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Lunt, Paul

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RESEARCH ARTICLE

Comparing the thermal conductivity of three artificial soils under differing moisture and density conditions for use in green infrastructure

Paul H. Lunt[1] | **Kate Fuller**[2] | **Matthew Fox**[3] | **Steve Goodhew**[3] | **Thomas R. Murphy**[1]

[1]School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK

[2]Royal HaskoningDHV, London, UK

[3]School of Art, Design & Architecture, University of Plymouth, Plymouth, UK

Correspondence
Paul H. Lunt, School of Geography, Earth and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK.
Email: paul.lunt@plymouth.ac.uk

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Abstract

Soil-based green infrastructure has the potential to improve building thermal performance and contribute to sustainable buildings. This study compares thermal conductivity response to soil moisture of three peat-free artificial soils to evaluate their potential use within green roofs and living walls. Thermal conductivity was measured with changing soil moisture and density. All soils showed higher thermal conductivity measures with increases in soil moisture. The 'Biochar-coconut coir compost' had the lowest thermal conductivity measures which displayed negligible response to density changes and exhibited the highest water holding capacity. When uncompacted, 'FabSoil' had low thermal conductivity measures, but when compacted, its measures were considerably higher. Results show the role of density on thermal performance will be soil type dependent. Overall, findings highlight the importance of considering substrate composition, density and suggest that peat-free artificial soil substrates that contain biochar, have a higher percentage organic matter content and a finer particle texture are likely to result in lower thermal conductivity and higher soil water holding capacity. The results also showed that ThetaProbe measures (volumetric) had a high equivalence to actual soil moisture content (gravimetric), across different soil types and soil bulk densities. This finding supports the use of ThetaProbe measures as an effective method for monitoring soil moisture; with the potential for integration into irrigation control systems for green infrastructure. The findings of this paper offer the potential to improve building thermal performance by informing soil substrate choice, irrigation control and load bearing requirements in the design of green infrastructure.

KEYWORDS

artificial soils, biochar, building thermal performance, green infrastructure, soil moisture, soil organic matter

1 | INTRODUCTION

Soils have the capacity to provide significant utility in urban settings as part of green infrastructure. Soil-based growth media in contrast to hydroponic plant growth systems are commonly used within green infrastructure due to evidence of increased thermal insulation, flooding management, pollutant filtration, plant growth and carbon sequestration (Barriuso & Urbano, 2021; Charoenkit & Yiemwattana, 2016; Jones & Somper, 2014).

Green infrastructure developments, such as green roofs and living walls, are becoming increasingly popular due to the multiple environmental, social and economic benefits they can provide (Barriuso & Urbano, 2021; Charoenkit & Yiemwattana, 2016; Manso & Castro-Gomes, 2015). These developments are regarded as potential options in reducing some of the negative environmental and social impacts of high-density urbanization (Barriuso & Urbano, 2021; Manso et al., 2021; Vijayaraghavan, 2016). Green roofs and walls involve systems and structures designed to support the growth of vegetation on buildings (Libessart & Kenai, 2018; Shafique et al., 2018), commonly aided by irrigation, drainage, nutrient application systems and a rooting media (Manso et al., 2021; Manso & Castro-Gomes, 2015). These structures are associated with enhanced building thermal performance (Fox et al., 2021), air temperature modification (Mazzali et al., 2013), sequestration of CO_2 (Charoenkit & Yiemwattana, 2016; Marchi et al., 2015), stormwater management (Manso & Castro-Gomes, 2015; Mentens et al., 2006) and improved air quality (Abhijith et al., 2017; Pugh et al., 2012). They also support biodiversity in urban areas, where space is limited and could aid developers in achieving net biodiversity gain (Manso & Castro-Gomes, 2015).

Globally buildings and building construction account for 36% of global energy- and 39% of process-related CO_2 emissions (UN Environment and International Energy Agency, 2017). Of these emissions, the greatest contribution comes from space heating and cooling (60% of energy use in UK Buildings) (Palmer & Cooper, 2011). In seeking to meet global targets of reaching Net Zero carbon by 2050, it is essential that consideration is given to methods aimed at minimizing the demand for space heating and cooling new and existing buildings. One such method is to lower fabric thermal conductivity. Inert insulation materials are a common method for lowering conductivity, yet research on living wall and roof systems has begun to demonstrate the potential for such systems to provide thermal insulation benefits to lower the energy consumption of buildings (Charoenkit & Yiemwattana, 2016; Cuce, 2017; Fox et al., 2021; Libessart & Kenai, 2018; Manso & Castro-Gomes, 2016). However, few studies focus on how soil or substrate characteristics affect their thermal capabilities (Charoenkit & Yiemwattana, 2016).

Organic matter and moisture content may affect soil thermal properties; organic matter reducing soil thermal conductivity (Charoenkit & Yiemwattana, 2016; Sailor & Hagos, 2011; Zhu et al., 2019) and moisture increasing conductivity (Libessart & Kenai, 2018; Ochsner et al., 2001; Sailor & Hagos, 2011). Materials with large independent air pockets such cork or wood fibre boarding are often used within insulating practices to reduce convection (Bergman et al., 2011). Liquids on the other hand show higher rates of thermal conduction (Bergman et al., 2011) and will have reduced insulation capabilities. Analyses of soil fractions have shown sand particles tend to have higher conductivities than clay or silt, and silt particles tend to show lowest thermal conduction values (Balland & Arp, 2005; Ochsner et al., 2001). The thermal conductivity of a mineral is mainly determined by composition, with quartz having the highest conductivity of the skeleton-forming minerals (Ye et al., 2022). Improved specification of soil in this application, therefore, has significant potential to increase the insulation capabilities offered by green infrastructure (Libessart & Kenai, 2018). Moreover, improved understanding of the influence of soil substrate properties on the thermal performance and subsequent effects on plant growth will alter both the thermal and other multiple benefits offered by green infrastructure developments (Vera et al., 2015).

The thermal conductivity of soils is dependent on moisture content, soil particle size, organic matter content and the volume of air within the soil (Figure 1 and Ochsner et al., 2001). Fine texture soils generally have higher specific heat and volumetric heat capacity than coarse soils for the same moisture content and soil density (Abu-Hamdeh, 2003).

The role of soils is important in maximizing the thermal performance of green infrastructure, both directly

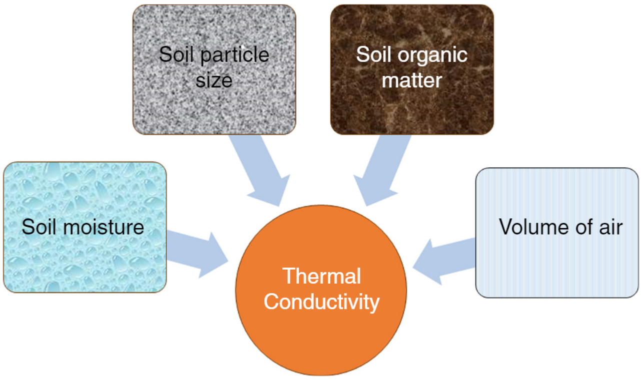

FIGURE 1 Schematic representation of the relationship between soil composition and thermal conductivity

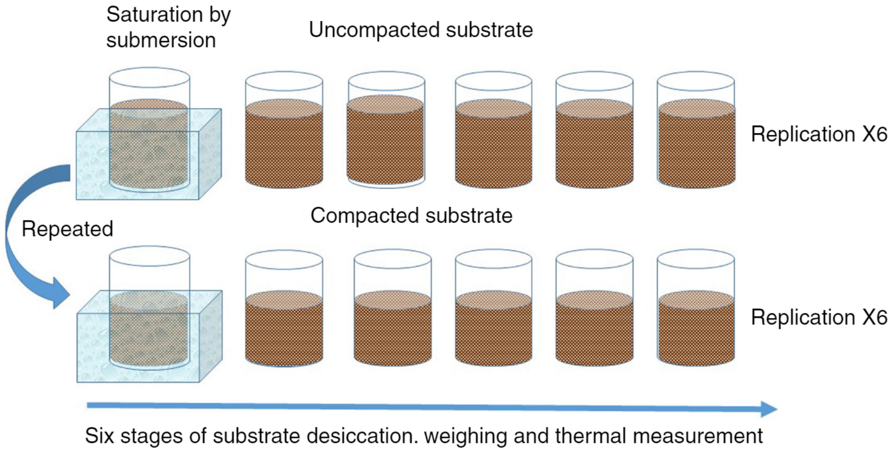

FIGURE 2 Experimental set-up showing six desiccation stages used to assess thermal conductivity and soil moisture relations

through soil thermal properties and indirectly via their impact on plant growth and performance.

The aim of this study was to compare the composition and thermal performances of different soils for use within green infrastructure and provide details on how these soils respond to changing soil moisture conditions. The information gained will be used to provide a better understanding of how green infrastructure suppliers can improve the composition of soil-based rooting material to maximize thermal insulation.

1.1 | Description of artificial soils

Three sustainably sourced, artificial soil-based substrates were compared in this investigation. They included FabSoil (Schofield et al., 2018; University of Plymouth. (n.d.), Green-waste compost (South West Composting Ltd) topsoil mix (Westland Topsoil) (50,50) and a Biochar-coconut coir multipurpose compost (Carbon Gold Ltd, Clevedon, BS21 9DN, www.carbongold.co.uk), containing a mix of 70% coconut coir, 20% biochar and a 10% mixture of seaweed, mycorrhizal fungi, worm casts and vegetable-based nutrients (Carbon Gold Ltd, 2021). FabSoil is fabricated from a mix of china clay mining waste which contains the breakdown products from granite, mainly quartz and feldspar combined with green waste, and bark material developed jointly by the University of Plymouth and the Eden project (Schofield et al., 2018; Agri-tech Cornwall, 2020). All three substrates were peat free and derived primarily from waste materials. The use of peat in horticulture represents a significant carbon emissions source with peat accounting for 56% of the volume of potting compost sold in the United Kingdom in 2015. In the United Kingdom from 2024 sales of peat-based compost to amateur gardeners will end and gardeners will have to transition to peat-free alternatives (Bek et al., 2020). Any alternative has to meet the following three criteria, (1) physical: high water and air capacity, homogenous and have a high structural stability (2) biological: free for pathogens, weeds and have beneficial microbes (3) chemical: easily adjusted pH and nutrient levels.

2 | METHODS

2.1 | Soil analysis

To give a breakdown of the particle size fractions found within each type of soil a Malvern Mastersizer 2000 was used (Shu et al., 2007). For each of the three soils, six replicate subsamples were analysed. To prepare the soils, the six subsamples were sieved using a 2 mm circular sieve. Five samples from each of the six subsamples were taken and 0.5–2 ml of the soil was placed into 12 ml vials. For each vial, 2–3 ml of 6% hydrogen peroxide was added, all the vials were then placed into a water bath and left for 4 h. The samples were then removed from the water bath, cooled down and another 2–3 ml of hydrogen peroxide was added to the vials. The process of placing the vials into the water bath before cooling them down and adding hydrogen peroxide again was repeated until all the large organic matter material had broken down. However, after adding 6% hydrogen peroxide twice, 12% hydrogen peroxide was then used to break the organic matter down. After these stages had been completed, the samples were then ready to be processed in the Malvern Mastersizer 2000.

Within the soil analysis, the loss on ignition of organic matter for each soil was measured. For this, the empty crucibles were firstly weighed. Soil samples were then sieved using a 2 mm circular sieve, then placed into the crucibles. For each of the three soils, eight crucible subsamples were made. These crucible samples were then weighed again to gain air-dry weight measurements. The crucibles were then placed into an oven for 24 h at 90–100°C. The samples were then removed from the oven and reweighed to gain oven-dry weight measurements. The samples were then placed in a furnace for 4 h at 550°C, before weighing

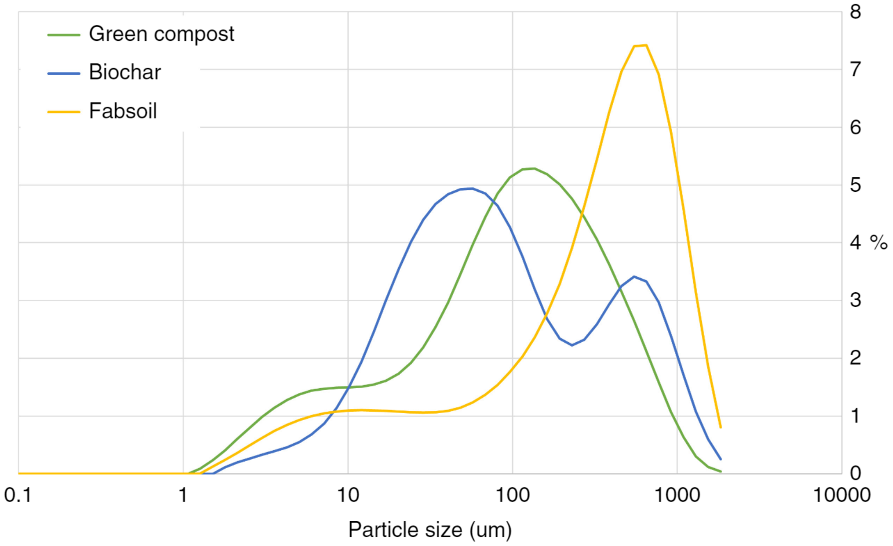

FIGURE 3 Percentage content (%) of particle sizes (μm) found in FabSoil, green-waste and biochar mixes

them again. Using the weight measurements, the loss on ignition of organic matter can be calculated.

$$\text{Loss on ignition calculation: } \frac{\text{``}\mathit{Initial\ loss}\text{''}}{\mathit{Initial\ weight}} \times 100$$

2.2 | Experimental set-up

Free draining plastic pipes (30 cm long, 12 cm diameter) were used to hold ~2.5 litre samples of soil for the manipulative experiment. For each of the three soils, six pipes were used (Figure 2). The weight of each empty pipe was measured before adding the soil. For the first stage, the soil was added into the pipe without compacting it, each pipe was then reweighed. Using the volume measures, the bulk density of the soil in each pipe was calculated.

$$\text{Bulk density calculation: } \frac{\mathit{Mass\ of\ dry\ soil}}{\mathit{Total\ volume\ of\ soil}}$$

At the beginning of the investigation, the 18 pipes, six containing each soil were placed into a tray of water for 24 h to enable the soil to become fully saturated (Figure 2). All excess water in the soils was allowed to drain away allowing the soils in the pipes to reach the point of field capacity. Weight, thermal conductivity, soil temperature and soil moisture measures were taken for each pipe; using a Decagon KD2 Pro with a single needle TR-1 sensor (10 cm long, 2.5 mm diameter) to measure thermal conductivity and temperature (Rubio, 2013) and a Delta-T ThetaProbe to measure volumetric soil moisture content (Matula et al., 2016). Pipes containing the different soil mixes were dried down simultaneously in 'desiccation stages' in a glasshouse over 7 days during mid-summer 2021. At each 24 h interval the weight, thermal conductivity and ThetaProbe measures were recorded for all pipes (Figure 2). Actual gravimetric water contents were calculated at each stage of drying using the weights of samples and oven-dried weights.

Once the first round of soil drying and measurements were complete, substrate levels in the pipes were compressed to a standard height to compact the material, and the bulk densities were recalculated. Soils were rewetted to saturation and thermal conductivity, ThetaProbe measures and air-drying procedures were repeated for the compacted soil samples (Figure 2).

2.3 | Data analysis

To carry out the statistical analysis R software version 3.6.2 was used (R Core Team, 2019). The thermal conductivity ($Wm^{-1}{}^{\circ}C^{-1}$) and soil moisture content (volumetric and gravimetric) measures were tested for normality using Normal Q-Q diagnostic plots, this showed the distributions to be normal. Several linear regression analyses were performed to test for the significance and interactions between thermal conductivity, soil type, moisture content (%) and compaction level. Linear regressions were also used to test the relationships and interactions between volumetric moisture content (% vol) measures, soil type, gravimetric moisture content (%) across two compaction states.

3 | RESULTS

Figure 3 shows that there were considerable differences in the particle size compositions of the three soils tested. FabSoil contained the highest proportions of larger particle sizes when compared with the other two soils, with the majority of particles in the 'fine' sand (125 µm) to 'coarse' (1000 µm) sand categories (Figure 3). The Green-waste compost samples also contained sand, but the majority of particles consisted of 'very fine' and 'fine sand' (62–250 µm). Out of the three soils, Figure 3 shows, that the Biochar-coconut coir compost had the highest percentages of smaller particles, with the highest percentages being in the 'very fine sand' and 'silt' category (4–125 µm).

The FabSoil and Green-waste composts have similar % organic matter content and dry and wet weight bulk densities (Table 1). While the Biochar mix contains significantly higher % organic matter content (~5x higher). The FabSoil and Green-waste composts are 6x heavier when dry and almost twice as heavy when wet, when compared to the equivalent dry and wet Biochar-coconut coir mix (Table 1).

The dry Biochar-coconut coir mix had a significantly lower bulk density than the other composts irrespective of level of compaction (Table 2). When saturated, the Biochar-coir showed significantly higher water content (~8x dry weight) but still with lower bulk densities than the other two composts.

There was minimal deviation in temperature during different thermal conductivity measurements between treatments in both uncompacted soils (FabSoil = 21.3 [+/− 0.3] Green-waste compost = 21.0 [+/− 0.2], Biochar-coconut coir = 21.1 [+/− 0.1]) and compacted soils (FabSoil = 22.2 [+/− 0.3] Green-waste compost = 21.5 [+/− 0.4], Biochar-coconut coir = 21.5 [+/− 0.2]).

There was a significant interaction between the predictor variables of gravimetric moisture content (%), soil type and compaction level with the thermal conductivity response ($Wm^{-1}°C^{-1}$) ($F_{7,244} = 50.2$, $p = .003$). Significant interactions were also seen between moisture content (%) and soil type ($p = .041$), and between moisture content (%) and compaction ($p = .001$).

Linear regression analysis showed highly significant ($p \leq 0.001$) relationships between thermal conductivity ($Wm^{-1}°C^{-1}$) and gravimetric soil moisture in both uncompacted and compacted composts. Figure 4 shows that the Biochar mix had the lowest thermal conductivity values (<0.5 $Wm^{-1}°C^{-1}$) of the soils at all gravimetric moisture contents; this difference was most noticeable at higher moisture contents. The FabSoil had the second lowest average thermal conductivity followed by the Green-waste compost. Thermal conductivities were higher following compaction in the non-biochar-containing soils (Figure 4). In the Biochar mix, compaction had no negligible effect on thermal conductivity. Compaction produced a slight increase in thermal conductivity across all moisture contents in the Green-waste mix and a marked increase in thermal conductivity in the FabSoil (Figure 4), at higher moisture contents.

Figure 5 shows that there was a significant difference in the initial saturated moisture contents ($F_{2,} = 114$, $p = .001$) and water loss ($F_{36,} = 251$, $p < .001$) of the three soils. The Biochar mix was highly absorbent and held twice its dry weight mass compared to the other soils which had similar saturated moisture contents at around 50% of their dry weight mass. Drying profiles were similar in the Green-waste and FabSoil, with both soils dropping to 7%–8% moisture content after 7 days continuous drying in the highly desiccating conditions of the glasshouse environment. In contrast, the Biochar-coir was able to retain 50% soil moisture content following the same 7 days. Soil compaction had no effect on loss of moisture in the FabSoil. However, the uncompacted Green-waste compost and Biochar mix had slightly higher saturated moisture contents at all stages of drying and in the case of the Biochar was more able to retain moisture during latter drying stages.

Regression analysis showed highly significant ($p \leq 0.001$) and strong linear relationship (r values >0.93) between volumetric ThetaProbe soil moisture measures (%vol) and gravimetric soil moisture (%) content, irrespective of level of compaction in all three composts (Figure 6). However, gravimetric moisture content reached 180% in the Biochar-coconut coir compared with equivalent volumetric (ThetaProbe) measures of 70%; showing that the accuracy of volumetric measures declined when the moisture content of Biochar-coconut coir mix exceeded ~60% (Figure 6).

4 | DISCUSSION

The energy intensity (buildings and construction) of the global buildings sector (kWh/m^2) needs to improve on average by 30% by 2030 (compared to 2015) to be on track to meet Net Zero global climate ambitions set forth

TABLE 1 Average organic matter (%) and wet and dry bulk densities (t/m^3) for each of the three soils

Soil type	Organic matter (%)	Dry bulk density (t/m^3)	Wet bulk density(t/m^3)
FabSoil	10.32	0.595	1.012
Green-waste compost topsoil mix	15.69	0.577	1.064
Biochar-coconut coir compost	75.64	0.084	0.667

TABLE 2 Dry and saturated weight wet weight bulk densities (g/cm^{-3}) in compacted and uncompacted composts. *Values +/− the means show standard deviation*

Compost/soil type	Compacted state	Dry weight bulk densities (g/cm^{-3})	Saturated weight wet bulk densities (g/cm^{-3})
FabSoil mix	Uncompacted	0.64+/−0.03	1.05+/−0.04
	Compacted	0.83+/−0.045	1.42+/−0.066
Green-waste compost mix	Uncompacted	0.62+/−0.016	1.15+/−0.039
	Compacted	0.81+/−0.041	1.5+/−0.067
Biochar-coconut coir compost	Uncompacted	0.1+/−0.004	0.8+/−0.042
	Compacted	0.13+/−0.007	1+/−0.063

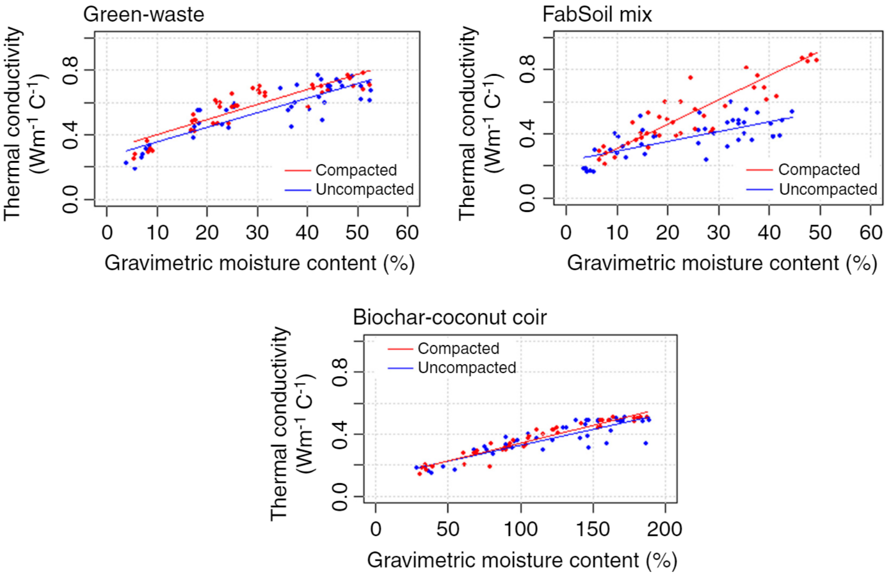

FIGURE 4 Thermal conductivity response (KD2 measures ($\mathrm{Wm}^{-1}{}^{\circ}\mathrm{C}^{-1}$)) to moisture content (%) when uncompacted and compacted for the FabSoil, green-waste and biochar-coconut coir composts

in COP26 (UN Environment and International Energy Agency, 2017). Soil thermal properties have important applications in the built environment, agriculture and local climate regulation. Our results provide improved information on the utility of three artificial soils for the optimization of thermal performance and soil moisture within green infrastructure and suggest the use of Biochar-coconut coir as a high-performing peat-free option. Research by Fox et al. (2021) showed a 31.4% improvement in thermal transmittance by retrofitting an existing masonry cavity with an external living-wall façade using standard multi-purpose potting compost. The findings from the present paper suggest that further thermal improvements could be gained by replacing the growing medium with an artificial low conductive soil such as a Biochar-coconut coir mix.

4.1 | Thermal conductivity

All three artificial soils showing a tripling of thermal conductivity ($\mathrm{Wm}^{-1}{}^{\circ}\mathrm{C}^{-1}$) with moisture content. The largest change occurred in the compacted FabSoil treatment, which increased from 0.2 ->0.8 $\mathrm{Wm}^{-1}{}^{\circ}\mathrm{C}^{-1}$. This finding has been reported by other authors (Libessart & Kenai, 2018), with Sailor and Hagos (2011) showing a tripling in thermal conductivities when soils went from dry to a saturated state, suggesting it is crucial to have moisture control for rooting materials within green infrastructure to optimize insulation.

The results show the Biochar-coconut coir mix had the lowest thermal conductivity out of the three soils tested, irrespective of moisture content and bulk density and the greatest potential to improve the thermal insulation properties of a building when used as the growth substrate on a green roof or in a living wall. This finding is in keeping with previous research, which indicates lower thermal conductivity with increased organic matter content (Charoenkit & Yiemwattana, 2016; Sailor & Hagos, 2011; Zhu et al., 2019). The thermal performance of the Biochar-coconut coir mix is further enhanced by its microporous structure, which retains the insulating effect of trapped air (Atinafu et al., 2021). This insulating effect shows no reduction under compaction suggesting that the trapped air consists of gas bubbles contained within the rigid microporous structure of the biochar (Atinafu et al., 2021).

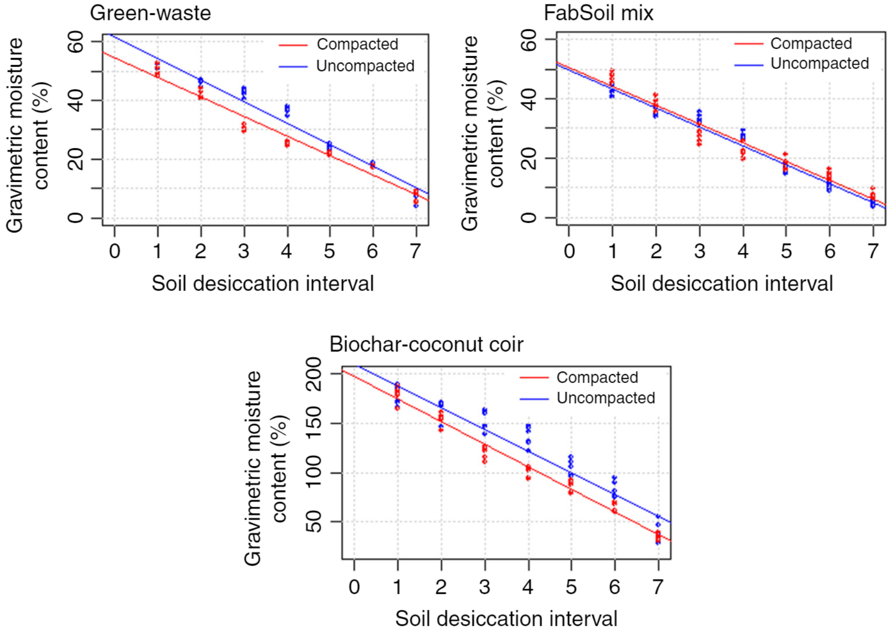

FIGURE 5 Comparison of gravimetric moisture content (%) and rate of desiccation (water loss) in uncompacted and compacted green-waste, FabSoil and biochar composts

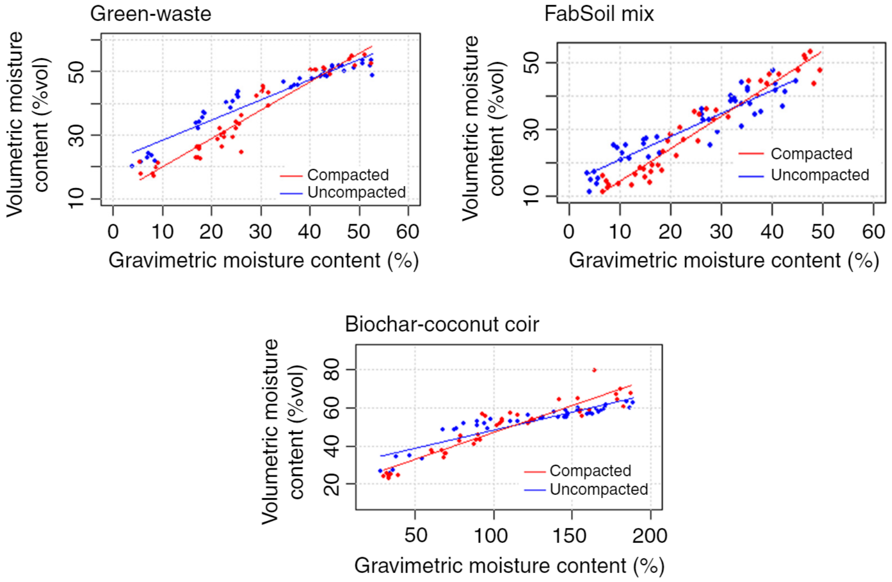

FIGURE 6 Relationship between volumetric soil moisture content (%), recorded using a theta probe and gravimetric soil moisture content (%vol) in compacted and uncompacted soils. *Green-waste compost ($F_{3,80}$ = 299.8, p-value = 8.18E-07). FabSoil mix ($F_{3,80}$ = 273, p-value = 8.77E-06) and biochar mix ($F_{3,80}$ = 108.6, p-value = 7.32E-05)*

The Biochar and Green-waste mixes also contain a higher fraction of silt-size particles (Figure 2), which have been associated with lower thermal conductivity (Abu-Hamdeh, 2003; Balland & Arp, 2005; Usowicz et al., 2016).

The coarser bark and quartz mix of the FabSoil showed relatively low thermal conductivities when uncompacted with marked increases at higher % moisture contents when compacted. This mix has a much courser structure, compared to the other mixes, with a higher percentage of macro air spaces in the uncompacted treatment, which would have reduced thermal conductivity (Zhu et al., 2019). The significant increase in thermal conductivity following compaction in the FabSoil mix most likely occurred from the squeezing out of air spaces between the coarser materials. The Green-waste mix showed significantly higher ($F_{2,249}$ = 33.09, $p < .001$) thermal conductivities with an average across all moisture contents and treatments of 0.56 +/−0.02SE Wm^{-1}°C^{-1}, compared to an average of 0.46 +/−0.02SE Wm^{-1}°C^{-1} and 0.37 +/−0.12SE Wm^{-1}°C^{-1} for the FabSoil and Biochar mixes respectively. Moisture in the Green-waste is absorbed by the higher organic matter, reducing overall thermal conductivity with relatively little effect of compaction. Other researchers (Abu-Hamdeh & Reeder, 2000; Sailor & Hagos, 2011) have observed similar increases in thermal conductivity with compaction in green roofs and naturally occurring soils.

4.2 | Soil water holding capacity

The water holding capacity of an artificial soil is determined by its composition. The FabSoil mix, containing coarser particles and a higher % of sands, had the steepest drying profile and reached the lowest gravimetric moisture content (Figure 5). The Green-waste compost mix with an intermediate particle range size, had an intermediate drying profile. Biochar-coir had a gravimetric moisture at field capacity of 180% and following 7 days in the drying environment of an unshaded summer glasshouse was able to maintain a 50% gravimetric moisture content. Biochar-coir mix had a 76% organic matter content, 5–6 x higher that the other two artificial soils confirming the beneficial effects of organic matter on soil water holding capacity (Charoenkit & Yiemwattana, 2016; Nektarios et al., 2011; Ondoño et al., 2016; Usowicz et al., 2016). The high water holding capacities and strong resistance to drying would suggest that the Biochar-coir mix would help minimize the risk of plant mortality in the highly desiccating environment of a living wall or green roof. An optimal volumetric soil moisture content for terrestrial plants would be in the range of 20%–60%. A high soil water holding capacity can help prevent plants from reaching the permanent wilting point, which occurs during the growing season when plants can become water stressed, particularly in the highly desiccating conditions associated with built environments (Barriuso & Urbano, 2021).

The soil moisture thermal conductivity relationships in this study can be used in green infrastructure planning for building insulation. From Table 1, we can calculate that a 10 cm depth of the fully saturated FabSoil or Green-waste compost mix would add ~10 tonnes to the weight-bearing requirements of a 100 m^2 (10 x 10 m) roof area or equivalent 4-storey living wall; almost half this weight for the equivalent area of the Biochar-coconut coir mix. While a 10 cm soil layer is a sufficient depth to enable reduced heat transfer (Jim & Tsang, 2011), greater depth will increase thermal insulation at the cost of adding considerably more weight.

4.3 | Application of ThetaProbe measures

The presence of highly significant linear relationships between volumetric (ThetaProbe) soil moisture and gravimetric soil moisture content (Figure 6), suggests that ThetaProbe measures have a high equivalence to actual soil moisture across different soil types and soil bulk densities. Findings from the study suggest that in situ continuous monitoring of volumetric water content using a ThetaProbe would be possible and could provide an accurate measure of moisture content. This novel finding suggests that outputs from the ThetaProbe may offer a more accurate control of an automated irrational system than conventional flow-based monitoring systems; minimizing the potential for over and under watering. Thereby helping to reduce the high management costs of green infrastructure by improving plant health and reducing the frequency of maintenance visits, as well as optimizing moisture-related insulation benefits. A spatial array of ThetaProbes could be incorporated within the green infrastructure to assess and control soil moisture at planting pocket scale. If deployed evenly but widely spaced, soil conductivity measures could be used to help identify and target maintenance and remediation requirements. Despite the high equivalence of the ThetaProbe with actual soil moisture, this relationship became weaker at the highest % soil moisture values, a discrepancy which should be considered in any future deployment.

4.4 | Multi-purpose sustainable soils

The use of soils in green infrastructure, compared to hydroponic systems, provides environmental gains such as enhanced biodiversity from soil inhabiting microbial and invertebrate communities, soil carbon sequestration, reduced water use, evaporative cooling from the soil surface, stormwater storage, nutrient recycling and the filtering effects of soils in improving water quality (Prodanovic et al., 2017; Vera et al., 2015). Previous studies have found that Biochar and coconut coir have good application in greywater treatment in living walls (Lakho et al., 2021). Further to this, when optimizing soils within green infrastructure it is important that the full suite of soil-associated benefits is considered and that wider sustainability benefits are identified. A lifecycle systems approach should be utilized to assess the sustainability of artificial soils in green infrastructure.

All three tested soils are peat free, which is vital to lower embedded carbon of the soil substrate and prevent the destruction of peat bogs (Bek et al., 2020). A key material within Biochar-coir mix is the coconut coir, intended to replace the peat component in soils with a sustainable and renewable resource (Carbon Gold, 2021).

Future work should help refine the % of biochar and coconut coir needed to optimize the thermal performance of this promising artificial soil mix. Further work is also required to refine plant choice in relation to thermal conductivity and in the optimization of the water holding capacity of soil substrates and their interactions with plant performance.

5 | CONCLUSION

Building on our investigation of the thermal performance of living walls (Fox et al., 2021) this study demonstrates the linkage between the thermal properties of artificial soils and their application in green infrastructure to achieve ultra-low carbon buildings. Results show that thermal performance was soil type, density and moisture content dependent Artificial soils that contain higher percentage organic matter and a finer texture had lower thermal conductivity. Out of the three soil types tested for use in green infrastructure, the Biochar-coconut coir compost would be the best option for a growth substrate to maximize thermal performance. This soil showed lower thermal conductivity measures; little effect of density changes; a high-water holding capacity and has potential for alternative uses such as greywater treatment. The highly density-dependent response seen with the FabSoil shows that air pockets within soil substrates significantly influence their thermal conduction potential. For all soil mixes tested, increased moisture significantly correlated with increased thermal conductivity. This relationship emphasizes the importance of moisture control in green infrastructure, where the aim is to ensure effective thermal insulation. The findings from this study are significant for building thermal performance, as the application of an artificial soil with lower thermal conductivity properties than traditional soil mediums could in part contribute to lowering heat losses from new and existing buildings.

Future work will explore the thermal conductivity of other artificial soils and the optimal proportion of biochar and coconut coir needed to maximize the benefit of living walls for a building's thermal insulation. Future studies will also investigate plant choice and the best artificial soil mix for plant health, survival and interactions with thermal conductivity.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request." cd_value_code="text

ORCID

Paul H. Lunt https://orcid.org/0000-0002-1736-317X

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