Optimizing Green Roof Substrates with Biochar and Frass for Improved Plant Performance

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Abstract. The urban heat island (UHI) effect, driven by rapid urbanization, can be mitigated through green roof systems, which offer thermal benefits such as reduced surface temperature and increased thermal insulation. However, their effectiveness is limited by nutrient-poor substrates, low water holding capacity and weed intrusion. This study evaluated the potential of palm kernel shell (PKS) biochar and black soldier fly larvae (BSFL) frass as sustainable additives to improve substrate quality and plant performance. Three combinations of biochar and frass (20%, 25%, and 30%) were incorporated into a soilless green roof medium and compared with a commercial substrate and a standard control. *Arachis pintoi* (pinto peanut) was selected as the model plant species. Growth performance was assessed via shoot number, chlorophyll content, percentage coverage, survival rate, and substrate characteristics (pH, moisture, and temperature). Substrates with 30% biochar and 20% frass, and 25% biochar and 25% frass, significantly improved plant growth and coverage compared to commercial substrate. Nutrient analysis showed the former enhanced micronutrient availability, while the latter increased macronutrient content. Although commercial substrate exhibited superior overall nutrient levels, the identified combinations present viable, low costs alternatifs for enhancing green roof vegetation. Future studies should extend the experimental duration to confirm long-term effectiveness under variable environmental conditions.

1 Introduction

In the past five decades, urbanization in developing nations like Malaysia has significantly increased owing to rapid population growth, industrialization, and rural-urban migration. The rapid urbanization of countries could alter natural equilibrium and relationships between food, water, energy, and the environment [1]. Expanding urban areas are arising various environmental impacts, such as increased exposure to abiotic stressors such as noise and air pollution, depletion of biodiversity and habitat fragmentation [2] as well as loss of green spaces. In Malaysia, major cities like Kuala Lumpur recorded noteworthy losses of green space from 24,222 hectares to 14,386 hectares in 2012 due to the rapid urbanization [3].

Urban agriculture and green roof systems have become pivotal in addressing critical challenges such as food security, urban heat island effects, and the environmental degradation

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associated with rapid urbanization. These systems offer a sustainable approach to urban development by integrating vegetation into building infrastructure, thereby enhancing biodiversity, improving air quality, and providing localized food production [4]. However, the development and efficiency of vegetation on green roofs are often constrained by inadequate nutrient supply and poor water availability owing to soilless and lightweight features of green roofs. Green roof substrates should be able to provide crucial resources, including nutrients, water, and support for the vegetation on the rooftop. An ideal green roof substrate should comprise 50-100% of lightweight mixtures to minimize the burden on the framework, 0-30% of fine-textured sandy granules for supporting and anchoring vegetation, 0-40% organic substances, and no clay or silt substances [5]. Mineral-based matters, such as shale, expanded shale, or other volcanic substances suggested to be used as a major component of green roof substrate, as heat-expanded slate is lightweight, durable, and has good drainage attributes.

Engineered soil, with a commonly known name as soilless media, is an alternative growth substrate for green roofs. The soilless media includes materials such as peat moss, rice husk, coco peat, coir, vermiculite, and perlite without the presence of traditional soil, resulting in nature of lightweight, cost-effective, and stable chemical characteristics [6]. The soilless and lightweight features typically resulted in a lack of suitable water/nutrient-retention materials to retain the excess water and nutrients. As a result, the growth and efficiency of plants on the green roof diminished as time passed. Thus, these challenges have prompted the exploration of alternative approaches that could enhance the nutrient availability and capacity of green roof substrates to retain water and nutrients, while retaining green roofs' lightweight and soilless features.

Recent studies have shown that biochar offers a range of environmental and efficient benefits when used as a substrate amendment in green roofs and soilless systems. Its high surface area and porous structure make biochar especially effective at retaining nutrients and enhancing water dynamics. For instance, biochar-amended green roof substrates significantly reduced nutrient leaching, particularly phosphorus, organic carbon, and nitrogen, into runoff water [7]. Combining 10 to 30% biochar by volume into green roof substrates can significantly improve water retention, nutrient availability, and plant growth while combining biochar with organic matter can reduce nutrient leaching and enhance nutrient use efficiency, thereby supporting sustainable crop production [8]. Apart from that, adding biochar to the green roof substrates has proven to reduce the nutrient leaching and enhance runoff water quality by increasing the pH of the rainfall especially in the event of acid rain [9]. Several studies also confirmed that adding biochar to either soil or soilless substrates significantly improves physicochemical properties, microbial activity, lowers bulk density and improves hydrological performance of the substrates.

Another potential amendment for green roof substrate is Black soldier fly larvae (BSFL) frass due to its nutrient content availability. Addition of BSFL frass is gaining attention as an organic fertilizer as BSFL frass has the potential to recapture nitrogen and phosphorus from the current food chain, enabling their utilization as fertilizers, thereby diminishing the reliance on synthetic fertilizers [10]. Several studies also indicate that BSFL frass could serve as a viable alternative to traditional and conventional nitrogen fertilizers due to its richness in micronutrients such as minerals and organic matter contents that could enhance vegetation growth by increasing nutrient availability to the vegetation. Although the addition of biochar and BSFL frass in planting substrate has been studied extensively separately, the combination of both bichar and BSFL frass and its specific application in green roof substrates is not yet well-studied. This study aims to evaluate the effectiveness of Palm Kernel Shell biochar (PKS biochar) and BSFL frass as additives for promoting plant growth, as well as to determine nutrient properties of green roof substrate with PKS biochar and BSFL frass.

2 Research method

The experiment was carried out at the Universiti Malaysia Terengganu (UMT) outdoor experimental plot, Bukit Kor, Marang (**Latitude:** 5.211439 | **Longitude:** 103.166862) from September to December 2023. Two layers of black netting were installed within 30cm × 30cm wooden frames to function as the drainage layer. The netting was securely fitted to ensure uniform coverage and prevent loss of substrate during watering or drain to ground. The experimental units were arranged following a Completely Randomized Design (CRD) to minimize positional and environmental bias. A total of 25 wooden frames were prepared using recycle wood pallete act as planting container as shown in figure 1.

Fig. 1 The planting container designed for this study. (a) Two layers of black netting were installed as a drainage layer at the bottom, and (b) A complete sample design consisting of a 30cm x 30cm wooden frame, drainage layers, and 3 liters of substrates.

The planting media formulations were prepared in advance, consisting a mixture of peat moss, perlite, vermiculite, PKS biochar and BSFL frass. Three liters of each combination substrates were carefully filled into the frames to achieve uniform depth and bulk density across treatments, ensuring consistency in initial growth conditions. The treatments used are layout in table 1.

Table 1 Details of substrate composition for each treatment involved in this study.

Treatment	Substrates ratio
Control (T1)	Commercial green roof
Treatment 2 (T2)	100% Soilless media - 2:1:1 (Peat : perlite : vermiculite)
Treatment 3 (T3)	50% soilless media : 25% PKS biochar : 25% frass
Treatmentt 4 (T4)	50% soilless media : 30% PKS biochar : 20% frass
Treatment 5 (T5)	50% soilless media : 20% PKS biochar : 30% frass

Pinto peanut cuttings with 10cm length were taken from Universiti Malaysia Terengganu (UMT) outdoor experimental plot, Bukit Kor and were used as plant samples in this study. Three cuttings were planted in each wooden frames at a 10cm distance as illustrated in figure 2, with five replications for each treatment.

Cuttings were left for two weeks of establishment period before evaluation parameters were conducted. Percentage coverage, number of new shoots, survival rate of cuttings, pH, substrate temperature (4-in-1 soil survey instrument) and mineral contents of the substrates were evaluated for 40 days with 5 days interval. There is no specific irrigation done as the plant samples were left in the outdoor environment to mimic the natural condition of the green roof and depending on the rainfall.

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Fig. 2 Illustration of the placement of pinto peanut cuttings in the wooden frame. (Created in https://BioRender.com)

Mineral contents in each treatment were also determined using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES), except for N value that were ascertained by using the Kjeldahl method. All of the collected data were analyse with One Way Anova with Tukey for pairwise comparison using SPSS (Statistical Package for the Social Sciences) software, version 26.0, on Windows.

3 Results and discussion

From day 5 to day 40, all treatments did not exhibit any significant differences in the coverage of *Arachis pintoi except* for Treatment 3. Treatment 3 showed a significant increment in coverage starting from day 15 to day 40 (Fig. 3). The inclusion of 25% biochar can impede the leaching of nitrogen and other nutrients in rice fields by forming an effective layer and dense barrier with its porous and hydrophobic structure. The slowed leaching of nitrogen enhances rhizosphere nitrogen bioavailability, impacting nitrogen utilization efficiency and leading to alterations in the morphology of the root (increased root length, reduced root diameter, and root tissue mass density), thereby facilitating the uptake of nitrogen and implying robust root proliferation [11]. Incorporation of frass could enhance activity of soil microbial and functional diversity [12]. Such increased microbial activity can aid in nutrient cycling, making nutrients more available to plants where coupled actions from both biochar and frass contribute to the increased percentage coverage in *the Arachis* plant.

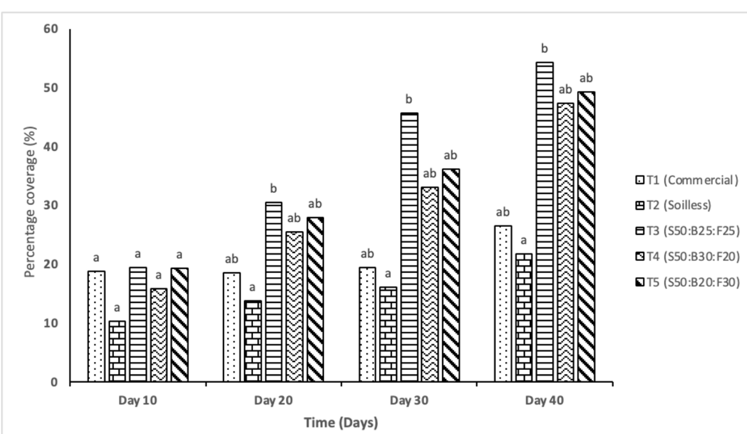

Fig. 3 Mean percentage coverage of *Arachis pintoi* over time (days). Error bars represent standard errors (n = 5). Different letters mean statistically significant differences at $p < 0.05$.

Significance of the shoot number was only notable after day 35 for treatment 4 and 5 as compared to other three treatments (Figure 4). This suggests that the soilless medium of all treatments from day 5 to day 30 already has sufficient nutrients, and the addition of biochar or frass may not lead to a noticeable improvement in shoot growth in *Arachis pintoi* as the positive outcome of frass in promoting shoot growth could only be noticed when the medium is relatively low in basal nutrients. This might be due both biochar and frass exhibit slow-release properties when integrated into a soilless medium. Biochar's release is slow owing to biochar's porous structure and large surface area, while frass's nutrients become available gradually as it breaks down through microbial action [12] Over time, biochar enhances water and nutrient retention, and the steady nutrient release from frass supports ongoing *Arachis* plant growth which contribute to the improved development of the plant's above-ground parts, such as shoots, over a longer duration.

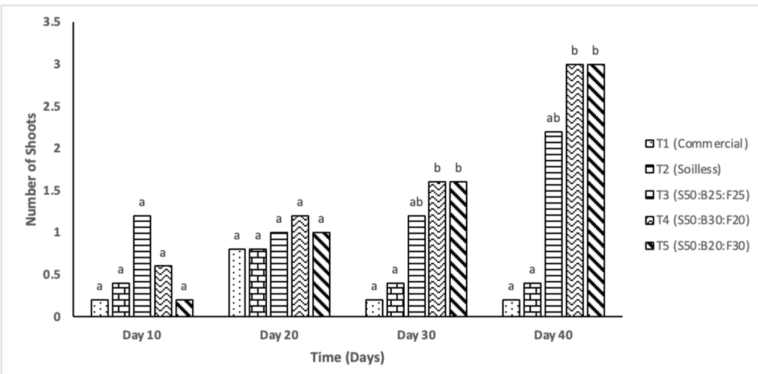

Fig. 4 Mean shoot number of *Arachis pintoi* in Treatment 1, Treatment 2, n = 5).
Different letters mean statistically significant differences at $p < 0.05$.

Figure 5 demonstrates a mean total chlorophyll content in *Arachis pintoi* over treatment. Treatment 3, 4 and 5 recorded higher total chlorophyll content but not significantly comparable between them. This may be attributed from variables like the biochar type and application rate, plant species, and growth conditions. Specifically, a 30% biochar concentration demonstrated an impact on plant leaves, indicating that increasing biochar levels in the medium is not always advantageous for leaf photosynthesis. While excessive biochar might hinder plant nitrogen uptake, reducing photosynthesis due to nitrogen immobilization, a phenomenon related to the high carbon-to-nitrogen ratio [12]. Biochar significantly elevates total chlorophyll content in C3 plants, which include *Arachis pintoi*, enhancing the stomatal conductance and rates of photosynthesis and transpiration. This increase in photosynthesis can lead to an increase in chlorophyll content, as chlorophyll is the pigment responsible for photosynthesis. frass raises chlorophyll levels by promoting plant growth and photosynthetic efficiency, which is attributed to its rich organic carbon and nitrogen content. The combination of biochar and frass may lead to synergistic effects that improve nutrient availability and microbial activity [11] all of which can contribute to increased chlorophyll content in *Arachis* plants.

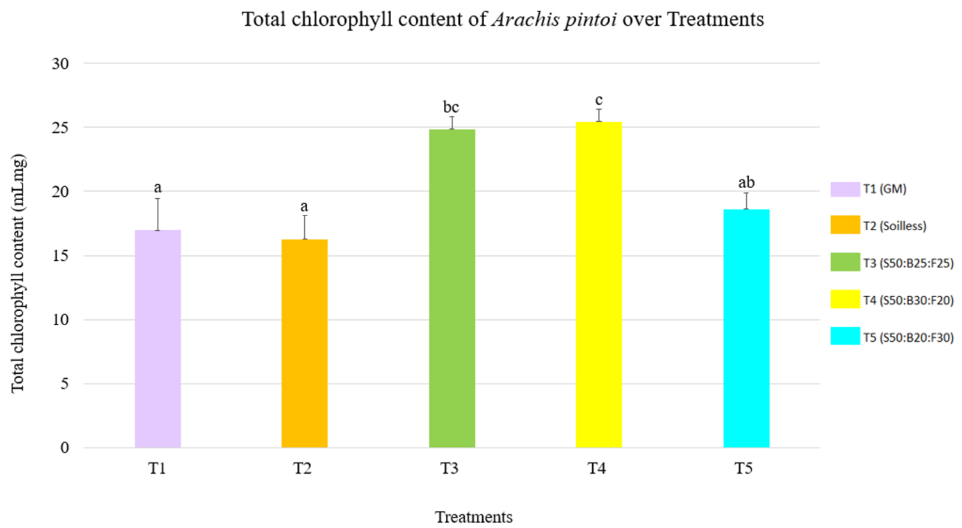

Fig. 5 Graph of mean total chlorophyll content of *Arachis pintoi* over treatments. Error bars represent standard errors (n = 5). Different letters mean statistically significant differences at $p < 0.05$.

Table 2 highlights that the growth response of *Arachis pintoi* is closely tied to nutrient balance and heavy metal availability, with clear implications for soil management and substrate design in sustainable systems such as green roofs. Excessive concentrations of Mn, Pb, Fe, and Al (Treatment 1) significantly impaired plant performance through oxidative stress, restricted root development, and reduced photosynthetic capacity [13].

Table2. Mineral content present in each treatment was determined by ICP-OES and the Kjeldahl method

Mineral content	**T1 (Mg/kg)**	**T2 (Mg/kg)**	**T3 (Mg/kg)**	**T4 (Mg/kg)**	**T5 (Mg/kg)**
Nitrogen (N)	20,217.20	20,609.60	56,879.78	63,957.70	54,672.64
Phosphorus (P)	1,311.80	165.93	1,874.50	1,014.30	1,676.50
Potassium (K)	3,669.10	1,968.00	1,771.00	1,556.60	1,546.70
Magnesium (Mg)	0.00	3,807.30	2,684.20	2,652.00	2,669.80
Zinc (Zn)	28.88	4.80	9.72	11.42	10.38
Manganese (Mn)	438.98	25.22	49.89	46.47	43.39
Iron (Fe)	1,3505.00	2,301.60	3,045.90	5,778.00	1,491.50
Cadmium (Cd)	1.79	0.29	0.32	0.59	0.17
Lead (Pb)	140.72	14.48	21.79	40.76	12.88
Aluminium (Al)	28,005.00	3,615.80	1,808.70	2,182.40	1,549.00
Chromium (Cr)	102.64	42.77	29.38	29.76	26.28
Nickel (Ni)	33.55	13.92	7.31	7.91	7.36
Arsenic (As)	0.04	0.01	0.19	0.24	0.00
Cobalt (Co)	85.95	14.80	1.41	31.13	9.27
Boron (B)	20.84	2.83	4.79	3.10	6.02
Copper (Cu)	89.78	6.92	11.46	4.80	7.64

Similarly, phosphorus deficiency and excessive magnesium (Treatment 2) constrained shoot and root growth, emphasizing the importance of maintaining adequate but not excessive nutrient supply [14]. In contrast, high phosphorus (Treatment 3) and elevated nitrogen (Treatment 4) markedly enhanced biomass production, root development, chlorophyll accumulation, and photosynthetic efficiency, demonstrating their role as critical drivers of productivity in *Arachis pintoi* [14, 15]. Furthermore, the combination of low aluminium and adequate iron (Treatment 5) promoted soluble sugar accumulation and dry biomass, supporting plant resilience under stress. Collectively, these results indicate that optimizing phosphorus and nitrogen inputs, while minimizing heavy metal accumulation and aluminium toxicity, is essential for maximizing Arachis pintoi performance in managed substrates such as green roofs.

4 Conclusion and recommendation

Commercial soilless green roof has been demonstrated as an efficient medium for rooftop gardens due to the survivality and growth of the *Arachis pintoi*. However, Treatment 4 could be regarded as a cost-effective substitute for commercial substrates in order to minimize the installation expenses of soilless medium rooftop gardens. This consideration is particularly relevant since combination of 30% biochar and 20% frass has a comprehensive positive impact on four growth aspects, including shoot development, chlorophyll synthesis, plant survival, and promotion of macronutrient within the soilless environment. Further studies are required to extend the experiment period beyond 40 days. *Arachis pintoi*, commonly used for animal feed and soil enhancement, reveals its complete growth cycle over a longer duration. A brief 40-day study might overlook crucial stages, such as full maturation, flowering, and seed production. Prolonged observation of *Arachis pintoi* is also essential for assessing its response to treatments during later growth stages and varied climatic conditions. This comprehensive analysis aims to determine whether *Arachis pintoi* is suitable as a commercially viable plant for green roofs.

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