ENHANCING THE MECHANICAL PROPERTIES OF WOOD PLASTIC COMPOSITES WITH BANANA PSEUDO-STEM BIOCHAR AS A SUSTAINABLE FILLER

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ABSTRACT

Malaysia faces significant waste management challenges, generating over 30,000 tons of waste daily with a recycling rate of approximately 5%. In this context, transforming plastic and agricultural residues into sustainable construction materials offers a promising solution. This study investigates the incorporation of banana pseudo-stem (BPS) biochar into wood-plastic composites (WPC) to form wood-plastic biochar composites (WPBC). The composites were formulated using recycled high-density polyethylene (rHDPE), *Pinus radiata* pinewood sawdust flour, vinyltrimethoxy silane as a coupling agent, and BPS biochar filler produced through slow pyrolysis at 450°C. Biochar loadings of 0, 6, 12, 18, 24, and 30 wt.% were studied. The composites were processed via extrusion and hot-press moulding, and compressive strength testing was performed according to ASTM D3501-05a. Results show that WPBC exhibited higher compressive strength compared to conventional WPCs, with optimum performance at 18–24 wt.% biochar. WPBC 24 achieved 37.2 MPa compared to 30.8 MPa for WPC, representing a 20% improvement. However, excessive biochar (30 wt.%) reduced strength due to brittleness. The study demonstrates that banana pseudo-stem biochar is an effective, low-cost, and sustainable filler that enhances the mechanical properties of WPCs while contributing to waste valorisation. WPBC offers potential as an eco-friendly structural panel material for the construction industry.

Keywords: *Wood plastic composites, biochar, recycled HDPE, banana pseudo-stem, compressive strength, sustainable materials*

INTRODUCTION

Malaysia generates an estimated 16,688 tonnes of food waste per day, with approximately 80% of it disposed of in landfills [1]. In Malaysia, the recycling rate for plastics was approximately 41.4% in 2019, with a focus mainly on polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP) plastics. Additionally, this industry faces challenges related to tainted recyclables and improper source segregation. While in the agricultural sector, banana cultivation in Malaysia generates large volumes of agricultural residues, particularly banana pseudo-stems (BPS), which are typically discarded after fruit harvesting. These pseudo-stems represent a significant source of lignocellulosic biomass, yet they are often underutilised, leading to waste management challenges. Improper disposal, such as open dumping and burning, contributes to environmental pollution and resource inefficiency [2].

BPS fibres have been used to produce biodegradable composites, paper pulp, textiles, and reinforced polymer products [3]. Beyond material applications, BPS sap and biomass are promising resources for biofertilisers and bioenergy, contributing to circular economy practices in agriculture [2]. Key challenges include a lack of awareness among farmers about the commercial value of pseudo-stem residues, insufficient infrastructure for biomass collection and processing, and limited integration of biorefinery technologies at scale [4]. In many developed countries, due to the increasing cost of raw materials and the continuous reduction of natural resources, the use of waste materials is a potential alternative in the construction industry [5]. One promising solution is the repurposing of recycled plastics with natural fillers such as sawdust and agricultural residues to produce wood–plastic composites (WPC). Overall, the integration of recycled plastics with plant-based fillers provides a practical pathway to reduce plastic waste while creating durable and sustainable products [1].

In this study, biochar filler was produced from banana pseudo-stem waste using the pyrolysis method and then added to WPC, consisting of wood sawdust flour, recycled high-density polyethene (rHDPE), and a coupling agent, to form wood-plastic biochar composites (WPBC). The WPCs are highlighted by challenges with mould, UV degradation, and flame retardancy, but showed progress with novel additives and modifications [6]. On the other hand, WPCs suffer from thickness swelling, thermal instability and low interfacial bonding. The hydrophilic nature of wood fibres leads to poor adhesion with hydrophobic thermoplastics. This incompatibility reduces stress transfer, resulting in inferior tensile, flexural, and compressive strength compared to neat polymers [7].

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The aforementioned disadvantages of the composites would be attempted to be overcome by the addition of biochar filler to the composites, which contain both wood and plastic. Biochar exhibits a high surface area and micro-porosity that facilitate polymer infiltration and mechanical interlocking, resulting in enhanced stress transfer and reduced moisture uptake. These attributes make biochar a technically and environmentally promising additive for improving WPC performance [8]-[10]. Recent studies [8]-[9],[11] have shown that biochar can substitute or reduce coupling agents in composite systems while maintaining or improving mechanical strength. Therefore, incorporating banana pseudo-stem biochar into WPCs provides a twofold benefit: (1) valorisation of agricultural residues and (2) enhancement of composite performance through improved interfacial bonding. Previous studies on WPCs indicate that coupling agents are often required to enhance interfacial bonding. However, biochar has emerged as an alternative filler that can improve compatibility while reducing the need for costly chemical treatments.

Recent studies, for instance [12], have shown that optimising filler–polymer interactions can balance toughness and stiffness. Previous research [13] has linked tensile strength to fatigue life, confirming the importance of mechanical reliability under repeated loads. The reduced weight of WPCs (lower specific gravity) relative to plastics infused with inorganic elements renders them appealing for multiple applications. Therefore, properties such as strength, stiffness, impact resistance, density, heat deflection temperature, colour stability, resistance to decay, ultraviolet light, and moisture are important considerations in many WPC applications [7].

The characteristics of wood flour encompass factors such as particle size and distribution, wood species, and the amount of wood flour incorporated. Particle size exerted a negligible impact on density, although it significantly affected mechanical strength and water absorption. Newer works confirm that while particle size distribution is important for processability and surface finish, the density increase of WPCs is primarily determined by filler content rather than size [8].

To overcome interfacial incompatibility, coupling agents such as silanes, maleated polyolefins, and titanates are used. These agents modify the surface chemistry of lignocellulosic fillers, introducing functional groups that bond with the polymer matrix. For example, silane treatment of natural fibres in WPCs has been shown to enhance bonding by improving fibreatrix compatibility and forming stronger interfacial linkages, resulting in increased strength, water resistance, and dimensional stability [14]. The use of coupling agents adds cost and processing steps, motivating interest in alternative fillers that naturally improve compatibility. The study aimed not to eliminate the coupling agent entirely, but to reduce its dependency by introducing biochar as a co-filler. The coupling agent was retained in small, constant proportions to ensure processability and comparability.

Produced through pyrolysis, biochar possesses a stable aromatic structure, high carbon content, and micro-porous surfaces. These properties make biochar thermally stable and capable of enhancing the dimensional stability of composites. When used as a filler in polymer composites, biochar can reduce water absorption, increase stiffness, and enhance interfacial bonding by providing a porous structure that facilitates polymer penetration [15]. Previous studies indicate that biochar produced at higher pyrolysis temperatures (>400°C) has better hydrophobicity and stability, while lower temperatures retain functional groups that can contribute to bonding [9].

The thermal degradation of wood began at approximately 30°C [8]. The thermal degradation of wood causes the composite to have pores, a low density, and compromises its mechanical properties [16]. Thus, the suitable matrix for the wood plastic composite is a thermoplastic polymer, which has a melting point below 200°C. Unlike thermoset, thermoplastic can be reheated and reshaped [17].

HDPE usually have a density (0.941 < density < 0.965 kg/m^3) with a 130°C melting temperature and composed of carbon and hydrogen atoms joined together forming long-chain high-molecular-weight products [18]. In contrast to amorphous structures, which have random arrangements of polymer chains and offer looser polymers in thermoplastics, semi-crystalline structures have well-aligned polymer chains that are compact and densely packed.

Rich in lignocellulosic content, the banana pseudo-stem can be converted into biochar with good porosity and surface area [19]. Utilising this waste aligns with sustainable practices and provides a low-cost source of biochar filler. Incorporating banana pseudo-stem biochar into WPCs not only addresses waste disposal but also adds value to agricultural by-products. Therefore, this study focuses on developing WPBC using recycled HDPE, pinewood sawdust, banana pseudo-stem biochar, and vinyltrimethoxy silane. The aim is to evaluate how different biochar loadings influence compressive strength and to determine the optimal formulation and compatibility of biochar in bricks composites for structural applications.

MATERIAL AND METHODOLOGY

Raw Materials Preparation and Processing Methods

Sawdust of softwood radiate pine (*Pinus radiata*) was collected from a local sawmill in Penang. Sawdust was then ground to a finer flour of 420 µm using the SIMA pulveriser machine, Model: PPF 250, and manually filtered to eliminate contaminants. It was then oven-dried at 102°C for 24 hours to achieve a moisture content of approximately 2–3% [20]. The moisture content was verified by weighing before and after drying to a constant mass. The residual moisture corresponds to bound water within cell walls and prevents thermal degradation of wood flour during processing. In this study, the wood sawdust was not subjected to any chemical surface treatment. It was only ground, filtered, and oven-dried to control moisture content. This was intentional to evaluate whether the inclusion of biochar could compensate for the absence of typical chemical modifications used to improve fibre–matrix adhesion.

Banana pseudo-stem biochar was produced at a 450°C slow pyrolysis temperature and ground into a finer dust with a particle size of ≤ 100 µm using the same wood flour drying method.

Recycled HDPE granules were obtained from a local plastic recycling company, Waste Management Sdn Bhd (Wespack). The measured properties of recycled HDPE show an MFI of 0.072 g/10 min at 190°C. The coupling agent used was STRUKTOL SCA 971 Vinyltrimethoxy Silane.

The extrusion process was performed for compounding and hot pressing for moulding. Extrusion is the most widely used method for processing thermoplastics and a cost-effective continuous process for producing shapes of constant section or long profiles. Hot-press composites, on the other hand, have relatively little water absorption and thickness swelling, making them stable in humid environments.

All the materials were premixed before being fed into the hopper for the compounding process, which was performed at 170°C and 60 rpm through a twin-screw co-rotating extruder, Prism TSE 16 TC. Table 1 shows the weight percentage of raw materials used in the samples. The extruded strand was passed through a water bath and subsequently pelletised. Before the specimens were made, the compounded pellets were dried at 60°C for 5 minutes to remove the remaining moisture.

Table 1 Weight percentage of WPC and WPBC's raw materials

Types of Composites	Wood flour wt.%	Silane wt.%	rHDPE wt.%	Biochar wt.%
1. WPC	30	4	66	-
2. WPBC 6	30	4	60	6
3. WPBC 12	30	4	54	12
4. WPBC 18	30	4	48	18
5. WPBC 24	30	4	42	24
6. WPBC 30	30	4	36	30

The pellets were then moulded in the hydraulically heated platen press by using an aluminium mould coated with a silicone releasing agent. The hot-press platens were heated to 180°C before placing the pellet-filled mould on the bottom platen. The pellets were then preheated without pressure for 5 minutes and subsequently heated for an additional 5 minutes under a pressure of 50 bars. After that, the mould and specimens were then transferred to a cold press and pressed for an additional 5 minutes at 50 bars. Finally, the specimens were conditioned at a temperature of 23 ± 2°C and a relative humidity of 50 ± 5% for at least 40 hours, as specified in ASTM D618-99.

Elemental Composition of Biochar

Elemental analysis was referred from recent studies with similar pyrolysis conditions. The data are presented in Table 2. According to [21], it is confirmed that banana pseudo-stem biochar produced by pyrolysis is rich in carbon and oxygen, with a variable nitrogen content depending on agricultural practices. Slow pyrolysis generally enhances the carbon content and stability of the biochar, making it suitable for environmental and energy applications [21]. These values provide an expected carbon percentage for banana pseudo-stem biochar, consistent with typical lignocellulosic feedstocks used in polymer composites.

Table 2 Elemental composition of banana pseudo-stem biochar [21]

Analysis	Fast Pyrolysis	Slow Pyrolysis
	Elemental analysis (%)	
C	41.28	43.23
H	0.09	0.00
N	28.48	19.96
S	0.00	0.00
O	30.15	36.81
HHV (MJ/kg)	13.6	23.40
pH	10.11	10.16

Compressive Strength Testing

The compressive strength of the panels was measured at the Structural and Material Laboratory, Faculty of Engineering and Life Sciences, Universiti Selangor. Compression strength is an important aspect in assessing the ability of a sample to bear [5]. The specimens for the compression tests were prepared using panels of dimensions 150 mm × 150 mm × 3 mm, in accordance with the ASTM D 3501-05a standard. The tests were performed in accordance with the BS EN 12390-3:2009. The ADR Touch 2000 BS EN Compression Machine with Digital Readout was used for the testing. The compression specimens are loaded at a constant deflection rate specified by ASTM D 695 (1998). All compressive strength measurements were conducted in triplicate (n = 3), and the results are reported as mean ± standard deviation.

RESULT AND DISCUSSIONS

Effect of Biochar on Compressive Strength

The averages of the load at failure were divided by the area of the specimen to get the value of compressive strength for each sample. The compressive strength was calculated according to the following equation:

$$\text{Compressive Strength}\left(\text{MPa}\right) = \frac{\text{Load}\left(\text{N}\right)}{\text{Area}\left(\text{mm}^2\right)} \quad (1)$$

Figure 1 shows the compressive strength of WPC and WPBC samples at different biochar loadings, whereas Table 3 shows the mean compressive strength (MPa) ± standard deviation for WPC and WPBC. The corresponding numerical values are summarised in Table 3. The results indicate a consistent improvement in compressive strength with increasing biochar content up to 24 wt.%. The mean compressive strength increased from 30.83 ± 1.16 MPa for the control WPC to 37.17 ± 0.40 MPa for WPBC 24, representing a 20% enhancement. The low standard deviation for WPBC 24 demonstrates excellent reproducibility and uniform filler dispersion.

The gradual rise in strength from WPBC 6 to WPBC 18 (33.73–37.13 MPa) indicates that moderate biochar additions enhance stress transfer through improved interfacial bonding and pore-assisted mechanical interlocking. The higher variability observed for WPBC 12 and WPBC 18 (SD ≈ 4.16 and 3.52 MPa) may reflect partial agglomeration at intermediate filler levels. At 30 wt.% biochar, the mean strength

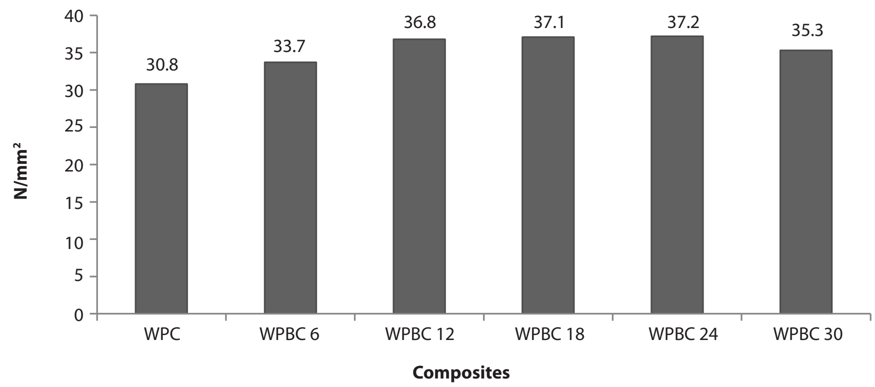

Figure 1 Compressive strength of WPC and WPBC samples

Table 3 Mean compressive strength (MPa) ± standard deviation for WPC and WPBC samples

Composite	Mean (MPa)	Standard Deviation
WPC	30.83	1.16
WPBC 6	33.73	0.87
WPBC 12	36.80	4.16
WPBC 18	37.13	3.52
WPBC 24	37.17	0.40
WPBC 30	35.33	3.18

dropped slightly to 35.33 ± 3.18 MPa, indicating that excessive carbon loading increases brittleness due to restricted polymer chain mobility and localised stress concentration. The higher carbon content increases the rigidity of the composite matrix, limiting polymer chain mobility and stress redistribution, which manifests as brittleness under compressive loading.

These findings confirm that the optimum biochar loading lies between 18–24 wt.%, consistent with other studies on biochar-reinforced polymer composites [11],[22]. At moderate biochar loadings (18–24 wt.%), improved mechanical interlocking and hydrophobic compatibility minimise void formation. Plus, there is not much difference between WPBC 18 and WPBC 24. It can simply be stated that the compressive strength of WPBC reached its optimum strength at 18 wt.% to 24 wt.% addition of biochar.

Meanwhile, the lowest strength is observed in the control sample WPC, with a value of 30.8 MPa. This is due to the strong interfacial bonding of the silane coupling agent, which facilitates better crosslinking between the wood and the polymer.

It shows the same great expected result for the compressive strength of WPCB 24, which reports that biochar addition enhances strength up to an optimum threshold before embrittlement occurs. The optimum strength formulation is achieved when 18 or 24 wt.% of biochar is used, due to improvements in the composite interfacial bonding. It is clear that the addition of biochar as a second filler into WPC in this study significantly improved the strength of WPC.

Comparative Literature Analysis

The comparison demonstrates that the compressive strength achieved in this study (37.2 MPa) is comparable to or superior to that of other biochar–polymer systems, confirming the reinforcing potential of banana pseudo-stem biochar as shown in Table 4.

CONCLUSION

Banana pseudo-stem biochar proved to be an effective filler for enhancing the mechanical properties of wood plastic composites. Incorporating 18–24 wt.% biochar produced optimal compressive strength values (~37 MPa), representing a 20% improvement compared to WPCs without biochar. Beyond 24 wt.%, excessive carbon reduced strength due to brittleness. The findings confirm the potential of WPBCs as sustainable structural panel materials, contributing to waste management and resource efficiency. Future research should investigate tensile and flexural behaviour, water absorption, durability, and long-term weathering resistance.

Table 4 Comparison of compressive strength of WPBC with similar composites from the literature

Study	Material System	Optimum Filler Loading	Compressive Strength (MPa)	Remarks
[16]	Wood/PP + biochar	20 wt.%	35.0	Improved stiffness and bonding
[23]	HDPE + rice husk biochar	15 wt.%	33.5	Enhanced dimensional stability
[11]	Bamboo fibre/HDPE + biochar	25 wt.%	36.8	Balanced strength and ductility
This study (WPBC)	rHDPE + pine sawdust + BPS biochar	24 wt.%	37.17	The highest compressive strength observed

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