-chip biochar adsorbed 19% more per unit of mass. So which biochar was more efficient? In conventional agriculture, biochar is often applied as kg/m^2 or tonnes/hectare. This can also be the case when applying biochar on top of existing green roofs. When adding materials into substrate mixtures for green roofs however, volume is the more common quantity. The matter is thus complicated even further. The efficiency of biochar as soil amendment not only depends on feedstock characteristics, pyrolysis temperature, and properties, but also on which type of quantity is used for its application. Researchers need to take these aspects into consideration, as biochar is used for different purposes and is studied across multiple scientific fields. The bulk density of the biochar used in tests should preferably be reported in all scientific literature, so that conversions between mass and volume is possible.

Since adsorption is a surface process, the surface area was hypothesized to have a larger impact on the results than it did. All adsorbents become more efficient with increased specific surface area (Aljamali et al., 2021). Physical adsorption by van der Waals forces is especially reliant on the surface area, as this adsorption acts the same on all surfaces. Chemical adsorption occurs due to chemical bonding and is much more powerful. Since chemical adsorption is also a surface process it is also highly affected by the surface area. However, a material with potent chemical adsorption and small specific surface area, may be a better adsorbent a material with a large specific surface area that lacks chemical affinity. This became very clear from the experimental results. When comparing $m_{ads}/A_{biochar}$ for each biochar, the granulated biochar was almost two orders of magnitude more efficient.

The adsorption tests for unsieved granulated biochar showed more variable results than in other tests. The unsieved biochar seemed like a better adsorbent for 2 g and 3.5 g by some margin, while results were similar to the sieved granulated biochar for 5 g of application. This improves the argument that more homogeneous size fractions are needed to generate reproducible results when using smaller sample sizes. When averaging across all tests however, the unsieved biochar was the better adsorbent. Comparisons can be seen below in Figure 10.

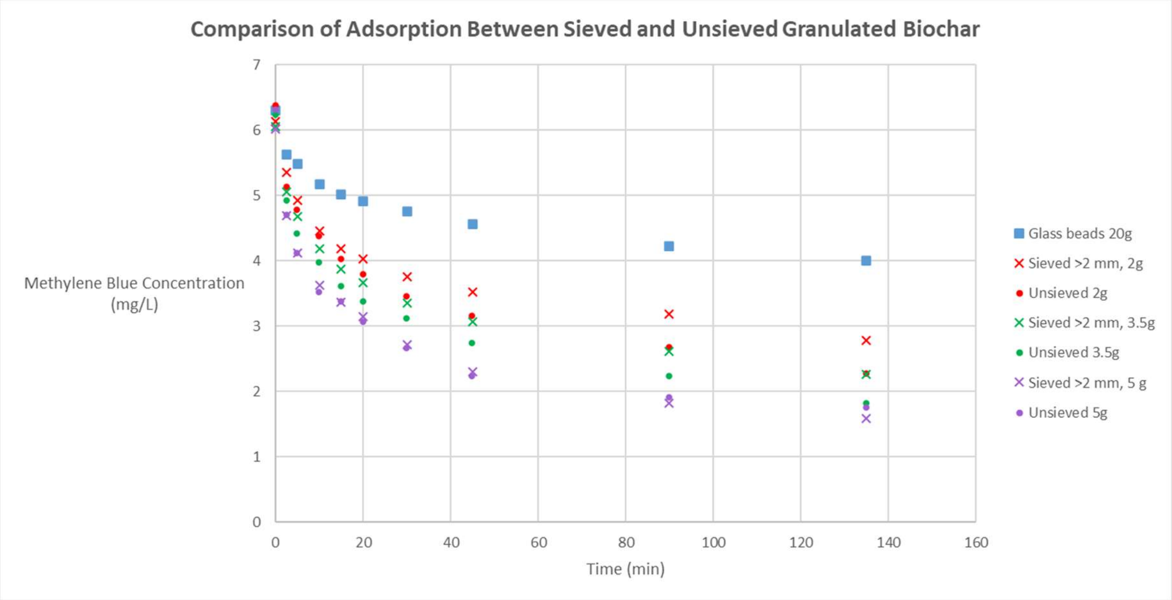

Figure 10. Comparison of adsorption between >2 mm sieved, and unsieved granulated biochar.

What the differences in adsorption capacity depends on is not entirely clear. The smaller fragments of biochar probably increased the adsorption efficiency due to the higher specific surface area that is inherent to smaller fragments. The very fine ash content, however, differed significantly in composition from the actual granules. According to the product sheet by the European Biochar Certificate, the ash content in the granulated biochar contained a lot of metals. It seemed heavier and sank in the liquid, while the granules were floating. While a high surface area does always correlate with high adsorption, as seen when comparing the biochars in Table 1, the small particles and ash content certainly had an effect. Whether this depended on the increased surface area or composition of the particles is hard to say. The reason why 3.5 g and 5 g of unsieved biochar managed to adsorb almost the same amount of MB can perhaps be attributed to the implicit stochasticity of not sieving a small sample of an inhomogeneous material. The choice to repeat the experiments using sieved samples of granulated biochar thus appears to have been scientifically justified.

4.2 Adsorption for Different Application Techniques

This experiment was set up so that if given enough time, every test would eventually reach the same MB concentration, slightly above 6 mg/L. So, in contrast to the setup in the previous section, there would always be an increase in MB concentrations over time. However, in both setups, the lowest concentration of MB at a given time was equal to the highest adsorption efficiency. It is perhaps easier to think of the tests in this section to measure the leached concentrations.

In this setup, different application methods of biochar were tested over time to see how they compared, as Beaker 1 was nearing the concentration equilibrium (C_{eq}) of MB. It was quite clear that when biochar was applied as a bottom layer below the substrate, it took longer for the solution in Beaker 1 to reach C_{eq} for MB. Surprisingly, there were no significant differences between completely mixing the biochar with the substrate, as opposed to applying it on the surface. In one test the surface biochar was less efficient while in another test it was more efficient, with mixed biochar falling in between for both tests. This is visualised in the graph of Figure 11 below.

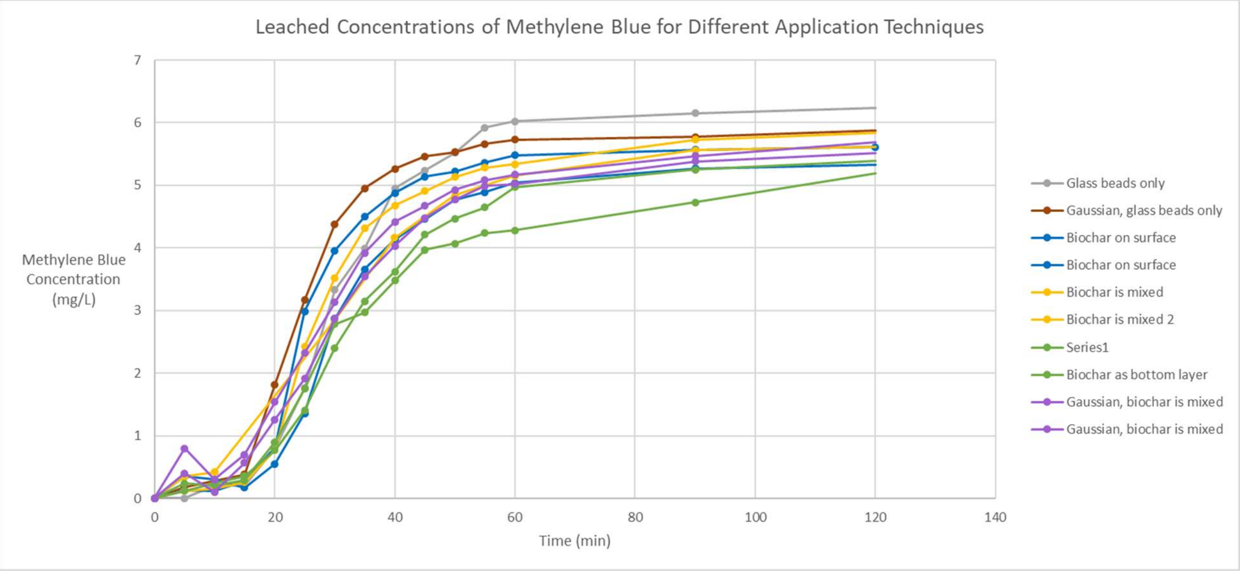

Figure 11. Concentrations of MB in the leachate for different application techniques over time.

It was also theorized that a Gaussian distribution of glass bead sizes would change the path length for diffusion and advection of MB and thereby affect adsorption. In the Gaussian distribution, 22% (v/v) of the glass beads measured 3 mm in diameter, while 77% were 1 mm, and 1% were 0.25-0.5 mm. The 1% of smaller fractions seemed insignificant in quantity while the 22% of bigger sizes would be thought to reduce adsorption and increase drainage. However, this effect was negligible, as no noteworthy differences were noted between the Gaussian distribution compared with only using 1 mm glass beads.

The adsorption was as hypothesized, most efficient when biochar was applied as a bottom layer. This was similar to the findings made by Kuoppamäki et al. (2016), who compared applying 10% (v/v) of biochar as either a top layer or bottom layer. In their study though, they found that the total amounts of leached TN and TP probably were reduced due to increased water retention. The concentrations of TN and TP in their tests were not very different from the water coming through the unamended substrate. While the adsorption of actual nutrients may not have increased in their study, it was still clear that biochar had a more pronounced effect on the results while applied as a bottom layer. Theoretically, that would be logical for the experiments in the present study as well. When the MB solution was dripped on top of the substrate in the cylinder, it would likely spread diffusely through the substrate while traveling downwards, before reaching the bottom layer. This is shown conceptually in Figure 12 below.

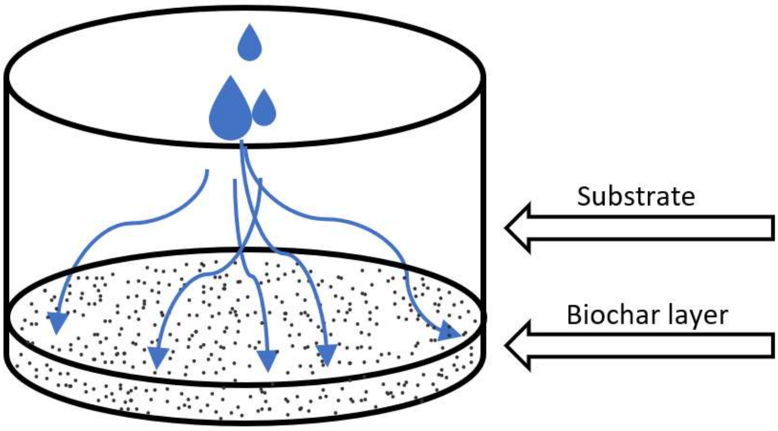

Figure 12. The Methylene blue diffuses as it travels through the substrate before reaching the bottom layer of biochar.

The surprising part was that biochar completely mixed with the glass beads did not perform better than biochar on the surface. According to the concept shown in Figure 12, mixed biochar should result in a larger impact than surface biochar. Two tests were conducted for each application method of biochar, and as stated previously, the tests for surface biochar performed quite differently from one another. It is possible that one of the tests was an outlier, and that more tests are needed to draw more definite conclusions. A degree of variability and stochasticity is inherent for all experimental procedures. For example, although the same flow rate was set on the pump for every test, it seemed that the spike in concentration started happening at different times. If conditions were perfect, the spike should take place simultaneously for all tests, but with different potencies.

4.3 Comparison of Water Retention

These tests ran until the scale below the substrate column measured 100 g, and readings from the scale were written down every minute. It took between 8-10 min until the first drops had infiltrated through the entire substrate and dripped into the beaker on the scale. To reach 100 g, it took between 33.5-35 minutes for all tests. In both tests for the granulated biochar, the first drops arrived quite early compared to the other tests. Over time though, it seemed like the granules started holding more water, similarly to the wood-chip biochar and the unamended substrate. See Figure 13. Water retention tests for unamended substrate, compared with wood-chip biochar-, and granulated biochar amended substrates.Figure 13 below.

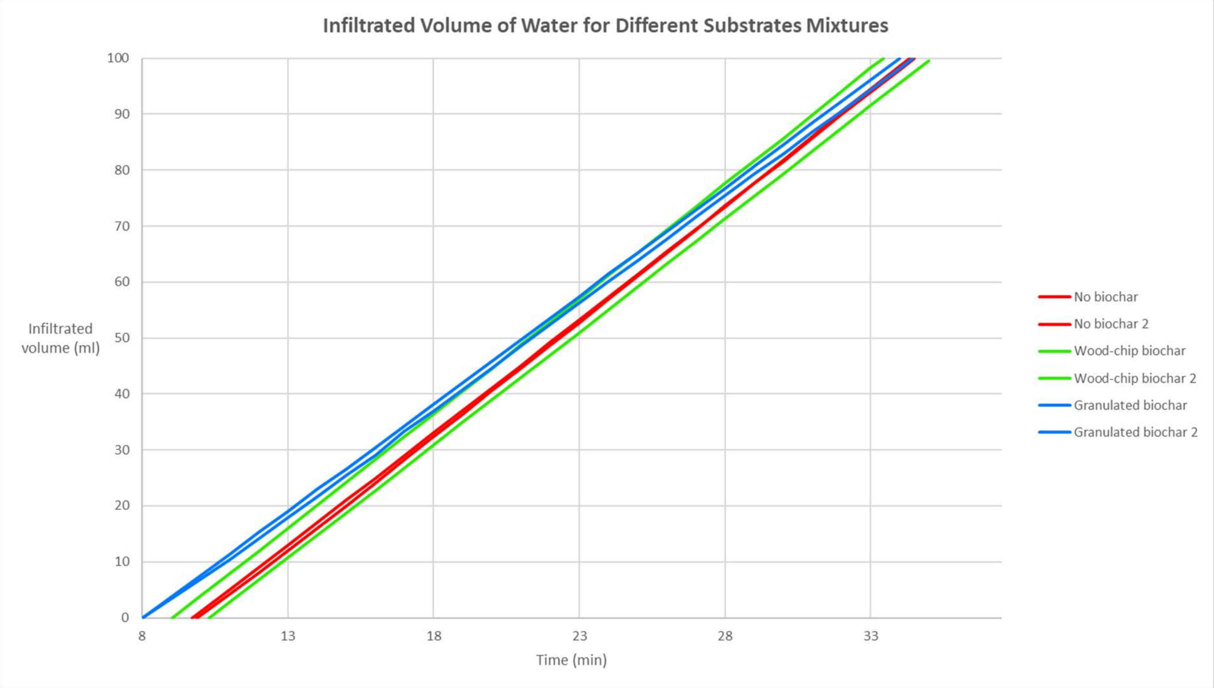

Figure 13. Water retention tests for unamended substrate, compared with wood-chip biochar-, and granulated biochar amended substrates.

There were no significant differences in performance between the different substrate compositions. The unamended substrate seemed able to hold quite a lot of water on its own, as advertised by the supplier. It was somewhat surprising how well the substrate fared, considering it largely consisted of pumice and sand which are known for their draining properties. However, soil organic matter such as compost is efficient at holding water. Qianqian et al. (2019) found that adding coconut shell biochar to a substrate of peat, vermiculite, perlite and sawdust negligible effect on water retention. This is not surprising, due to the high content of peat and sawdust. Kuoppamäki et al. (2016) saw significant effects of biochar on water retention for a substrate with 85% crushed brick and 15% organic materials. So, the effect of biochar on water retention is highly dependent on the other materials.

Due to differing results from individual studies in scientific literature, Razzaghi et al. (2020) conducted a meta-analysis on the effect of biochar on water retention in soils. They found that biochar increased the average water content at field capacity for coarse- and medium-textured soils, while not doing so for fine-textured soils. Small biochar particles were argued to increase the micropores in spaces available between larger fragments, while biochar generally decreased the quantity of micropores for finer soils. The substrate used in the present study might seem coarse due to the high content of pumice. Based on qualitative judgement though, the sand and organic material seemed like a quite even mix of medium and fine-textured fragments. Pumice contains a lot of macropores where the compost and sand will surely enter and reduce available space, to perhaps generate more micropores. In any case it was evident from these tests that the incorporation of either biochar did not significantly alter the water holding capacity of a substrate already quite adept in that regard. While biochar may increase the water holding capacity for some soils, it may not be the most efficient soil amendment purely for that purpose. It was also evident that even though the granulated biochar contained mostly larger fragments, it did not reduce the water holding capacity over the course of the tests.

4.4 Dissolving of Fertilizer Pellets

The dissolution of quick-release fertilizer pellets was dependent on the turbulence of the surrounding water. The three beakers were either not stirred, lightly stirred, or heavily stirred. In the heavily stirred beaker, the pellets dissolved within a few minutes. In completely calm conditions, the pellets seemed intact for 1.5 hours. Then, during some brief and heavy manual stirring, they immediately dissolved in the water. In lightly stirred conditions, the pellets laid still on the bottom of the beaker, seeming intact for the first 10 minutes, even though the water was lightly moving around. But again, manual stirring which caused turbulence then immediately dissolved the pellets. When dissolved, the previously de-ionized water had a conductivity of 700 microSiemens (µS). It was challenging to know whether the pellets were really dissolved, or just brittle shells of binding still being held together.

The tests for slow-release fertilizer pellets were conducted in the same manner as the tests for slow-release pellets. It was expected that the pellets would dissolve more quickly than 4 months during heavily stirred conditions, even though they were branded as 4 months slow-release pellets. This was due to the disparate conditions between a heavily stirred beaker of de-ionized water, and regular soil conditions. The water was evaporating at a quick pace during the course of the test, particularly in heavily stirred conditions. Replenishments of new de-ionized water was needed with regular intervals. The last measurement of conductivity that was performed accurately, when the volume of water was replenished to 1 L, was performed only 12 days after the start of the experiment. The conductivity measured 84 µS, 265 µS, and 340 µS for calm, lightly stirred, and heavily stirred conditions, respectively. As such, the heavily stirred liquid with slow-release pellets measured half of the conductivity after two weeks, compared with fully dissolved quick-release pellets. It is not certain that the complete dissolving of slow-release pellets would result in the same conductivity as quick-release pellets, as they differed slightly in nutrient composition. More than two weeks further into the experiment, the pellets still seemed quite intact. However, no more conductivity measurements were taken. By that time, algae and biofilm had started growing in the beakers, approximately one month after the start of the experiment. The tests were then cancelled due to hygienic reasons in the laboratory environment. Conductivity measurements would not produce credible results as the microorganisms would have consumed some of the available nutrients. In summary, the tests for dissolving fertilizer pellets were difficult in terms of planning and were not concluded in the desired fashion.

4.5 Suggestions and Recommendations for Improvements

The experiments mostly generated useful data, but they were also laborious and sensitive to the present conditions. Much knowledge and experience was gained during the laboratory work, but many experiments required do-overs due to mistakes early on. Even though the same settings were used on the pipette every time when applying methylene blue (MB), the absorbance readings from the UV-spectrophotometer could slightly differ for every batch of MB-solution. This was probably attributed to how deeply the pipette was lowered into the MB concentrate for extraction, before applying it to the MB solution. If any mini droplet from the outer surface of the pipette managed to follow while discharging the main contents, it could affect the concentration of MB quite a bit. It would be recommended to first apply a bit too much MB, and then slowly apply more of the clear buffer solution until the preferred absorbance was reached. Also, the same small piece of glassware in the spectrophotometer was used for all samples. This required using part of each sample to wash and prepare the glassware for the actual measurement, to prevent dilution. At first, the samples were not centrifuged, but it was later discovered that this had a major effect on the analyses. Centrifuging the sample vials quickly made unwanted biochar particles settle in the bottom. Clean samples could then be extracted with a pipette before being subjected to analysis in the UV-spectrophotometer. It was also noted that the volume had decreased too much towards the end of the experiments, because so many samples had been extracted. The experiments were then conducted again, where samples were returned to the liquid that was circulating through the substrate. All these aspects were learned during the course of the study and do-overs were very time-consuming, which resulted in fewer data points than preferred for the final results.

To make the adsorption capacity experiments (which compared two biochars) less laborious, they should perhaps not have been sampled as frequently. For the final analysis, where m_{ads} was divided by either the mass, volume, or surface area of the biochar, only the first (C_0) and final (C_{eq}) measurements were needed. If the tests were less laborious, perhaps more tests could have been conducted. With more tests and more data points for m_{ads}, it might also have been possible to analyze the Freundlich adsorption isotherm. However, it was also important to know that the concentration equilibrium was close to being reached. This required a few samples to see clearly that the graph was being flattened, at least for the first few tests.

For the experiments analyzing adsorption based on application method of biochar, the buffering chemicals might not have been needed. The buffering chemicals were used to reduce the impact of biochar pH on the liquid for the adsorption capacity tests, but in this setup the solution was not circulated through the substrate. The solution only passed through the substrate once, similar to real conditions for green roofs. As such, the impact of biochar pH would not have been exaggerated.

All the water retention tests should probably have been conducted right after gathering the substrate from storage. Initial moisture content may have differed slightly in between different tests. The biochars could also have been tested on their own in the water retention experiment, without any green roof substrate. This would have made the impact of each biochar more noticeable and simplified the process of comparing them.

The tests for dissolving slow-release fertilizer pellets should have been started earlier on in the study. This would have enabled a restart after the failed attempt. The experiments should also have been conducted in a low-light, and perhaps lower temperature setting to prevent algae and biofilm growth.

4.6 General discussion

In the beginning of the study, it seemed like the wood-chip biochar would be performing better in the experiments. The first impression was that the high surface area and porosity of this variant would result in better adsorption. At first glance, that is what the tests showed. Although the difference was not huge, it was still clear an equal mass of wood-chip biochar adsorbed more methylene blue (MB) than the granulated variant. The granulated biochar contained less carbon, but more oxygen, nutrients, and ash content. These aspects, as well as its crop-based origins and slightly lower pyrolysis temperature, indicates that it contains more functional groups than its counterpart. As such, it was thought that the granulated biochar might do more for plant growth, even though wood-chip biochar provided better adsorption. As the literature study progressed however, it became apparent that weight might not be the best quantity to use for a comparison in this case. Previous research pointed out that choosing an application rate for biochar based on volume was generally more consistent and reliable for generating desired results in planted soils. After analysing the test data in a way more in line with these recommendations it became clear that the granulated biochar was better for the purpose of adsorption. The tests thus showed that surface area and porosity are not nearly as important as the chemical properties of the surface for generating adsorption.

It is not entirely clear how well the adsorption of methylene blue would translate to nutrients from conventional fertilizers. It is however likely that the trends between the two biochars seen for adsorption in these tests would translate. The surface area and number of active sites on biochar should result in adsorption of both dissolved organic carbon, as well as nutrients.

Liao et al. (2022b, 2022a) showed that a granulated biochar had elevated levels of oxygen, hydrogen and nutrients compared to a conventional biochar. Those two wood-based biochars were otherwise almost identical in feedstock, pyrolysis temperature, and residence time. The granulation of biochar may thus increase functional groups and the cation exchange capacity (CEC). Like other studies, they also discussed the potential benefits of granulated biochar with regards to erosion susceptibility (Briens & Bowden-Green, 2020; Liao, Sifton, et al., 2022). The larger granules are thought to be less likely to erode than smaller particles of conventional biochar. However, caution should always be exercised when applying biochar to existing green roofs due to these problems, perhaps by using some sort of injection method. Green roofs are often subjected to high wind speeds and are sometimes installed on with a slight incline. The substrate may also consist of a quite thin layer compared to the quantities of water that fall during large storms. These aspects likely make the question about erosion even more relevant. However, the granulated biochar in the present study contained 13.6% ash content, of which 17.5% was phosphorus (P). These smaller particles should theoretically erode more readily, which might contribute to leaching. This requires further examination. While many biochars reduce the leaching of P, studies showed that some types of biochar might even contribute to increased leaching of total P (Cheng et al., 2022; Kuoppamäki et al., 2016; Qianqian et al., 2019).

For the water retention tests, differences between the two biochars were negligible. That was also the case when using no biochar at all in the substrate. According to scientific literature, biochar increases the water retaining capacity for coarse grained soils on average. While the substrate used in the tests contained a lot of pumice and sand, the particles seemed to have aggregated well with the compost and held quite a lot of water without any biochar. As such, the amendment had no significant effect. However, the timeframe for all the experiments on biochar in this study were quite short. Blanco-Canqui (2019) stated that as biochar ages, it aggregates with the soil particles and the water retention may increase further.

The aspect of time and ageing of biochar also impact other properties. Several authors stated that functional groups and the CEC of biochar increases as it ages (Dai et al., 2020; Weber & Quicker, 2018). While the wood-chip biochar may not have contained the same chemical affinity as the granulated variant in the short term, it is more difficult to draw conclusions for the long-term effects of either biochar. This an important limitation of this thesis. No study was found that compared which types of biochar benefits most from the ageing process. However, the porosity and increased aeration from biochar help with providing a habitat for beneficial microorganisms in the soil

(Fransson et al., 2020; Joseph et al., 2021). Microbes contribute to the aging process of biochar, a process that can enhance its water retention capacity. Additionally, microbes and the aging process promote the increase of surface functional groups and boost the biochar's ability to retain nutrients. Although, results from a meta-analysis by Li et al. (2020) showed that low temperature biochar from nutrient rich feedstocks resulted in more microbial biomass. This was attributed to higher nutrient contents, and a lower specific surface area. Joseph et al. (2021) also stated that nutrient contents of the soil was important for microorganisms. That can easily be solved with fertilizer use, instead of using biochar from nutrient rich feedstocks. The nutrient rich feedstocks as well as their low specific surface areas, are however correlated with less porosity, which previously mentioned sources claimed to be important for microorganisms. There is thus a discrepancy in literature between the impact of porosity on microorganisms. Microbial activity is an important aspect for the long-term effects of biochar, while the porosities and specific surface areas were important differences between the two biochars in this study. Making a qualitative comparison on the long term-effects is thus challenging.

Results from the laboratory tests showed that adsorption is more efficient when biochar is applied as a bottom layer, rather a top layer or mixed with the substrate. Results from the literature study however showed that plants can greatly benefit if the roots can interact with biochar in the soil. Especially with certain biochars, and if they are applied at a volume-to-volume rate of 10-15%. So as a nutrient retention tool for treating runoff, using biochar in the bottom might be the best way. But for benefiting plants, mixing evenly in the substrate seems most logical. One interesting strategy would thus be to include both options. That would maximize all benefits, including carbon sequestration. Rest till Bäst did several tests where they tried up to 50% application rate of biochar, and several other studies used up to 40%. If this was done just for the purpose of curiosity is not clear. But if using higher amounts of biochar is possible, there would probably be a demand from some actors.

That also brings up the question of cost, which is often a significant factor for many newer technologies. However, this subject was not discussed much in scientific literature, which could be interpreted as the cost of biochar not being that much of an issue. Gan et al. (2021) stated that biochar implementation in green roofs is probably economically feasible if local waste is used as feedstock, but that a cost-benefit analysis is needed. Mohammadi et al. (2020) did a cost-benefit analysis of biochar, but for use in paddy fields, and stated that it can be economically feasible in some conditions. Rest till Bäst noted that biochar can be quite expensive, but that there are several ways to decrease costs. These include using rest products that has no other area of application, using products that you get paid to manage, and using products that are as clean as possible (Fransson et al., 2020). As the technology matures however, biochar will likely become cheaper. In modern production facilities, combustible gases and tar generated during pyrolysis are captured and used to sustain the process. There are also pyrolysis facilities that are connected to district heating, furthering economic benefits.

5 Conclusion

Between the wood-chip and the granulated biochar, the latter seemed more adaptable for green roofs. When mixing substrates, biochar is best applied on a volume basis, and the granulated biochar had the best adsorption capacity per unit of volume. Aspects such as erosion susceptibility due to its larger particle sizes, and plant benefits due to it appearing to contain more surface functional groups, also plays in its favor. The experiments also showed that chemical affinity is far more important for adsorption capacity than surface area and porosity. When mixed into a green roof substrate, there were no noteworthy differences between the two biochars in terms of water retention. While biochar can increase water retention in some substrates, this is mainly the case in coarse substrates with lower water holding capacities. Though scientific literature suggests that the nutrient and water retention capacity of biochar improves with age, it remains unclear whether specific types of biochar benefit more from the ageing process.

The optimal application technique for short-term adsorption efficiency appears to be the application of biochar as a bottom layer in a substrate. For sustained plant health, the most beneficial effects are observed with a volume application of 10-15% biochar, and ensuring it is accessible to plant roots. This suggests that an even mixture of biochar with the substrate provides optimal conditions for plant growth. Therefore, incorporating both techniques could present an effective alternative that enhances both short- and long-term outcomes, while maximizing carbon sequestration.

While the tests for fertilizer pellets did not conclude as intended, they showed that the quick-release pellets dissolved very quickly, making them unfit for many green roof applications. The slow-release pellets proved to be recalcitrant even in extreme conditions, which indicates that they can be effective for green roof applications, that requires a nutritional balance to reduce leaching.

Current literature lacks a consistent approach when researching biochar. To increase useful knowledge, future studies should be conducted more in line with current industry standards. More studies are needed where biochar is applied in commercial green roof substrates at a rate of 10-15% on a volume basis, and when the biochar is primed with nutrients. Individual studies should also analyze the effects of biochar on both plant health and nutrient retention, as both these aspects need to be satisfactory for biochar to be successful.

6 References

Akdeniz, N. (2019). A systematic review of biochar use in animal waste composting. *Waste Management*, *88*, 291–300. https://doi.org/10.1016/j.wasman.2019.03.054

Aljamali, N. M., Baqi Aldujaili, R. A., & Alfatlawi, I. O. (2021). Physical and Chemical Adsorption and its Applications. *International Journal of Thermodynamics and Chemical Kinetics*, *7*(2). https://doi.org/(Journal):10.37628/IJTCK

Allohverdi, T., Mohanty, A. K., Roy, P., & Misra, M. (2021). A Review on Current Status of Biochar Uses in Agriculture. *Molecules*, *26*(18), 5584. https://doi.org/10.3390/molecules26185584

Ameloot, N., Graber, E. R., Verheijen, F. G. A., & De Neve, S. (2013). Interactions between biochar stability and soil organisms: review and research needs. *European Journal of Soil Science*, *64*(4), 379–390. https://doi.org/10.1111/ejss.12064

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and Soil*, *337*(1–2), 1–18. https://doi.org/10.1007/s11104-010-0464-5

Azzi, E. S., Karltun, E., & Sundberg, C. (2019). Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm. *Environmental Science & Technology*, *53*(14), 8466–8476. https://doi.org/10.1021/acs.est.9b01615

Bamdad, H., Papari, S., Moreside, E., & Berruti, F. (2022). High-Temperature Pyrolysis for Elimination of Per- and Polyfluoroalkyl Substances (PFAS) from Biosolids. *Processes*, *10*(11), 2187. https://doi.org/10.3390/pr10112187

Beninde, J., Veith, M., & Hochkirch, A. (2015). Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation. *Ecology Letters*, *18*(6), 581–592. https://doi.org/10.1111/ele.12427

Berardi, U. (2016). The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy and Buildings*, *121*, 217–229. https://doi.org/10.1016/j.enbuild.2016.03.021

Besir, A. B., & Cuce, E. (2018). Green roofs and facades: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *82*, 915–939. https://doi.org/10.1016/j.rser.2017.09.106

Bird, R., & Yeung, D. (2012). How do investors react under uncertainty? *Pacific-Basin Finance Journal*, *20*(2), 310–327. https://doi.org/10.1016/j.pacfin.2011.10.001

Blanco-Canqui, H. (2019). Biochar and Water Quality. *Journal of Environmental Quality*, *48*(1), 2–15. https://doi.org/10.2134/jeq2018.06.0248

Brewer, C. E., & Levine, J. (2015). Weight or Volume for Handling Biochar and Biomass? *The Biochar Journal*, *16*. https://www.biochar-journal.org/en/ct/71

Briens, L., & Bowden-Green, B. (2020). A comparison of liquid binders for drum granulation of biochar powder. *Powder Technology*, *367*, 487–496. https://doi.org/10.1016/j.powtec.2020.03.065

Brown, T. R., Wright, M. M., & Brown, R. C. (2011). Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts and Biorefining*, *5*(1), 54–68. https://doi.org/10.1002/bbb.254

Cao, C. T. N., Farrell, C., Kristiansen, P. E., & Rayner, J. P. (2014). Biochar makes green roof substrates lighter and improves water supply to plants. *Ecological Engineering*, *71*, 368–374. https://doi.org/10.1016/j.ecoleng.2014.06.017

Chen, H., Du, X., Lai, M., Nazhafati, M., Li, C., & Qi, W. (2021). Biochar Improves Sustainability of Green Roofs via Regulate of Soil Microbial Communities. *Agriculture*, *11*(7), 620. https://doi.org/10.3390/agriculture11070620

Chen, H., Ma, J., Wei, J., Gong, X., Yu, X., Guo, H., & Zhao, Y. (2018). Biochar increases plant growth and alters microbial communities via regulating the moisture and temperature of green roof substrates. *Science of The Total Environment*, *635*, 333–342. https://doi.org/10.1016/j.scitotenv.2018.04.127

Cheng, Y., Vaccari, D. A., Johannesson, B. G., & Fassman-Beck, E. (2022). Multiyear Study on Phosphorus Discharge from Extensive Sedum Green Roofs with Substrate Amendments. *Journal of Sustainable Water in the Built Environment*, *8*(4). https://doi.org/10.1061/JSWBAY.0000999

Dai, Y., Wang, W., Lu, L., Yan, L., & Yu, D. (2020). Utilization of biochar for the removal of nitrogen and phosphorus. *Journal of Cleaner Production*, *257*, 120573. https://doi.org/10.1016/j.jclepro.2020.120573

Dai, Y., Zhang, N., Xing, C., Cui, Q., & Sun, Q. (2019). The adsorption, regeneration and engineering applications of biochar for removal organic pollutants: A review. *Chemosphere*, *223*, 12–27. https://doi.org/10.1016/j.chemosphere.2019.01.161

Francis, L. F. M., & Jensen, M. B. (2017). Benefits of green roofs: A systematic review of the evidence for three ecosystem services. *Urban Forestry & Urban Greening*, *28*, 167–176. https://doi.org/10.1016/j.ufug.2017.10.015

Fransson, A. M., Gustafsson, M., Malmberg, J., & Paulsson, M. (2020). *Biokolhandboken - för användare*. https://biokol.org/publikationer/pdf/biokolhandboken

Gai, X., Wang, H., Liu, J., Zhai, L., Liu, S., Ren, T., & Liu, H. (2014). Effects of Feedstock and Pyrolysis Temperature on Biochar Adsorption of Ammonium and Nitrate. *PLoS ONE*, *9*(12), e113888. https://doi.org/10.1371/journal.pone.0113888

Gan, L., Garg, A., Huang, S., Wang, J., Mei, G., & Zhang, K. (2022). Experimental and numerical investigation on rainwater management of dual substrate layer green roofs using biochar-amended soil. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-02754-0

Gan, L., Garg, A., Wang, H., Mei, G., & Liu, J. (2021). Influence of biochar amendment on stormwater management in green roofs: experiment with numerical investigation. *Acta Geophysica*, *69*(6), 2417–2426. https://doi.org/10.1007/s11600-021-00685-4

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The “Terra Preta” phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, *88*(1), 37–41. https://doi.org/10.1007/s001140000193

Głodowska, M., Husk, B., Schwinghamer, T., & Smith, D. (2016). Biochar is a growth-promoting alternative to peat moss for the inoculation of corn with a pseudomonad. *Agronomy for Sustainable Development*, *36*(1), 21. https://doi.org/10.1007/s13593-016-0356-z

Goldschmidt, A., & Buffam, I. (2023). Biochar-amended substrate improves nutrient retention in green roof plots. *Nature-Based Solutions*, 100066. https://doi.org/10.1016/j.nbsj.2023.100066

Haeldermans, T., Puente Torres, J., Vercruysse, W., Carleer, R., Samyn, P., Vandamme, D., Yperman, J., Cuypers, A., Vanreppelen, K., & Schreurs, S. (2023). An Experimentally Validated Selection Protocol for Biochar as a Sustainable Component in Green Roofs. *Waste*, *1*(1), 176–194. https://doi.org/10.3390/waste1010013

Hassan, M., Liu, Y., Naidu, R., Parikh, S. J., Du, J., Qi, F., & Willett, I. R. (2020). Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: A meta-analysis. *Science of The Total Environment*, *744*, 140714. https://doi.org/10.1016/j.scitotenv.2020.140714

Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., Kirkham, M. B., Chowdhury, S., & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, *2*(4), 379–420. https://doi.org/10.1007/s42773-020-00065-z

Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, *2*(4), 421–438. https://doi.org/10.1007/s42773-020-00067-x

Janu, R., Mrlik, V., Ribitsch, D., Hofman, J., Sedláček, P., Bielská, L., & Soja, G. (2021). Biochar surface functional groups as affected by biomass feedstock, biochar composition and pyrolysis temperature. *Carbon Resources Conversion*, *4*, 36–46. https://doi.org/10.1016/j.crcon.2021.01.003

Jeffery, S., Verheijen, F. G. A., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biology and Biochemistry*, *101*, 251–258. https://doi.org/10.1016/j.soilbio.2016.07.021

Jeffery, S., Verheijen, F. G. A., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, *144*(1), 175–187. https://doi.org/10.1016/j.agee.2011.08.015

Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., Kuzyakov, Y., Luo, Y., Ok, Y. S., Palansooriya, K. N., Shepherd, J., Stephens, S., Weng, Z. (Han), & Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy*, *13*(11), 1731–1764. https://doi.org/10.1111/gcbb.12885

Kamali, M., Jahaninafard, D., Mostafaie, A., Davarazar, M., Gomes, A. P. D., Tarelho, L. A. C., Dewil, R., & Aminabhavi, T. M. (2020). Scientometric analysis and scientific trends on biochar application as soil amendment. *Chemical Engineering Journal*, *395*, 125128. https://doi.org/10.1016/j.cej.2020.125128

Khan, M. N., & Mohammad, F. (2014). Eutrophication: Challenges and Solutions. In *Eutrophication: Causes, Consequences and Control* (pp. 1–15). Springer Netherlands. https://doi.org/10.1007/978-94-007-7814-6_1

Kim, H.-B., Kim, J.-G., Kim, T., Alessi, D. S., & Baek, K. (2020). Mobility of arsenic in soil amended with biochar derived from biomass with different lignin contents: Relationships between lignin content and dissolved organic matter leaching. *Chemical Engineering Journal*, *393*, 124687. https://doi.org/10.1016/j.cej.2020.124687

Kim, J.-Y., Oh, S., & Park, Y.-K. (2020). Overview of biochar production from preservative-treated wood with detailed analysis of biochar characteristics, heavy metals behaviors, and their ecotoxicity. *Journal of Hazardous Materials*, *384*, 121356. https://doi.org/10.1016/j.jhazmat.2019.121356

Kumar, A., Elad, Y., Tsechansky, L., Abrol, V., Lew, B., Offenbach, R., & Graber, E. R. (2018). Biochar potential in intensive cultivation of <scp> *Capsicum annuum* </scp> L. (sweet pepper): crop yield and plant protection. *Journal of the Science of Food and Agriculture*, *98*(2), 495–503. https://doi.org/10.1002/jsfa.8486

Kuoppamäki, K., Hagner, M., Lehvävirta, S., & Setälä, H. (2016). Biochar amendment in the green roof substrate affects runoff quality and quantity. *Ecological Engineering*, *88*, 1–9. https://doi.org/10.1016/j.ecoleng.2015.12.010

Kuoppamäki, K., & Lehvävirta, S. (2016). Mitigating nutrient leaching from green roofs with biochar. *Landscape and Urban Planning*, *152*, 39–48. https://doi.org/10.1016/j.landurbplan.2016.04.006

Kuoppamäki, K., Setälä, H., & Hagner, M. (2021). Nutrient dynamics and development of soil fauna in vegetated roofs with the focus on biochar amendment. *Nature-Based Solutions*, *1*, 100001. https://doi.org/10.1016/j.nbsj.2021.100001

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char Sequestration in Terrestrial Ecosystems – A Review. *Mitigation and Adaptation Strategies for Global Change*, *11*(2), 403–427. https://doi.org/10.1007/s11027-005-9006-5

Lehmann, S. (2014). Low carbon districts: Mitigating the urban heat island with green roof infrastructure. *City, Culture and Society*, *5*(1), 1–8. https://doi.org/10.1016/j.ccs.2014.02.002

Leng, L., & Huang, H. (2018). An overview of the effect of pyrolysis process parameters on biochar stability. *Bioresource Technology*, *270*, 627–642. https://doi.org/10.1016/j.biortech.2018.09.030

Li, L., Long, A., Fossum, B., & Kaiser, M. (2023). Effects of pyrolysis temperature and feedstock type on biochar characteristics pertinent to soil carbon and soil health: A meta-analysis. *Soil Use and Management*, *39*(1), 43–52. https://doi.org/10.1111/sum.12848

Li, S., Harris, S., Anandhi, A., & Chen, G. (2019). Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses. *Journal of Cleaner Production*, *215*, 890–902. https://doi.org/10.1016/j.jclepro.2019.01.106

Li, X., Wang, T., Chang, S. X., Jiang, X., & Song, Y. (2020). Biochar increases soil microbial biomass but has variable effects on microbial diversity: A meta-analysis. *Science of The Total Environment*, *749*, 141593. https://doi.org/10.1016/j.scitotenv.2020.141593

Li, Y., & Babcock, R. W. (2014). Green roofs against pollution and climate change. A review. *Agronomy for Sustainable Development*, *34*(4), 695–705. https://doi.org/10.1007/s13593-014-0230-9

Liao, W., Drake, J., & Thomas, S. C. (2022a). Biochar granulation enhances plant performance on a green roof substrate. *Science of The Total Environment*, *813*, 152638. https://doi.org/10.1016/j.scitotenv.2021.152638

Liao, W., Drake, J., & Thomas, S. C. (2022b). Biochar granulation, particle size, and vegetation effects on leachate water quality from a green roof substrate. *Journal of Environmental Management*, *318*, 115506. https://doi.org/10.1016/j.jenvman.2022.115506

Liao, W., Sifton, M. A., & Thomas, S. C. (2022). Biochar granulation reduces substrate erosion on green roofs. *Biochar*, *4*(1), 61. https://doi.org/10.1007/s42773-022-00186-7

Liu, H., Kong, F., Yin, H., Middel, A., Zheng, X., Huang, J., Xu, H., Wang, D., & Wen, Z. (2021). Impacts of green roofs on water, temperature, and air quality: A bibliometric review. *Building and Environment*, *196*, 107794. https://doi.org/10.1016/j.buildenv.2021.107794

Manso, M., Teotónio, I., Silva, C. M., & Cruz, C. O. (2021). Green roof and green wall benefits and costs: A review of the quantitative evidence. *Renewable and Sustainable Energy Reviews*, *135*, 110111. https://doi.org/10.1016/j.rser.2020.110111

Matuštík, J., Hnátková, T., & Kočí, V. (2020). Life cycle assessment of biochar-to-soil systems: A review. *Journal of Cleaner Production*, *259*, 120998. https://doi.org/10.1016/j.jclepro.2020.120998

Mohammadi, A., Khoshnevisan, B., Venkatesh, G., & Eskandari, S. (2020). A Critical Review on Advancement and Challenges of Biochar Application in Paddy Fields: Environmental and Life Cycle Cost Analysis. *Processes*, *8*(10), 1275. https://doi.org/10.3390/pr8101275

Naeem, M. A., Khalid, M., Ahmad, Z., & Naveed, M. (2016). Low Pyrolysis Temperature Biochar Improves Growth and Nutrient Availability of Maize on Typic Calciargid. *Communications in Soil Science and Plant Analysis*, *47*(1), 41–51. https://doi.org/10.1080/00103624.2015.1104340

Odutola Oshunsanya, S. (2019). Introductory Chapter: Relevance of Soil pH to Agriculture. In *Soil pH for Nutrient Availability and Crop Performance*. IntechOpen. https://doi.org/10.5772/intechopen.82551

Olszewski, M. W., & Eisenman, S. W. (2017). Influence of biochar amendment on herb growth in a green roof substrate. *Horticulture, Environment, and Biotechnology*, *58*(4), 406–413. https://doi.org/10.1007/s13580-017-0180-7

Pandey, D., Daverey, A., & Arunachalam, K. (2020). Biochar: Production, properties and emerging role as a support for enzyme immobilization. *Journal of Cleaner Production*, *255*, 120267. https://doi.org/10.1016/j.jclepro.2020.120267

Paulsson, M. (2020). *Sammanfattande slutrapport för projektet Rest till Bäst (steg 2)*. https://biokol.org/publikationer/pdf/sammanfattande-slutrapport-steg-2

Pettersson Skog, A., Malmberg, J., Emilsson, T., Jägerhök, T., & Capener, C.-M. (2021). *Grönatakhandboken* (2nd ed.). AB Svensk Byggtjänst.

Phillips, C. L., Meyer, K. M., Garcia-Jaramillo, M., Weidman, C. S., Stewart, C. E., Wanzek, T., Grusak, M. A., Watts, D. W., Novak, J., & Trippe, K. M. (2022). Towards predicting biochar impacts on plant-available soil nitrogen content. *Biochar*, *4*(1), 9. https://doi.org/10.1007/s42773-022-00137-2

Qianqian, Z., Liping, M., Huiwei, W., & Long, W. (2019). Analysis of the effect of green roof substrate amended with biochar on water quality and quantity of rainfall runoff. *Environmental Monitoring and Assessment*, *191*(5), 304. https://doi.org/10.1007/s10661-019-7466-4

Rafiq, M. K., Bai, Y., Aziz, R., Rafiq, M. T., Mašek, O., Bachmann, R. T., Joseph, S., Shahbaz, M., Qayyum, A., Shang, Z., Danaee, M., & Long, R. (2020). Biochar amendment improves alpine meadows growth and soil health in Tibetan plateau over a three year period. *Science of The Total Environment*, *717*, 135296. https://doi.org/10.1016/j.scitotenv.2019.135296

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, *361*, 114055. https://doi.org/10.1016/j.geoderma.2019.114055

Shafique, M., Kim, R., & Rafiq, M. (2018). Green roof benefits, opportunities and challenges – A review. *Renewable and Sustainable Energy Reviews*, *90*, 757–773. https://doi.org/10.1016/j.rser.2018.04.006

Shafique, M., Luo, X., & Zuo, J. (2020). Photovoltaic-green roofs: A review of benefits, limitations, and trends. *Solar Energy*, *202*, 485–497. https://doi.org/10.1016/j.solener.2020.02.101

Tan, H., Lee, C. T., Ong, P. Y., Wong, K. Y., Bong, C. P. C., Li, C., & Gao, Y. (2021). A Review On The Comparison Between Slow Pyrolysis And Fast Pyrolysis On The Quality Of Lignocellulosic And Lignin-Based Biochar. *IOP Conference Series: Materials Science and Engineering*, *1051*(1), 012075. https://doi.org/10.1088/1757-899X/1051/1/012075

Thoma, E. D., Wright, R. S., George, I., Krause, M., Presezzi, D., Villa, V., Preston, W., Deshmukh, P., Kauppi, P., & Zemek, P. G. (2022). Pyrolysis processing of PFAS-impacted biosolids, a pilot study. *Journal of the Air & Waste Management Association*, *72*(4), 309–318. https://doi.org/10.1080/10962247.2021.2009935

Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, *19*(1), 191–215. https://doi.org/10.1007/s11157-020-09523-3

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews*, *57*, 740–752. https://doi.org/10.1016/j.rser.2015.12.119

Wang, J., & Wang, S. (2019). Preparation, modification and environmental application of biochar: A review. *Journal of Cleaner Production*, *227*, 1002–1022. https://doi.org/10.1016/j.jclepro.2019.04.282

Weber, K., & Quicker, P. (2018). Properties of biochar. *Fuel*, *217*, 240–261. https://doi.org/10.1016/j.fuel.2017.12.054

Werdin, J., Conn, R., Fletcher, T. D., Rayner, J. P., Williams, N. S. G., & Farrell, C. (2021). Biochar particle size and amendment rate are more important for water retention and weight of green roof substrates than differences in feedstock type. *Ecological Engineering*, *171*, 106391. https://doi.org/10.1016/j.ecoleng.2021.106391

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(1), 56. https://doi.org/10.1038/ncomms1053

Wu, P., Ata-Ul-Karim, S. T., Singh, B. P., Wang, H., Wu, T., Liu, C., Fang, G., Zhou, D., Wang, Y., & Chen, W. (2019). A scientometric review of biochar research in the past 20 years (1998–2018). *Biochar*, *1*(1), 23–43. https://doi.org/10.1007/s42773-019-00002-9

Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., Tsang, D. C. W., Ok, Y. S., & Gao, B. (2020). Biochar technology in wastewater treatment: A critical review. *Chemosphere*, *252*, 126539. https://doi.org/10.1016/j.chemosphere.2020.126539

Xiong, W., Li, J., Wang, H., Wu, Y., Li, D., & Xue, J. (2023). Biochar Addition and the Runoff Quality of Newly Constructed Green Roofs: A Field Study. *Sustainability*, *15*(5), 4081. https://doi.org/10.3390/su15054081

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management*, *36*(1), 2–18. https://doi.org/10.1111/sum.12546

Zhang, J., Liu, J., & Liu, R. (2015). Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate. *Bioresource Technology*, *176*, 288–291. https://doi.org/10.1016/j.biortech.2014.11.011

7 Appendices

7.1 Appendix 1 - Conversion from Mass to Volume

Conversion of mass into volume for the biochars used in research by Liao et al. (2022a, 2022b):

Substrate bulk density = 0.92 g/cm^2
Conventional biochar bulk density = 0.16 g/cm^2
Granular biochar bulk density = 0.32 g/cm^2

Biochar was added as 4.5% of total weight in both instances.

For Conventional Biochar:

$$V_{CB} = \frac{4.5/0.16}{(4.5/0.16) + (95.5/0.92)} \sim 0.2132 \; or \; 21.32\%$$

For Granular Biochar:

$$V_{CB} = \frac{4.5/0.32}{(4.5/0.32) + (95.5/0.92)} \sim 0.1194 \; or \; 11.94\%$$

7.2 Appendix 2 – Gaussian Function

In simulations we target a Gaussian function (in number of particles) with mean 1 mm, and standard deviation ~0.375 mm.

This gives us a soft limit range of the Gaussian:

$$mean \pm 2 * standard\_deviation = [0.25{:}\,1.75]\ mm$$

The big particles have a diameter d3 bigger than 1.75 mm.
But we simplify so that:

- p1=9% <0.5mm
- p2=90% [0.5-1.9] mm
- p3=1% >1.9 mm

We pick up our single particle volumes with the 3 mean diameters:

- d1 = 0.375 mm (mean between 0.25 and 0.5)
- d2 = 1 mm
- d3 = 3 mm

$$Vn = dn^3 * \frac{\pi}{6}$$

Volume fractions were calculated with (V=total volume):

$$V1/V = \frac{P1 * V1}{V1 * P1 + V2 * P2 + V3 * P3} \sim 1\%$$

$$V2/V = \frac{P2 * V2}{V1 * P1 + V2 * P2 + V3 * P3} \sim 77\%$$

$$V2/V = \frac{P3 * V3}{V1 * P1 + V2 * P2 + V3 * P3} \sim 22\%$$

7.3 Appendix 3 – Adsorption Capacity Tests

Table 2 Adsorption capacity test with glass beads and no biochar.

Glass beads only, 20 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.630	6.3
2.5	0.563	5.63
5	0.548	5.48
10	0.517	5.17
15	0.502	5.02
20	0.491	4.91
30	0.476	4.76
45	0.456	4.56
90	0.422	4.22
135	0.401	4.01

Table 3 Adsorption capacity test with 2.0 g of wood-chip biochar.

HJELMSÄTER, 0.5-2 mm, 2.0 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.618	6.18
2.5	0.523	5.23
5	0.511	5.11
10	0.454	4.54
15	0.417	4.17
20	0.390	3.9
30	0.361	3.61
45	0.326	3.26
90	0.286	2.86
135	0.230	2.3

Table 4 Adsorption capacity test with 2.0 g of granulated biochar.

SKÅNEFRÖ, >2 mm, 2.0 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.613	6.13
2.5	0.535	5.35
5	0.492	4.92
10	0.446	4.46
15	0.419	4.19
20	0.403	4.03
30	0.376	3.76
45	0.353	3.53
90	0.319	3.19
135	0.279	2.79

Table 5 Adsorption capacity test with 3.5 g of wood-chip biochar.

HJELMSÄTER, 0.5-2 mm, 3.5 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.621	6.21
2.5	0.545	5.45
5	0.505	5.05
10	0.457	4.57
15	0.402	4.02
20	0.377	3.77
30	0.340	3.4
45	0.306	3.06
90	0.249	2.49
135	0.205	2.05

Table 6 Adsorption capacity test with 3.5 g of granulated biochar.

SKÅNEFRÖ, >2 mm, 3.5 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.605	6.05
2.5	0.505	5.05
5	0.468	4.68
10	0.418	4.18
15	0.388	3.88
20	0.367	3.67
30	0.336	3.36
45	0.307	3.07
90	0.261	2.61
135	0.226	2.26

Table 7 Adsorption capacity test with 5.0 g of wood-chip biochar.

HJELMSÄTER, 0.5-2 mm, 5.0 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.637	6.37
2.5	0.512	5.12
5	0.482	4.82
10	0.415	4.15
15	0.387	3.87
20	0.359	3.59
30	0.316	3.16
45	0.272	2.72
90	0.194	1.94
135	0.139	1.39

Table 8 Adsorption capacity test with 5.0 g of granulated biochar.

SKÅNEFRÖ, >2 mm, 5.0 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.602	6.02
2.5	0.469	4.69
5	0.412	4.12
10	0.363	3.63
15	0.337	3.37
20	0.315	3.15
30	0.272	2.72
45	0.230	2.3
90	0.182	1.82
135	0.159	1.59

Table 9 Adsorption capacity test with 2.0 g of unsieved granulated biochar.

SKÅNEFRÖ, unsieved, 2.0 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.637	6.37
2.5	0.513	5.13
5	0.478	4.78
10	0.437	4.37
15	0.403	4.03
20	0.379	3.79
30	0.345	3.45
45	0.316	3.16
90	0.267	2.67
135	0.227	2.27

Table 10 Adsorption capacity test with 3.5 g of unsieved granulated biochar.

SKÅNEFRÖ, unsieved, 3.5 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.623	6.23
2.5	0.492	4.92
5	0.441	4.41
10	0.397	3.97
15	0.361	3.61
20	0.337	3.37
30	0.311	3.11
45	0.274	2.74
90	0.223	2.23
135	0.182	1.82

Table 11　　Adsorption capacity test with 5.0 g of unsieved granulated biochar.

SKÅNEFRÖ, unsieved, 5.0 g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.631	6.31
2.5	0.470	4.7
5	0.411	4.11
10	0.352	3.52
15	0.337	3.37
20	0.306	3.06
30	0.266	2.66
45	0.223	2.23
90	0.191	1.91
135	0.175	1.75

7.4 Appendix 4 – Adsorption Based on Application Technique Tests

Table 12 Adsorption based on application technique, control.

Glass beads only, 100g		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.000	0
10	0.020	0.2
15	0.020	0.2
20	0.080	0.8
25	0.176	1.76
30	0.333	3.33
35	0.399	3.99
40	0.495	4.95
45	0.524	5.24
50	0.552	5.52
55	0.592	5.92
60	0.602	6.02
90	0.615	6.15
120	0.623	6.23

Table 13 Adsorption when biochar was applied as a bottom layer.

HJELMSÄTER (15% v/v) and 85 g glass beads, BOTTOM		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.024	0.24
10	0.021	0.21
15	0.029	0.29
20	0.090	0.9
25	0.175	1.75
30	0.278	2.78
35	0.297	2.97
40	0.348	3.48
45	0.397	3.97
50	0.407	4.07
55	0.424	4.24
60	0.428	4.28
90	0.473	4.73
120	0.519	5.19

Table 14 Adsorption when biochar was applied as a bottom layer, second try.

HJELMSÄTER (15% v/v) and 85 g glass beads, BOTTOM 2		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.012	0.12
10	0.024	0.24
15	0.036	0.36
20	0.077	0.77
25	0.141	1.41
30	0.240	2.4
35	0.315	3.15
40	0.362	3.62
45	0.421	4.21
50	0.447	4.47
55	0.465	4.65
60	0.497	4.97
90	0.525	5.25
120	0.539	5.39

Table 15 Adsorption when biochar was applied as a surface layer.

HJELMSÄTER (15% v/v) and 85 g glass beads, SURFACE		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.035	0.35
10	0.030	0.3
15	0.017	0.17
20	0.055	0.55
25	0.136	1.36
30	0.287	2.87
35	0.366	3.66
40	0.414	4.14
45	0.446	4.46
50	0.477	4.77
55	0.489	4.89
60	0.504	5.04
90	0.527	5.27
120	0.533	5.33

Table 16 Adsorption when biochar was applied as a surface layer, second try.

HJELMSÄTER (15% v/v) and 85 g glass beads, SURFACE 2		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.013	0.13
10	0.012	0.12
15	0.028	0.28
20	0.082	0.82
25	0.299	2.99
30	0.396	3.96
35	0.450	4.5
40	0.488	4.88
45	0.514	5.14
50	0.522	5.22
55	0.536	5.36
60	0.548	5.48
90	0.557	5.57
120	0.561	5.61

Table 17 Adsorption when biochar was mixed with the substrate.

HJELMSÄTER (15% v/v) and 85 g glass beads, MIXED		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.035	0.35
10	0.042	0.42
30	0.285	2.85
40	0.416	4.16
50	0.484	4.84
60	0.515	5.15
90	0.556	5.56
120	0.561	5.61

Table 18 Adsorption when biochar was mixed with the substrate, second try.

HJELMSÄTER (15% v/v) and 85 g glass beads, MIXED 2		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.012	0.12
10	0.016	0.16
15	0.026	0.26
20	0.078	0.78
25	0.242	2.42
30	0.352	3.52
35	0.431	4.31
40	0.468	4.68
45	0.491	4.91
50	0.513	5.13
55	0.528	5.28
60	0.534	5.34
90	0.573	5.73
120	0.584	5.84

Table 19 Adsorption with Gaussian distribution of glass beads, control.

GAUSSIAN glass beads only		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.018	0.18
10	0.028	0.28
15	0.038	0.38
20	0.182	1.82
25	0.317	3.17
30	0.438	4.38
35	0.495	4.95
40	0.526	5.26
45	0.546	5.46
50	0.553	5.53
55	0.566	5.66
60	0.573	5.73
90	0.577	5.77
120	0.588	5.88

Table 20 *Adsorption with Gaussian distribution of glass beads mixed with biochar.*

GAUSSIAN glass beads, HJELMSÄTER FULLY MIXED		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.040	0.4
10	0.01	0.1
15	0.057	0.57
20	0.126	1.26
25	0.191	1.91
30	0.287	2.87
35	0.354	3.54
40	0.403	4.03
45	0.448	4.48
50	0.477	4.77
55	0.499	4.99
60	0.502	5.02
90	0.538	5.38
120	0.552	5.52

Table 21 *Adsorption with Gaussian distribution of glass beads mixed with biochar, second try.*

GAUSSIAN glass beads, HJELMSÄTER FULLY MIXED 2		
samples (after X min)	**Absorbance (680 nm)**	**Conc. (mg/L)**
0	0.000	0
5	0.080	0.8
10	0.03	0.3
15	0.070	0.7
20	0.154	1.54
25	0.232	2.32
30	0.313	3.13
35	0.392	3.92
40	0.442	4.42
45	0.467	4.67
50	0.493	4.93
55	0.508	5.08
60	0.517	5.17
90	0.547	5.47
120	0.569	5.69

7.5 Appendix 5 – Water Retention Tests

Table 22 Water retention test with no biochar.

NO BIOCHAR, only substrate	
Time (min)	**Water weight (g)**
9 min 52 s	0.00
12	8.00
13	12.06
14	16.02
15	19.96
16	24.09
17	28.27
18	32.41
19	36.40
20	40.56
21	44.56
22	48.75
23	52.73
24	56.95
25	61.14
26	65.23
27	69.38
28	73.72
29	77.74
30	81.88
31	86.03
32	90.43
33	94.42
34	98.64
34 min 20 s	100.00

Table 23 Water retention test with no biochar, second try.

NO BIOCHAR 2, only substrate	
Time (min)	**Water weight (g)**
9 min 43 s	0.00
11	5.07
13	12.95
15	21.09
16	24.92
17	28.97
18	33.00
19	37.03
20	41.07
21	45.06
22	49.24
23	53.20
25	61.33
26	65.46
27	69.48
28	73.47
29	77.72
30	81.55
31	85.81
32	89.92
33	93.95
34	97.88
34 min 30 s	100.00

Table 24 Water retention test with wood-chip biochar.

HJELMSÄTER, 15% v/v	
Time (min)	**Water weight (g)**
9 min 2 s	0.00
10	3.92
12	11.83
13	15.97
14	20.11
15	24.19
17	32.32
18	36.33
19	40.44
20	44.50
21	48.81
22	52.82
23	56.96
24	61.23
25	65.19
26	69.30
27	73.40
28	77.63
29	81.62
30	85.71
31	89.95
32	94.02
33	98.26
33 min 27 s	100.00

Table 25 Water retention test with wood-chip biochar, second try.

HJELMSÄTER 2, 15% v/v	
Time (min)	**Water weight (g)**
10 min 18 s	0.00
11	2.80
13	10.85
14	14.75
15	18.76
16	22.72
17	26.79
18	30.82
19	34.90
20	38.92
21	42.94
22	46.95
23	50.94
24	55.06
25	59.11
26	63.21
27	67.30
28	71.41
29	75.31
30	79.39
31	83.49
32	87.52
33	91.55
34	95.60
35	99.60
35 min 6 s	100.00

Table 26 Water retention test with granulated biochar.

SKÅNEFRÖ, 15% v/v	
Time (min)	**Water weight (g)**
8 min 0 s	0.00
11	11.37
12	15.28
13	19.00
14	23.00
15	26.63
16	30.47
18	38.18
19	41.96
20	45.83
21	49.63
22	53.53
23	57.40
24	61.54
25	65.16
26	69.03
27	72.90
28	76.73
29	80.77
30	84.63
31	88.50
32	92.20
33	96.05
34 min 2 s	100.00

Table 27 Water retention test with granulated biochar, second try.

SKÅNEFRÖ 2, 15% v/v	
Time (min)	**Water weight (g)**
8 min 0 s	0.00
11	10.38
13	17.88
14	21.60
15	25.48
16	29.10
17	33.26
18	36.96
19	40.75
20	44.63
21	48.51
22	52.41
23	56.28
24	60.18
25	63.79
26	67.65
27	71.59
28	75.44
29	79.30
30	82.96
31	86.89
32	90.50
33	94.38
34	98.20
34 min 26 s	100.00

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY