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Biochar

ORIGINAL RESEARCH

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Quantifying the benefits of incorporating biochar in green roof substrates: field study on the highrise rooftop in temperate climate setting

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Abstract

Biochar is a promising material with a wide range of applications. One area of application is as an additive in substrates for green roofs. Green roofs are a way of mitigating climate change, with biochar offering an opportunity to further enhance this benefit and upscale practice. In this field study, the effect of a 5-vol.% addition of wood-based biochar to a green roof substrate is evaluated with respect to a water balance (reduced runoff, increased evapotranspiration, increased plant available water) and hydrophysical properties. Substrate, with and without biochar amendment, was used in different green roof sections. Laboratory hydrophysical analysis, in-situ Volumetric Water Content and meteorological measurements, alongside vegetation monitoring, enabled the development of a 1D Hydrus water balance model and revealed differences between both of the surveyed green roofs. The study demonstrated that the addition of biochar to the substrate improved its hydrophysical properties, leading to increased water retention (7.7% increase in maximum water capacity) and enhanced vegetation growth The biochar amendment resulted in the minor changes in grain size distribution (increase in the 0.01 to 0.1 mm fraction) and increased substrate moisture, which is related to an increase in the plant-available water content (14.2%). This was observable in the retention curves and resulted in an increased moisture availability for plants, leading to an increase in vegetation cover in areas with biochar. The numerical analysis using Hydrus-1D soil hydraulic model showed that the inclusion of biochar in the substrate resulted in a 23.5% increase in evapotranspiration and a 54.7% decrease in runoff. These findings suggest that the addition of biochar to the green roof substrate could enhance the system's capacity to retain water, reduce runoff and bulk density, and increase the amount of water available for plant growth. The study provides evidence for the potential of wood-based biochar as a sustainable and effective addition to green roof substrates, contributing to the development of more resilient and sustainable urban environments.

Highlights

- The addition of biochar to the rooftop substrate (ROOFChar®) increased water retention and enhanced vegetation growth due to increased PAW.
- The model outputs demonstrated a 23.5% increase in evapotranspiration and a 54.7% decrease in runoff for ROOFChar®.

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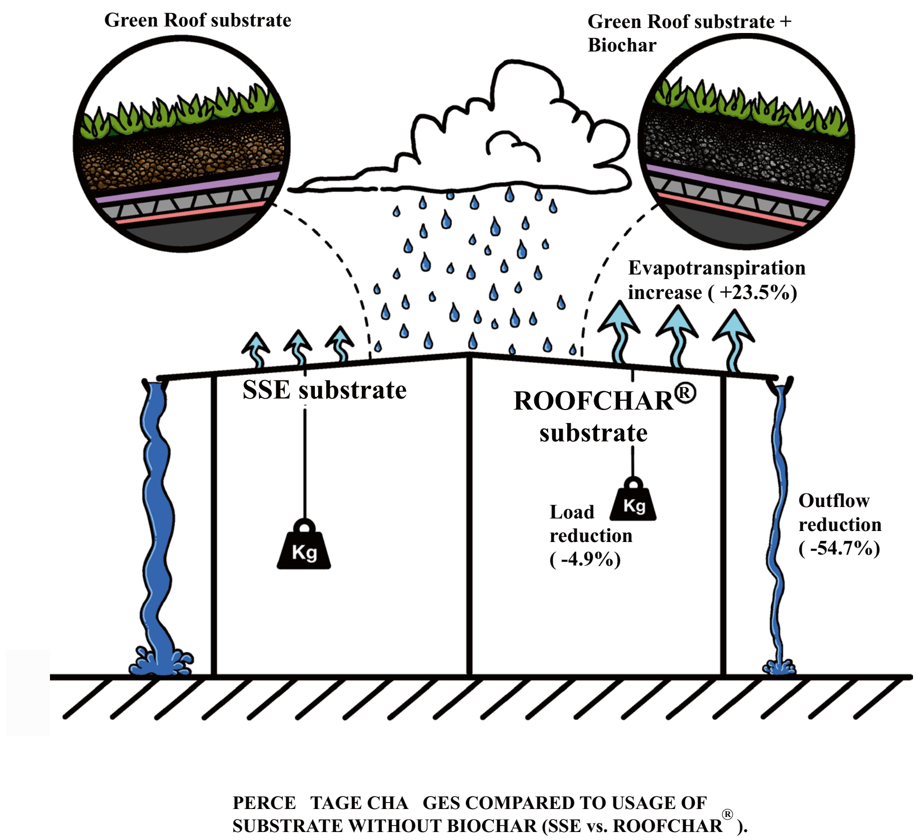
- The effect of biochar admixture was verified in a real-life condition on a high-rise building and interpreted by a numerical model.
- ROOFChar® use in rooftop meant better water retention with lower static load on the building.
- The use ROOFChar® in green roofs led to the development of more resilient and sustainable urban environments.

Keywords Green roof, Biochar, Soil hydraulic properties, Soil water modelling, Water retention, Sustainable cities

Graphical Abstract



1 Introduction

With 70% of the world's population predicted to live in cities by 2050, and the urban's spatial coverage tripling globally by the same date, there is an urgent need for more work on creative sustainability solutions within the built environment (Lwasa et al. 2022; UN 2024). The drastic nature of the metropolitan development places significant strain on such landscapes by, among other pressures, significantly altering rainfall-runoff patterns. In turn, this can lead to water rapidly draining away from cities, resulting in negative impacts to urban soils and disruptions to the drainage systems of the environment. As a result, there is a limited amount of water available for evapotranspiration, an important cooling mechanism of nature landscapes that can be effective in urban environments (Grimmond and Oke 1999; Zou et al. 2019). As outlined in several studies, there is a direct link here to the growing urban heat island effect problem (Li et al. 2014; Yang et al. 2016), which itself is exacerbated by the advancing effects of climate change (Lwasa et al. 2022; Shukla et al. 2022). With these connected issues in mind, there is an urgent need for measures to adapt cities and buildings to this challenging future (Cabeza et al. 2022).

In recent times, there has been an increased interest in the role of Green Infrastructure (GI) as a tool for mitigating and adapting to these challenges (Washbourne and Wansbury 2023). This has particularly focused on 'radical' solutions, such as green roofs (GR), living walls and bioretention systems (Dunnett and Kingsbury 2008; Lwasa et al. 2022). The former has received substantial support recently, with a range of policies, such as the UK's Biodiversity Net Gain legislation, leading to a burgeoning body of actors mainstreaming this GI asset [see for instance Hardman et al. (2024a)]. In the context of urban stormwater management, GR have been proposed as a solution which could generate an array of benefits for cityscapes (Andrés-Doménech et al. 2018; Rowe and Getter 2006). Such benefits range from increasing biodiversity in urban settings, to the potential for food production and nature-based therapies [see for example Hardman et al. (2024a, b)]. With water retention, a greater thickness of the substrate layer of the GR increases its capacity of the system (Meng et al. 2021; Mentens et al. 2006), and at the same time, expands the vegetation types that can be planted within the space (Vandegrift et al. 2019). However, the substrate accounts for 80–90% of the GR weight, resulting in major issues for enabling this on a large scale (Lösken et al. 2018). The structure must be designed accordingly, making the entire construction more expensive, thus increasing the environmental impact of the development through the materials and associated costs.

Whilst other challenges exist for mainstreaming green roofs, from issues around accessibility to the potential to retrofit certain buildings, by far the largest surrounds the weight capacity; thus lightweight green roof substrates with high water retention are desired by an array of stakeholders. Our paper reflects on the potential of biochar: a light material with promising highwater retention properties. Biochar is a solid carbon-rich material obtained by the thermochemical conversion of biomass in an oxygen-limited and elevated pressure environment; this results in a chemically and biologically more stable form than original biomass. In the context of green roofs, it is a promising substrate additive and could potentially lead to the further mainstreaming of the practice (Beesley et al. 2024; Chen et al. 2018; Qianqian et al. 2019). It is regularly used in agriculture soils due to its high water retention capacity (Basso et al. 2013; Seyedsadr et al. 2022), low bulk density, high porosity and surface area (Cao et al. 2014; Seyedsadr et al. 2022), significant nutrient sorption efficiency (Jha et al. 2010; Laird et al. 2010) and the ability to increase and alter microbial activity in soil (Chen et al. 2018; Latini et al. 2019). Moreover, biochar sequesters carbon, preventing its release into the atmosphere when applied as a soil additive (Ahmad Bhat et al. 2022; Lehmann et al. 2006; Smith 2016; Xie et al. 2022).

A study by Beck et al. (2011) showed that the addition of biochar to green roof substrate improved both runoff water quality and retention. Additionally, admixture showed increased water retention and significant decreases in the discharge of total nitrogen, total phosphorus and organic carbon. Similarly, Chen et al. (2018) found that biochar from sewage sludge in quantities of 10–15% exerted the most significant positive effects on both microbial and plant biomass. Kuoppamäki et al. (2016) discovered that wood feedstock biochar surface application on substrate is less effective than the biochar buried into the substrate. Surface biochar improved the retention by ca. 5% (75% of rainfall was retained) while buried biochar by an additional 5% (80% retained). In a later paper, Kuoppamäki (2021) described retention throughout the sessions. Highest retention ca. 80%, was found in summer even though it was the very rainy season. Winter retention was 30–40%. Biochar improved retention at a maximum of about 10%. Gan et al. (2021) found that 10% of rice straw biochar produced at 500 °C had the best results in terms of peak runoff reduction and longest runoff delay when used in the substrate. An admixture of 5% achieved the highest reduction in total runoff and the longest delay in peak runoff. Studies attributing no effect on water retention to biochar are in the minority (Qianqian et al. 2019). The effect of admixture of different amounts of biochar in modified soil as substrate for GR was investigated in a study by Gan et al. (2021). Without biochar, 18.4% of the rainfall was retained performing column experiments. With 5%, 10% and 15% biochar rice straw, 24.7%, 27.5% and 25.2% of the rainfall was retained. An addition of 10% biochar had the greatest effect in reducing peak flow, and 5% has the longest peak runoff delay (Gan et al. 2021, 2022). An admixture of 5% biochar appears to be the best option for GR, with an amount of more than 10% not being ideal (Gan et al. 2021). Beck et al. (2011) performed a GR runoff experiment with and without amendment of 7% by weight feedstock biochar. The plot, without biochar, retained 28.3% of the rainfall, while the plot with biochar retained 30.5% (Beck et al. 2011); this links well to the aforementioned study of Gan et al. (2021), in terms of the total amount of water retained in the experiment. Unconventionally, Kuoppamäki (2021) applied birch (*Betula* spp.) biochar as a 10-mm thick layer (10 vol. %) to a 100-mm thick meadow GR experimental plot in Finland. In the context of this study, water runoff retention was increased by 10% during the first two years of the experiment, but the effect decreased over the 4-year observation period (Kuoppamäki 2021). The application of granulated biochar of various particle size (intervals 1–6.3 mm) into a green roof substrate enhances plant performance measured as a biomass growth, leaf area and chlorophyll content; it also addresses erosion losses (Liao et al. 2022). The application of finer biochar (< 2 mm) resulted in a reduction in infiltration capacity, which is undesirable for green roof substrate. Coarser biochar (2–10 mm) contributed less to increased retention capacity but did not reduce infiltration capacity and air-filled porosity.

The effect of biochar admixture has been investigated in many of the studies described above with effects on runoff quality, water retention, hydraulic conductivity (K_S) and microbial activity. These parameters were dependent on the feedstock materials, production temperature, grain size, amount of biochar added and also the method of application. Finer biochar particles and buried applications appear to be more effective at increasing water retention, while lower concentrations (5–10%) are often sufficient for optimal results. The well-developed internal structure of the so-called mesopores in biochar has been proven to be very effective for water retention (Seyedsadr et al. 2022). These pores are larger than micropores, so that water can enter in larger amounts, but smaller than macropores, which drain easily and cannot entrapped water. Fine biochar can reduce Ks and thus increase water retention. Woody biochar has better retention properties and ability to capture both pollutants and nutrients due to its higher specific surface area than sewage sludge biochar, but is significantly more expensive. However, there is still a significant gap in the literature base with regards to the effect of biochar in GR under real building conditions.

The aim of the study is threefold: firstly, we intended to test, under laboratory conditions, the effect of the presence of wood-based biochar in the roof substrate on its physical and hydraulic properties. This involved a series of controlled experiments to determine how the biochar amendment alters maximum water capacity, plant available water, bulk density, and hydraulic conductivity. Secondly, our objective was to implement and test under field conditions throughout the growing season, spanning from June 2021 to June 2022. This phase assessed the performance and sustainability of the biochar-enhanced substrate in a live environment, monitoring its interaction with plant growth and weather patterns. Lastly, we aimed to build a variable saturation waterflow model based on Richard's equation to simulate the water balance for both scenarios for a whole season. The model predicted how each substrate manages rainfall runoff and affects the evapotranspiration rate and plant available water. In doing so, we hoped to critically explore the role of biochar in helping to further mainstream the GR agenda.

2 Materials and methods

2.1 Substrates

The study aimed to assess the impact of incorporating wood-based high-temperature biochar in green roof substrates. For this purpose, a standard GR substrate (Florcom SSE, BB Ltd. Czech Republic) was amended with 5 vol. % of the biochar during the production process, resulting in a new substrate ROOFChar®. The application rate was selected based on previous studies (Meng et al. 2021) and the expertise of the research team. In terms of the lower application rate, this was applied for a range of reasons: firstly, the price of used biochar was 800 €/ton, and the addition of biochar makes the substrate more expensive. Secondly, too high of biochar levels could negatively affect microbial recovery of the substrate (Palansooriya et al. 2019). Therefore, admixtures above 10% vol. are not advisable as per the literature base. Although even higher rates were investigated (Beck et al. 2011; Cao et al. 2014; Chen et al. 2021, 2018; Gan et al. 2022, 2021).

According to the technical specification of the substrate produced by BB Com Ltd., the extensive green roof (EGR) substrate SSE is intended to be used for drought-tolerant plants and sedum vegetation mats. It consists of lightweight 2/8 Liadrain crushed aggregate, crushed brick from non-standard products 2/12, porous slag 2/8, peat 0/7, compost, dolomitic limestone and fertilizer. The content of organic substances is declared to be less than 15% by volume. The biochar (registered as a soil additive by the Central Institute for Supervising and Testing in Agriculture, CZE) was produced through gasification of wood chips (from wooden pallets) in a fixed-bed multi-stage gasifier using high-temperature pyrolysis between 500 and 600 °C for 6 h, ensuring it has a solid structure, which is reflected by a very high BET surface > 500 $m^2 g^{-1}$ (Brynda et al. 2020). A detailed description of the material is available in the supplementary material 6.

2.1.1 Laboratory measurements

Maximum water capacity (MWC), bulk density (BD), soil moisture retention functions, saturated hydraulic conductivity (K_S), and grain size distribution were determined for both substrates in triplicates.

The bulk density and maximum water capacity (often called 'field capacity', see Supplement 2) were determined according to the FLL Green Roof Guidelines (Lösken et al. 2018) on 1850 cm^3 samples compacted by three blows of the Proctor hammer. MWC was determined after 24 h of underwater saturation and 2 h of gravitation draining. The bulk density of each sample was calculated from the mass of the soil at dry state divided by volume of the sample. A combination of Casagrande's sedimentation method and sieve analysis was used for particle size

Fig. 1 The layout of experimental green roof plots on the roof of the building (foto June 2022). B = plot with substrate amended with biochar (ROOFChar®), other plots with SSE substrate. Red dot = TEROS sensors position in experiental plots

distribution curves. A detailed description is mentioned in the Supplement 3.

A simplified evaporation method (Peters and Durner 2008) was used to measure retention curves using the HYPROP device (HYPROP, METER Group, Inc., USA) (METER Group 2015). The 250 cm^3 samples were opted for in this study. To specify the retention curves in the area of higher suction pressure heads, the measurements in HYPROP were combined with measurement using the WP4C soil water potential instrument (WP4C, METER Group, Inc., USA) (METER Group 2021). A bimodal van Genuchten model of the retention curve was used. More details are shown in Supplement 5.

Saturated hydraulic conductivity was determined using KSAT device (KSAT, METER Group, Inc., USA) and pH of a substrate aqueous extract was determined according to ČSN ISO 10390 using a glass electrode.

2.2 Research site

Open-air measurements were carried out on an experimental green roof located on the roof terrace of the 12-story building in Prague-Stodůlky, Czech Republic (GPS: 50.0496703N, 14.3378058E), 315 m above sea level, 7 km southwest of the city center. The terrace is partially shaded by an apartment on the top floor of the building around which the experimental terrace is located. The site is exposed to considerable wind due to its rooftop location, a trait shared with many other similar sites, both within the Czech Republic and on a more global level. Adding to this, the air conditioning unit does not appear to be affecting the vegetation. The climate on the city is generally affected by the semi-continental weather patterns.

In April 2021, the construction of a green roof was completed, and measurements were initiated in May 2021. Six GR experimental plots were in the western section of the roof terrace; each one is separated from the other by an aluminum rail. Each plot of EGR is 1.35×1.70 m^2. The layout of the experimental plots is shown in Fig. 1. Experimental green roof plots were established and monitored to observe the performance of substrates with and without biochar under the same conditions, thereby minimizing the variabilities of the results. The experimental plots were planted with a drought-tolerant mixture of grasses and herbs. Plants were randomly distributed. While *Hieracium pilosella*, *Achillea millefolium*, *Verbascum phoeniceum* and *Aquilegia vulgaris* share good drought tolerance and lower transpiration rates, *Deschampsia caespitosa* would have higher water need and transpiration rate. With the exception of *Deschampsia caespitosa*, the plant species are moderately drought tolerant or drought tolerant and of similar size, therefore similar hydrological effect can be expected. There were 31 plants on SSE plots and 19 in ROOFChar® plots in total. There were three plants of *Deschampsia caespitosa* planted in SSE plots and seven in ROOFChar® plots. During the study period, spontaneous vegetation expansion occurred in all areas. New 112 plants grew in the SSE plots and 109 plants in the ROOFChar® plots. Because the study was performed short after the installation the plant coverage is low. An abundance analysis (vegetation cover) was conducted on the plots in June 2022 and November 2022. The initial abundance was determined to be 28% (SSE) and 30% (ROOFChar). An increase in abundance of 4% and 10% was found for the plots with SSE and ROOFChar® substrate, respectively. The green roof structure is installed on older roof bearing construction with a slope 1.5% to allow free water drainage. The slope of flat roofs is usually designed between 1.5% and 5% and the slope used is therefore rather less than the slope usually used. There is a new PVC impermeable foil with resistance to root growth at the bottom covering the bearing construction; this foil is protected by a geotextile (300 g m^{-2}) layer. Excess water is taken away by a cuspated drainage board with the height of 25 mm. In order to prevent the clogging of the drainage layer, the cuspated drainage board is covered with a filter geotextile (110 g m^{-2}) on which the substrate and the plants are placed. There is 90 mm of the growing medium on the EGR. The EGR plots are planted with seedlings of various types of arid perennials and grasses able to grow in direct sunlight.

Each of the 6 experimental plots was equipped with two soil moisture and temperature sensors (TEROS 11, METER Group, Inc., USA). Sensors were placed in a horizontal position 50 mm below the soil surface below a bare soil. A specific calibration was performed for the moisture sensors in the green roof substrate used (Supplementary material 7). The specific calibration agreed well with the calibration equation provided by sensor manufacturer for "Soilless media". The difference was only noticeable in the very dry measurement region between 0 and 10% Volumetric Water Content (VWC). The resulting equation used, $VWC = 8.63 \times 10^{-10} \times RAW - 6.632 \times 10^{-6} \times RAW + 0.0171393 18699 \times RAW - 14.492116489349$, which was obtained by interleaving the 33 measurements obtained by the specific calibration and the values for "Soilless media". The RAW variable in the calibration equation represents the sensor signal value before calibration. To collect more data, a weather station (ATMOS41, METER Group, Germany) located on the rooftop approximately 10 m to the experimental plots provides complex meteorological measurements of solar radiation, precipitation, air temperature, barometric pressure, vapor pressure, relative humidity, wind speed, and wind direction.

2.3 Simple 1D hydraulic model

The complex monitoring system enabled the utilization of a standard one-dimensional hydraulic rainfall-runoff model in HYDRUS-1D (Šimůnek et al. 2008) for the green roof system. Hydrus has proven to be a suitable for modelling in GR ranging from very dry (Palermo et al. 2019) to wet conditions (Broekhuizen et al. 2021). The period from June 2021 to June 2022 was modelled, enabling a reflection over a 13-month period and ensuring all seasons are recorded in the study. The HYDRUS-1D model, designed for one-dimensional fluxes, is based on the modified Richards equation with the assumption that air phase interactions with the liquid flow process might be neglected, and water flow due to thermal gradients is also insignificant. The model version, using the dual porosity (Durner 1994) model of hydraulic properties, was adopted for this study. This model setup enabled the utilization of the bimodal soil water retention curves of more complex pore systems. The bimodal soil hydraulic model was selected due to the bimodal character of the roof substrate, where both the larger fraction of the lightweight aggregate grains and the finer component are represented. The porous material can be divided into two overlapping regions, each being represented by a specific set of van Genuchten–Mualem function (van Genuchten 1980) of soil hydraulic properties.

The upper boundary condition was represented by the measured precipitation and reference evapotranspiration estimated by the Penman–Monteith formula as presented in FAO Drainage Paper No. 56 (Allen et al. 1998). Actual root water uptake was calculated according to the Feddes equation (Feddes et al. 1974), restricting the reference evapotranspiration by the function of specific water content. The lower boundary condition was represented by the seepage face often utilized for finite soil columns exposed to the atmosphere with gravity drainage. The flux was triggered when the pressure head of −10 cm was reached. The depth of the modeled soil profile was 9 cm, and each column was formed by a single material with the soil hydraulic properties presented in Table S2 (Supplementary material 4). EGR plots with SSE and ROOFChar® substrates did not differ significantly in the extent of above-ground biomass. A Leaf Area Index (LAI) value of 1.4 (m^2/m^2) was used in the model.

3 Results and discussions

3.1 Laboratory analysis

3.1.1 Substrate properties affected by the biochar admixture

The biochar amendment caused changes in both physical and hydrophysical properties of the rooftop substrate. These changes were only minor in terms of the grain size distribution. The substrate with biochar admixture shows slightly higher proportion of grains with a diameter of about 0.01 to 0.1 mm (Fig. 2). However, most grains of both substrates are larger than 1 mm in diameter. The change is given by the fraction of added biochar.

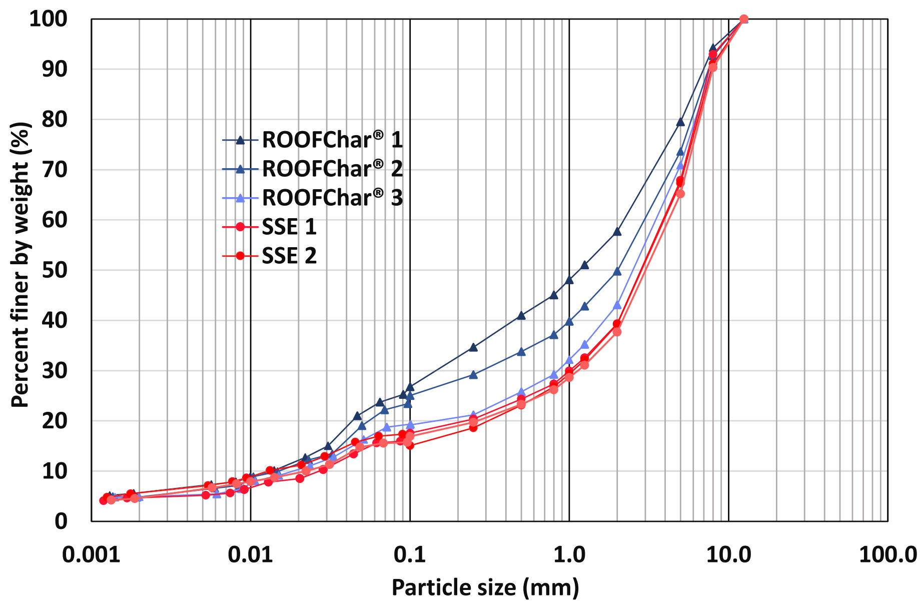


Fig. 2 Particle size distribution curve of substrates used on experimental green roof plots

Table 1 Soil physical and hydrophysical parameters, ± represents the standard deviation

	MWC (vol. %)	Dry BD (kg m^{-3})	BD at max MWC (kg m^{-3})	Water retained (kg m^{-3})	K_s at 10 °C (m s^{-1})
ROOFChar®	60.1 ± 1.9	530.4 ± 4.1	1131.1 ± 16.2	600.7 ± 19.4	$2.9.10^{-4} \pm 5.4 \times 10^{-5}$
SSE	52.4 ± 1.1	665.2 ± 44.1	1189.2 ± 32.9	524.0 ± 11.3	$7.8.10^{-4} \pm 1.8 \times 10^{-4}$
Difference	7.7	134.8	58.1	76.7	$4.9.10^{-4}$

There was a low variation between SSE substrate replicates, but high variation between ROOFChar® plots. The difference may be due to inhomogeneity during GR installation, where finer particles may have fallen into deeper layers, but the difference in grain size did not translate into a difference in retention curves, and thus the difference may not be due to a difference in the amount of biochar in each replicate.

The higher water retention of the biochar-amended substrate (ROOFChar®) was confirmed by the MWC measurements as shown in Table 1. All samples amended with biochar showed a higher MWC value and lower bulk density. The addition of 5 vol. % biochar to the SSE extensive green roof substrate caused a 14.7% increase in MWC in average. The bulk density in dried substrate (temperature 105 °C) as well as at MWC is lower for substrates with admixture of the biochar. In addition, more water is retained by the biochar-amended substrate (Table 1). The dry biochar-enriched substrate is lighter due to the low bulk density of the biochar used (163 kg m^{-3}), therefore its addition decreases bulk density of the substrate as whole. This confirmed the earlier findings of several studies (Cao et al. 2014; Liao et al. 2022; Werdin et al. 2021). At the same time, it confirmed the assumption that incorporating biochar into the substrate increases its ability to retain water (Chen et al. 2018; Huang et al. 2020; Qianqian et al. 2019). Specifically, a substrate containing biochar retains 76.7 L more water per cubic meter of substrate than a substrate without biochar admixture. The mechanism of biochar in retaining water is described in the next chapter.

Perhaps one of the most important elements of this finding is that even with such a significant increase in water retention capacity, the biochar substrate is still by 4.9% lighter (in weight) even with the retained water considering MWC. The application of biochar increased the proportion of fine particles in the substrate, which is related to the decrease in K_S after the application of biochar. However, the reduction in K_S is not very significant and it's still in the same order of magnitude (Table 1). This would be consistent with the study findings (Ahmad Bhat et al. 2022), which also associated K_S primarily with the change in grain size based on a comparison of the available literature. In terms of hydraulic conductivity,

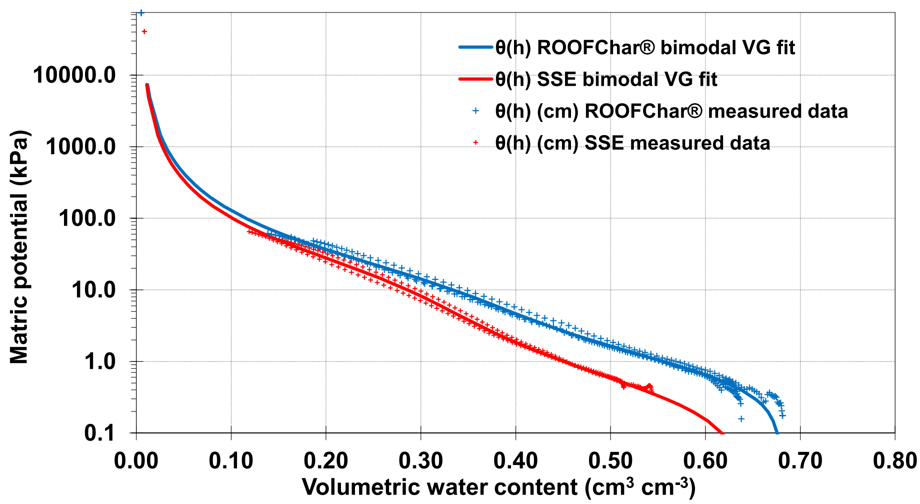


Fig. 3 The course of the retention curve functions with marked points of own measurement of three samples of each substrate using the HYPROP device (RMSE ROOFChar® = 0.0113; RMSE SSE = 0.0080)

the influence of biochar corresponds to its grain size distribution. Where the admixture of biochar into coarse-grained material tends to decrease K_S, the admixture of a larger fraction of biochar into fine-grained material with initially lower K_S may rather increase K_S.

The pH of the substrate was not significantly affected by the addition of biochar, when ROOFChar® had a pH of 8.3 and the SSE substrate had a pH of 8.6.

3.1.2 Effect of the biochar presence on the substrate water retention

Based on the VG bimodal model, soil retention parameters were estimated, and retention curves were drawn. The retention curves of both types of substrates showed very good agreement between the repetitions. Figure 3 illustrates that the biochar amendment caused a notable displacement of retention curves towards higher water content in the region near saturation. There was an elevation in saturation levels throughout the range of suction pressure values for the ROOFChar® substrate. The introduction of biochar significantly improved the volume of capillary water held within the substrate at a given suction pressure head. This water is released from the biochar under elevated suction pressure conditions. In other words, the biochar retains the water available to plants when subjected to higher suction pressures (Seyedsadr et al. 2022).There are two main mechanisms of biochar functioning in relation to water retention. These are physical water fixation and chemisorption via hydrogen bond and weak π bonds (Jačka et al. 2018). Physical mechanisms include improved aggregate stability and soil structure (case especially in arable soils) (Hardie et al. 2014), filling of larger substrate pores with relatively smaller biochar particles (Liu et al. 2017), and direct involvement of the internal biochar pores with large surface area, high internal porosity and significant proportion of mesopores in retaining the water (Hyväluoma et al. 2018; Werdin et al. 2021). Chemical water retention mechanisms then include hydration interaction with base cations (Kutilek and Nielsen 1994) and direct interaction of water with the biochar surface due to π interaction to the carbon surface, and hydrogen bonds on carboxyl groups (Conte et al. 2013).

It is clear from the course of the retention curves (Fig. 3), which converge toward each other with increasing pressure head, that biochar increased the PAW of the substrate. The addition of 5% (v/v) biochar in this experiment resulted in an increase in PAW of 14.2% and an increase in PAW_{NGW} of 18.3%. This is in line with many earlier findings (Cao et al. 2014; Chen et al. 2018; Liu et al. 2022; Werdin et al. 2021). Cao et al. (2014) demonstrated a direct dependence of 10%, 20%, 30% and 40% (v/v) of urban green waste biochar (production temperature 550 °C) in the roof substrate on PAW, which increased linearly from 17.5% with 0% biochar, to 20; 22.5, resp. 28% with 5; 20 respectively 40% biochar content. In the context of broader studies, Liu et al. (2022) reached the same finding when investigating the addition of 0%, 5%, 10%, 15% and 20% (v/v) biochar from wood produced at 400 °C to the roof substrate. PAW was increased by 7.6, respectively. 18.9%. with 5, resp. 20% biochar amendment. Chen et al. (2018) measured 39.3% increase in PAW with 20% sludge biochar (production temperature 600 °C) in a green roof substrate. Werdin et al. (2021) is consistent with the findings of other studies in his experiments. The admixture of 0%, 20% and 40%

Table 2 Significant points on the retention curve

	ROOFChar®	SSE
Ψ_6kPa	0.380	0.322
FC 33 kPa	0.213	0.186
PWP (1500 kPa)	0.025	0.023
PAW_{NGW} (6–1500 kPa)	0.359	0.303
PAW (33–1500 kPa)	0.192	0.168

(v/v) biochar from *E. nitens* (production temperature 550 °C) led to an increase in PAW from 14.7% in control without the biochar, depending on the coarseness of the biochar. Finer biochar increased PAW more than coarse biochar. The addition of 40% fine biochar led to a PAW of 26% (77% increase). The addition of 40% coarse biochar led to a PAW of 21% (44% increase). The increase in PAW with biochar does not only apply to green roof substrates, but also to agricultural soils, where 5% cornstalk biochar improved the PAW of sandy soil by 17% (Cornelissen et al. 2013).

Result of this study are consistent with the literature available. The inclusion of biochar in the substrate significantly increases the amount of water available to plants (PAW). The specific values of substrates used in this study are shown in Table 2.

Higher PAW contributes to higher evapotranspiration (Slatyer 1956), thus cooling the nearby environment and thus reducing the urban heat island (QIU et al. 2013).

3.2 Experimental green roof monitoring

Figure 4 shows the one-year course of the volumetric water content (VWC) reading in experimental plots of the extensive green roofs in response to the rainfall episodes from June 2021 to June 2022. The figure clearly shows the increase of the VWC measured on rainfall and the subsequent decrease until the next precipitation episode. The data confirm what has already been indicated by the retention curves (Fig. 3); the ROOFChar® plots were able to retain more water during rainfall (higher maximum VWC). After rainfall, the ROOFChar® typically reached a slightly higher absolute VWC; the maximum VWC was around 40% to 45%. During the entire study period, there was no decrease in day average VWC below 6.0, resp. 11.6% for ROOFChar®, resp. SSE. ROOFChar® was able to release the water for plants (PAW) in the following rainless period (steeper decline in VWC). This is especially true in the warmer months (from May to October), where the effect of the biochar is more significant and the differences in VWC between plots with and without the biochar more apparent. In contrast, differences were not very evident in the cold months when the VWC fluctuations were much lower. However, the accuracy of measurements in winter can be negatively affected by partial freezing of water in the substrate.

Our measurements confirm the finding of Tan and Wang (2023) that biochar improves the water retention capacity of the green roof substrate and increases the saturated water content (Gan et al. 2021). This finding is generally well known (Cao et al. 2014; Liu et al. 2022), however, there are a lack of studies examining this green roof behavior as a case study with long term monitoring in a real-world setting. A rare example is a study of Petreje et al. (2023) comparing substrate with 10% vol. of a sludge biochar with a substrate in which the biochar was replaced by peat, the latter of which has a considerable water retention capacity. This resulted in the peat substrate showing higher VWC values than the sludge biochar substrate. However, it should be noted that the sludge biochar, despite its other advantages, has a significantly lower water retention capacity than the wood-based biochar used in this study. Furthermore, the measurements used were indicative in nature to describe the trend in moisture content over time rather than to derive an exact absolute value of VWC. A similar attempt to compare the VWC over time was made by Kuoppamäki et al. (2016). The plots with surface application of wood-based biochar showed a lower moisture content than the plots without biochar during the summer months. However, Kuoppamäki et al. (2016) pointed out the lack of sensor calibration. This contradicts the findings of the current study, where the VWC on the biochar plots is higher in the summer months. The lack of exploration only underscores the need for further research in this area.

The biochar addition did not have significant impact on substrate average temperature. Throughout the monitored session from June 2021 to June 2022, SSE substrate showed insignificantly higher temperature (0.2 °C) than ROOFChar®. In summer average months ROOFChar® demonstrated insignificantly higher temperature (0.1 °C) than SSE on average. This is in contrast with Tan and Wang (2023) who measured 3–5 °C lower upper surface roof temperature after 10 and 20% vol. biochar amendment and also partly with Chen et al. (2018), who measured temperature decreased in summer when sludge biochar addition rate was 0–10% vol. and temperature increase when the biochar addition was 10–20% vol. However, in the present study, the minimum daily temperature in the ROOFChar® plots was recorded to be lower, falling to −2.3 °C on some days. The minimum temperature in the SSE substrate plots was around 0 °C. The reason for the relatively low effect on the temperature regime may be caused due to the lower dose of biochar used in this study.

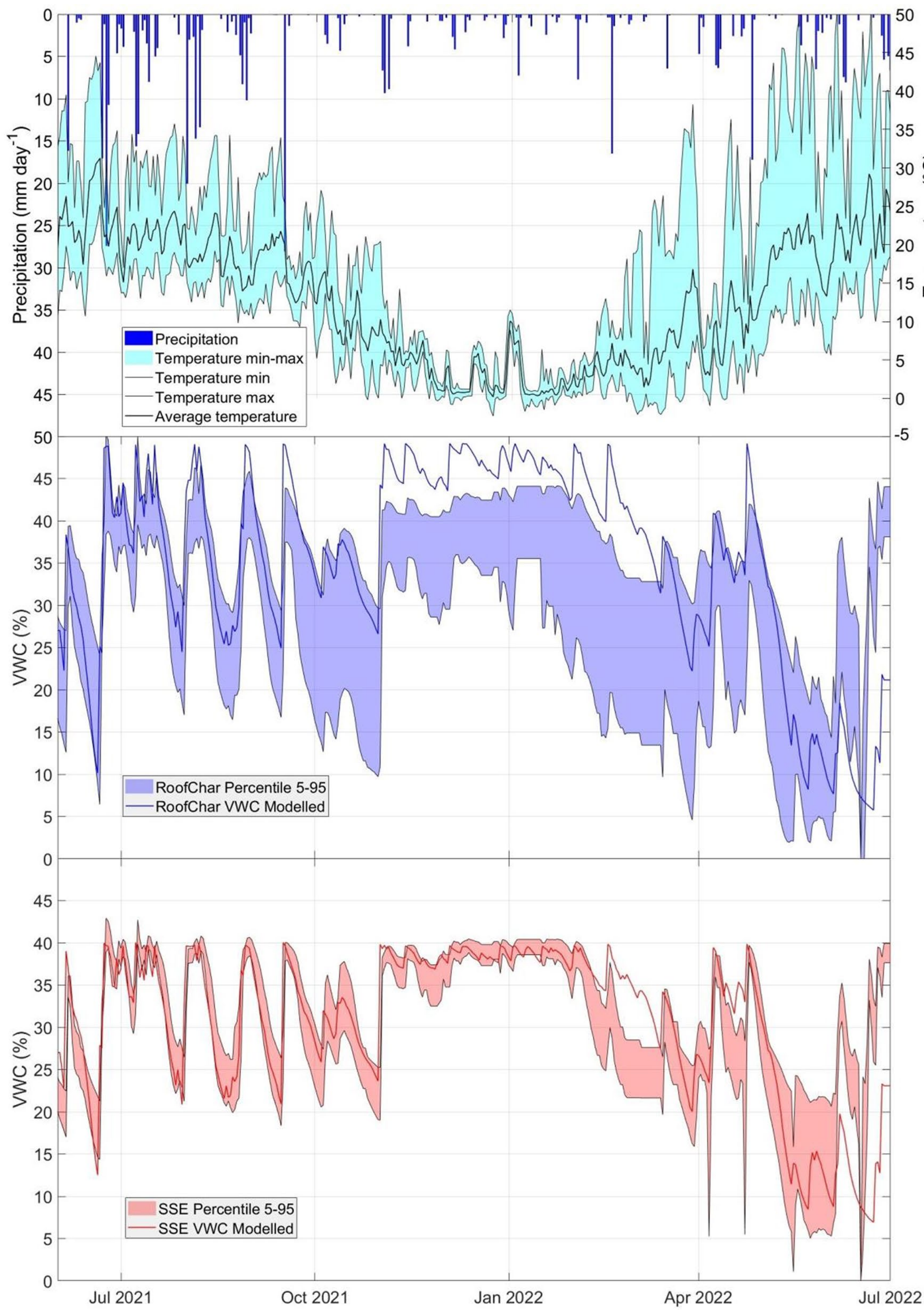


Fig. 4 Substrate volumetric water content (VWC, percentile 5–95—averaged all measurements) and Substrate temperature dynamics on experimental plots: Precipitation-driven responses of VWC from June 2021 to July 2022 fitted by Hydrus 1D model

3.3 Water balance modeling

The 'volumetric soil moisture content modeled' and 'observed volumetric soil moisture' contents are depicted in Fig. 4. The root means square error of the simulations equaled to 4.58% and 8.00% in the case of SSE and ROOFChar® plots, respectively. In both cases, the model was able to capture the rainfall-runoff dynamics in a reasonable way. During the summer and autumn, the model fitted the measured VWC very well. The main discrepancies were observed in the winter and spring periods. The reasons can be two-fold: first, in periods with partial or complete soil water freezing, the moisture measurement is uncertain due to change in dielectric constant of frozen water. Periods when the model for ROOFChar® does not accurately fit the measured moisture in the winter period match exactly the period when negative substrate temperatures have been recorded on the ROOFChar® plot. Second, the pore size distribution of the green roof substrate could have undergone structural changes as the shallow substrate layer soil temperature reached 0 °C and sometimes dropped to negative temperatures for short periods of time (especially from November to March); however second explanation could not be verified by collecting another set of samples and repeating the retention curve measurements because of the limited access to the experimental site after the end of the study period. This could cause a difference between the retention curve characteristics captured in the laboratory measurements before the field study period and the substrate on the green roof influenced by freeze–thaw cycle. This effect is not yet well described for green roofs.

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In terms of the wider literature on this, the influence of freeze–thaw cycles on the soil hydraulic properties was documented by Bodner et al. (2008) and Hu et al. (2012). Additionally, soil hydraulic properties can vary thorough the year even from different reasons (biological activity, initial wetness or raindrops impacts) as documented by Bodner et al. (2013), Císlerová et al. (1988), Hu et al. (2009). These changes are not implemented in current modelling practices which rely on time-invariable parameters (De Vos et al. 2010). For this reason, the modeling of VWC during this period is subject to uncertainty. Šípek and Tesar (2016, 2017) reported a declined soil moisture modeling efficiency during the dormant season in forested areas. Hlavinka et al. (2011) also reported higher modeled soil moisture in the dormant season compared to measurements. Contrarily, the underestimation of winter soil moisture content was reported by Keshta et al. (2012) when modeling of the soil moisture storage in Alberta, Canada. Additionally, winter precipitations are generally more susceptible to measurement error than summer ones (Dingman 2014). On the other hand, the deviation of the model from the measurements in winter months does not significantly affect the final water balance result. In the winter period with low evapotranspiration and high substrate saturation, most of the water from both types of plots drains directly. The green roof thus behaves rather passively in terms of water retention. This can be observed in Fig. 4 in the low amplitude of the measured and modeled VWC. Therefore, the absolute value of the VWC does not play an important role in determining the water balance regime as a result of the change in humidity.

The modeled water balance of the SSE plot indicated that the 482 mm of rainfall was divided into 333 mm of evapotranspiration and 147 mm of runoff (the rest represents the change in substrate VWC). The evapotranspiration can be further divided into 32 mm of transpiration flux and 301 mm of soil evaporation. The low ratio between transpiration and evaporation is due to low vegetation cover. The evapotranspiration flux was higher by 23.5% in the case of biochar enriched plots (ROOFChar®), which resulted in the drainage lower by 54.7%. The evaporation of the bare soil was 11.0% higher at ROOFChar® plot. The differences between the two plots gradually thorough the entire 13 month inspected period (Fig. 5). This represents an increase in evapotranspiration, respectively a reduction in runoff by 80.4 L per the

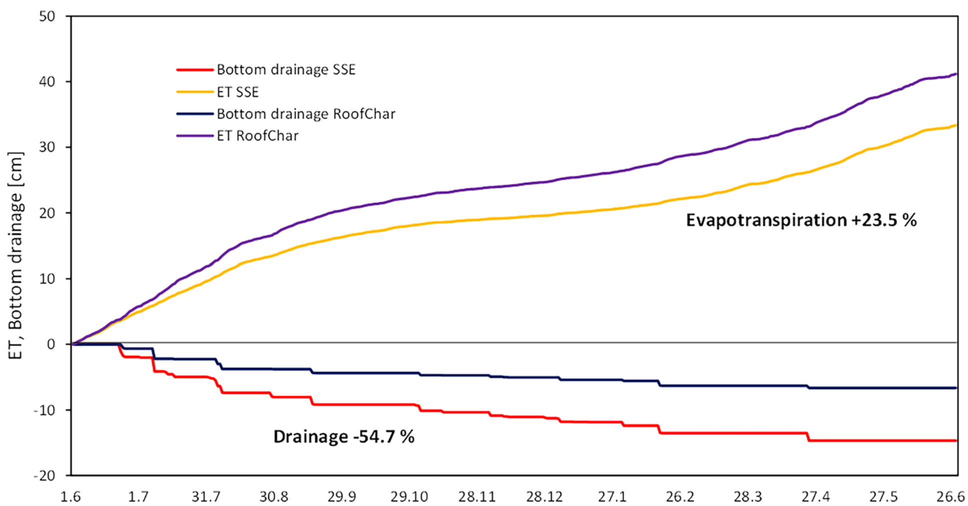

Fig. 5 Modeled difference in water retention between SSE and biochar-enriched ROOFChar® plots shown on the timeline

period per 1 m^2 of green roof using substrate amended with biochar and thus increased cooling effect. These findings suggest that the addition of biochar to the green roof substrate could enhance the system's capacity to retain moisture, reduce runoff, and increase the amount of water available for plant growth.

Transpiration behavior is closely related with the vegetation growth and cover described in Sect. 2.2 and depicted in Supplementary material 9. The effect of biochar amendment on vegetation cover was observed. Biochar contributed to the spontaneous spread of vegetation in the experimental plots during the observation season of 2021 due to its ability to provide the vegetation with more PAW to support its growth. The plots with ROOFChar® showed a greater increase in the cover of spontaneously spreading vegetation between the months of June and November. Plots without biochar (SSE) showed an average increase in abundance of 4%, while plots with biochar showed an average increase of 10%.

If the modeled data will be extrapolated to a green roof of 100 m^2, the GR without biochar can evapotranspirate 33.3 m^3 of water per 13 month inspected period. The same size GR with added biochar can evapotranspirate by an additional 7.8 m^3 of water. Extrapolating the results to a 10-year period, it could be found that a GR without resp. with biochar of 100 m^2 can evaporate 307 resp. 380 m^3 of water. This is also related to the reduction of rainwater runoff to the sewer and the impact on the wastewater treatment plant. The addition of biochar will reduce rainfall runoff of 100 m^2 GR by 74.2 m^3 every year thus contributing to the distressed "Sponge City" effect.

The results also highlight the potential of the one-dimensional hydraulic model in HYDRUS 1D to provide valuable insights into the hydrological behavior of GR systems and the impact of substrate amendments on their performance.

With interest in green roofs and broader radical approaches to GI at an all-time high, this study provides crucial evidence on how to scale-up more effective solutions in the built environment. Of particular note, the study provides crucial evidence on how to increase the effectiveness of these assets, linking to calls for creative ways to support the broader urban greening agenda (see for instance Washbourne and Wansbury 2023). The increased attention by a range of actors, from the private sector to public authorities and beyond, means that these findings highlight the potential of utilizing biochar to increase the impacts of green roofs: enabling better use of urban spaces, increasing natural coverage and potentially leading to more innovative rooftop projects within cityscapes. The findings also provide important evidence with regards to emerging legislation around green roofs in Europe and beyond, such as the aforementioned Biodiversity Net Gain act in the UK; in this sense, the study reveals how biochar can lead to richer, more diverse spaces if enacted on a larger scale. Further research is needed to explore the potential benefits of different types of biochar and their feedstock materials on substrate performance. In addition, more work is needed to explore how this can translate to practice on the ground, such as financial impacts, responses from legislation and the likely uptake by key actors in this environment. In doing so, the upscaled use of biochar within the context of green roofs could lead to major impacts for cityscapes globally.

4 Conclusions

This case study has demonstrated that the addition of biochar to the substrate of green roofs can improve their hydrophysical properties, resulting in increased water retention and improved vegetation growth. The biochar amendment caused minor changes in the grain size distribution. The results of real-world green roof monitoring showed that biochar amendment caused an increase in substrate moisture related to increase in plant available water content. This in turn was observable on retention curves and increased maximal water capacity, resulting in enhanced moisture availability to plants, which can be evidenced an increase in vegetation cover in areas with biochar. Furthermore, the 1D Hydrus hydraulic modeling conducted in this study showed that the inclusion of biochar in the substrate resulted in an increase of 23.5% in the amount of evapotranspiration, while the amount of runoff decreased by 54.7%. These findings suggest that the addition of biochar to the green roof substrate could enhance the system's capacity to retain moisture, reducing runoff, and increasing the amount of water available for plant growth.

In summary, the study provides evidence for the potential of the wood-based biochar as a sustainable and effective amendment to green roof substrates, which could contribute to the development of more resilient and sustainable urban environments.

Abbreviations

GR	Green roof
EGR	Extensive green roof
VG	Van Genuchten
VWC	Volumetric water content ($cm^3\ cm^{-3}$)
Ψ_6kPa	Soil Water Potential (6 kPa)
FC	Field capacity (33 kPa)
PWP	Water content at permanent wilting point (1500 kPa)
PAW_{NGW}	Plant available water content in groundwater proximity (≥ 6–1500 kPa)
PAW	Plant available water content (≥ 33–1500 kPa)
MWC	Maximum water capacity
GI	Green Infrastructure

Supplementary Information

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Supplementary Material 1.

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Authors' contribution
Marek Petreje: Investigation, Methodology, Visualization, Writing - original draft, Funding acquisition; Michal Sněhota: Conceptualization, Formal analysis, Methodology, Writing - original draft; Václav Šípek: Investigation, Software, Writing - original draft; Tereza Hnátková: Resources, Validation; Jan Punčochář: Formal analysis, Methodology, Validation; Stanislav Buchtelík: Methodology, Resources, Validation; Michael Hardman: Investigation, Writing - review & editing; Lukáš Trakal: Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing.

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Data availability
Data will be made available on request.

Declarations

Competing interests
Lukáš Trakal is an AE of the journal Biochar, he was not involved in the peer-review or handling of the manuscript. The authors have no other competing interests to disclose.

Research involving human participants and/or animals informed consent
Not applicable.

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References

Ahmad Bhat S, Kuriqi A, Dar MUD, Bhat O, Sammen SS, Towfiqul Islam ARM, Elbeltagi A, Shah O, Ai-Ansari N, Ali R, Heddam S (2022) Application of biochar for improving physical, chemical, and hydrological soil properties: a systematic review. Sustainability. https://doi.org/10.3390/su141711104

Allen R, Pereira L, Raes D, Smith M (1998) FAO: crop evapotranspiration—guidelines for computing crop water requirements

Andrés-Doménech I, Perales-Momparler S, Morales-Torres A, Escuder-Bueno I (2018) Hydrological performance of green roofs at building and city scales under mediterranean conditions. Sustain 10:1–15. https://doi.org/10.3390/su10093105

Basso AS, Miguez FE, Laird DA, Horton R, Westgate M (2013) Assessing potential of biochar for increasing water-holding capacity of sandy soils. GCB Bioenergy 5:132–143. https://doi.org/10.1111/gcbb.12026

Beck DA, Johnson GR, Spolek GA (2011) Amending greenroof soil with biochar to affect runoff water quantity and quality. Environ Pollut 159:2111–2118. https://doi.org/10.1016/j.envpol.2011.01.022

Beesley L, Cancelo BC, Hardman M, Lebrun M, Mitchell K, Trakal L (2024) Biochar and heavy metals. Biochar Environ Manag Sci Technol Implement. https://doi.org/10.4324/9781003297673-21

Bodner G, Loiskandl W, Buchan G, Kaul HP (2008) Natural and management-induced dynamics of hydraulic conductivity along a cover-cropped field slope. Geoderma 146:317–325. https://doi.org/10.1016/j.geoderma.2008.06.012

Bodner G, Scholl P, Loiskandl W, Kaul HP (2013) Environmental and management influences on temporal variability of near saturated soil hydraulic properties. Geoderma 204–205:120–129. https://doi.org/10.1016/j.geoderma.2013.04.015

Broekhuizen I, Sandoval S, Gao H, Mendez-Rios F, Leonhardt G, Bertrand-Krajewski JL, Viklander M (2021) Performance comparison of green roof hydrological models for full-scale field sites. J Hydrol X 12:100093. https://doi.org/10.1016/j.hydroa.2021.100093

Brynda J, Skoblia S, Pohořelý M, Beňo Z, Soukup K, Jeremiáš M, Moško J, Zach B, Trakal L, Šyc M, Svoboda K (2020) Wood chips gasification in a fixed-bed multi-stage gasifier for decentralized high-efficiency CHP and biochar production: long-term commercial operation. Fuel 281:118637. https://doi.org/10.1016/j.fuel.2020.118637

Cabeza LF, Bai Q, Bertoldi P, Kihila JM, Lucena AFP, Mata É, Mirasgedis S, Novikova A, Saheb Y (2022) IPCC Chapter 9, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York. https://doi.org/10.1109/TSG.2017.2673783.Chapter

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

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. Sci Total Environ 635:333–342. https://doi.org/10.1016/j.scitotenv.2018.04.127

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. https://doi.org/10.3390/agriculture11070620

Císlerová M, Šimůnek J, Vogel T (1988) Changes of steady-state infiltration rates in recurrent ponding infiltration experiments. J Hydrol 104:1–16. https://doi.org/10.1016/0022-1694(88)90154-0

Conte P, Marsala V, De Pasquale C, Bubici S, Valagussa M, Pozzi A, Alonzo G (2013) Nature of water-biochar interface interactions. GCB Bioenergy 5:116–121. https://doi.org/10.1111/gcbb.12009

Cornelissen G, Martinsen V, Shitumbanuma V, Alling V, Breedveld GD, Rutherford DW, Sparrevik M, Hale SE, Obia A, Mulder J (2013) Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. Agronomy 3:256–274. https://doi.org/10.3390/agronomy3020256

De Vos NJ, Rientjes THM, Gupta HV (2010) Diagnostic evaluation of conceptual rainfall-runoff models using temporal clustering. Hydrol Process 24:2840–2850. https://doi.org/10.1002/hyp.7698

Dingman SL (2014) Physical hydrology, 3rd edn. Waveland Press Inc., Long Grove

Dunnett N, Kingsbury N (2008) Planting green roofs and living walls. Timber Press, Portland

Durner W (1994) Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resour Res 30:211–223. https://doi.org/10.1029/93WR02676

Feddes RA, Bresler E, Neuman SP (1974) Field test of a modified numerical model for water uptake by root systems. Water Resour Res 10:1199–1206. https://doi.org/10.1029/WR010i006p01199

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 Geophys 69:2417–2426. https://doi.org/10.1007/s11600-021-00685-4

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 Convers Biorefin. https://doi.org/10.1007/s13399-022-02754-0

Grimmond CSB, Oke TR (1999) Evapotranspiration rates in urban areas. IAHS-AISH Publ. pp 235–243

Hardie M, Clothier B, Bound S, Oliver G, Close D (2014) Does biochar influence soil physical properties and soil water availability? Plant Soil 376:347–361. https://doi.org/10.1007/s11104-013-1980-x

Hardman M, Adams D, Larkham P (2024a) UK cities need greener new builds—and more of them

Hardman M, Hubbard L, Watson H (2024b) Upscaling green social prescribing and urban agriculture in cities: reflections on social and horticultural therapy in the United Kingdom. Prof Geogr 76:170–179. https://doi.org/10.1080/00330124.2023.2286591

Hlavinka P, Trnka M, Balek J, Semerádová D, Hayes M, Svoboda M, Eitzinger J, Možný M, Fischer M, Hunt E, Žalud Z (2011) Development and evaluation of the SoilClim model for water balance and soil climate estimates. Agric Water Manag 98:1249–1261. https://doi.org/10.1016/j.agwat.2011.03.011

Hu W, Shao M, Wang Q, Fan J, Horton R (2009) Temporal changes of soil hydraulic properties under different land uses. Geoderma 149:355–366. https://doi.org/10.1016/j.geoderma.2008.12.016

Hu W, Shao MA, Si BC (2012) Seasonal changes in surface bulk density and saturated hydraulic conductivity of natural landscapes. Eur J Soil Sci 63:820–830. https://doi.org/10.1111/j.1365-2389.2012.01479.x

Huang S, Garg A, Mei G, Huang D, Chandra RB, Sadasiv SG (2020) Experimental study on the hydrological performance of green roofs in the application of novel biochar. Hydrol Process 34:4512–4525. https://doi.org/10.1002/hyp.13881

Hyväluoma J, Kulju S, Hannula M, Wikberg H, Källi A, Rasa K (2018) Quantitative characterization of pore structure of several biochars with 3D imaging. Environ Sci Pollut Res 25:25648–25658. https://doi.org/10.1007/s11356-017-8823-x

Jačka L, Trakal L, Ouředníček P, Pohořelý M, Šípek V (2018) Biochar presence in soil significantly decreased saturated hydraulic conductivity due to swelling. Soil Tillage Res 184:181–185. https://doi.org/10.1016/j.still.2018.07.018

Jha P, Biswas AK, Lakaria BL, Subba Rao A (2010) Biochar in agriculture—prospects and related implications. Curr Sci 99:1218–1225

Keshta N, Elshorbagy A, Carey S (2012) Impacts of climate change on soil moisture and evapotranspiration in reconstructed watersheds in northern Alberta, Canada. Hydrol Process 26:1321–1331. https://doi.org/10.1002/hyp.8215

Kuoppamäki K (2021) Vegetated roofs for managing stormwater quantity in cold climate. Ecol Eng. https://doi.org/10.1016/j.ecoleng.2021.106388

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

Kutilek M, Nielsen DR (1994) Soil hydrology. Catena Verlag, Gzira

Laird D, Fleming P, Wang B, Horton R, Karlen D (2010) Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158:436–442. https://doi.org/10.1016/j.geoderma.2010.05.012

Latini A, Bacci G, Teodoro M, Gattia DM, Bevivino A, Trakal L (2019) The impact of soil-applied biochars from different vegetal feedstocks on durum wheat plant performance and rhizospheric bacterial microbiota in low metal-contaminated soil. Front Microbiol. https://doi.org/10.3389/fmicb.2019.02694

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems—a review. Mitig Adapt Strateg Glob Chang 11:403–427. https://doi.org/10.1007/s11027-005-9006-5

Li D, Bou-Zeid E, Oppenheimer M (2014) The effectiveness of cool and green roofs as urban heat island mitigation strategies. Environ Res Lett. https://doi.org/10.1088/1748-9326/9/5/055002

Liao W, Drake J, Thomas SC (2022) Biochar granulation enhances plant performance on a green roof substrate. Sci Total Environ 813:152638. https://doi.org/10.1016/j.scitotenv.2021.152638

Liu Z, Dugan B, Masiello CA, Gonnermann HM (2017) Biochar particle size, shape, and porosity act together to influence soil water properties. PLoS ONE 12:1–19. https://doi.org/10.1371/journal.pone.0179079

Liu J, Garg A, Wang H, Huang S, Mei G (2022) Moisture management in biochar-amended green roofs planted with *Ophiopogon japonicus* under different irrigation schemes: an integrated experimental and modeling approach. Acta Geophys 70:373–384. https://doi.org/10.1007/s11600-022-00725-7

Lösken G, Ansel W, Backhaus T (2018) FLL Green roof guidelines—guidelines for the planning, construction and maintenance of Green roofs

Lwasa S, Seto KC, Bai X, Blanco H, Gurney KR, Kilkiş S, Lucon O, Murakami J, Pan J, Sharifi A, Yamagata Y (2022) IPCC Chapter 8, Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. https://doi.org/10.1017/9781009157926.010

Meng R, Zhang Q, Li D, Wang H (2021) Influence of substrate layer thickness and biochar on the green roof capacity to intercept rainfall and reduce pollution in runoff. Polish J Environ Stud 30:4085–4103. https://doi.org/10.15244/pjoes/132810

Mentens J, Raes D, Hermy M (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landsc Urban Plan 77:217–226. https://doi.org/10.1016/j.landurbplan.2005.02.010

METER Group, I.U. (2015) Manual HYPROP, Version 2015
METER Group, I.U. (2021) Manual WP4C, Version 2021, Meter
Palansooriya KN, Wong JTF, Hashimoto Y, Huang L, Rinklebe J, Chang SX, Bolan N, Wang H, Ok YS (2019) Response of microbial communities to biochar-amended soils: a critical review. Biochar 1:3–22. https://doi.org/10.1007/s42773-019-00009-2
Palermo SA, Turco M, Principato F, Piro P (2019) Hydrological effectiveness of an extensive green roof in Mediterranean climate. Water. https://doi.org/10.3390/w11071378
Peters A, Durner W (2008) Simplified evaporation method for determining soil hydraulic properties. J Hydrol 356:147–162. https://doi.org/10.1016/j.jhydrol.2008.04.016
Petreje M, Sněhota M, Chorazy T, Novotný M, Rybová B, Hečková P (2023) Performance study of an innovative concept of hybrid constructed wetland-extensive green roof with growing media amended with recycled materials. J Environ Manag 331:117151. https://doi.org/10.1016/j.jenvman.2022.117151
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. Environ Monit Assess. https://doi.org/10.1007/s10661-019-7466-4
Qiu G-Y, Li H-Y, Zhang Q-T, Chen W, Liang X-J, Li X-Z (2013) Effects of evapotranspiration on mitigation of urban temperature by vegetation and urban agriculture. J Integr Agric 12:1307–1315. https://doi.org/10.1016/S2095-3119(13)60543-2
Rowe DB, Getter KL (2006) The role of extensive green roofs in sustainable development. HortScience 41:1276–1285
Seyedsadr S, Šípek V, Jačka L, Sněhota M, Beesley L, Pohořelý M, Kovář M, Trakal L (2022) Biochar considerably increases the easily available water and nutrient content in low-organic soils amended with compost and manure. Chemosphere. https://doi.org/10.1016/j.chemosphere.2022.133586
Shukla PR, Skea J, Slade R, Al Khourdajie A, van Diemen R, McCollum D, Pathak M, Some S, Vyas P, Fradera R, Belkacemi M, Hasija A, Lisboa G, Luz S, Malley J (2022) IPCC Full report, Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.Cambridge University Press, Cambridge, New York. https://doi.org/10.1017/9781009157926
Šimůnek J, Genuchten MT, Šejna M (2008) Development and applications of the HYDRUS and STANMOD software packages and related codes. Vadose Zo J 7:587–600. https://doi.org/10.2136/vzj2007.0077
Šípek V, Tesar M (2016) Validation of a mesoscale hydrological model in a small-scale forested catchment. Hydrol Res 47:27–41. https://doi.org/10.2166/nh.2015.220
Šípek V, Tesar M (2017) Year-round estimation of soil moisture content using temporally variable soil hydraulic parameters. Hydrol Process 31:1438–1452. https://doi.org/10.1002/hyp.11121
Slatyer RO (1956) Evapotranspiration in relation to soil moisture. Neth J Agric Sci 4:73–76. https://doi.org/10.18174/njas.v4i1.17777
Smith P (2016) Soil carbon sequestration and biochar as negative emission technologies. Glob Chang Biol 22:1315–1324. https://doi.org/10.1111/gcb.13178
Tan K, Wang J (2023) Substrate modified with biochar improves the hydrothermal properties of green roofs. Environ Res 216:114405. https://doi.org/10.1016/j.envres.2022.114405
UN (2024) SDG11: sustainable cities and communities
van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x
Vandegrift DA, Rowe DB, Cregg BM, Liang D (2019) Effect of substrate depth on plant community development on a Michigan green roof. Ecol Eng 138:264–273. https://doi.org/10.1016/j.ecoleng.2019.07.032
Washbourne C, Wansbury C (2023) ICE manual of infrastructure the manual in context.
Werdin J, Conn R, Fletcher TD, Rayner JP, Williams NSG, 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. Ecol Eng 171:106391. https://doi.org/10.1016/j.ecoleng.2021.106391
Xie Y, Wang L, Li H, Westholm LJ, Carvalho L, Thorin E, Yu Z, Yu X, Skreiberg Ø (2022) A critical review on production, modification and utilization of biochar. J Anal Appl Pyrol. https://doi.org/10.1016/j.jaap.2021.105405
Yang L, Qian F, Song DX, Zheng KJ (2016) Research on urban heat-island effect. Proced Eng 169:11–18. https://doi.org/10.1016/j.proeng.2016.10.002
Zou Z, Yang Y, Qiu GY (2019) Quantifying the evapotranspiration rate and its cooling effects of urban hedges based on three-temperature model and infrared remote sensing. Remote Sens 11:1–18. https://doi.org/10.3390/rs11020202