



Physico-Mechanical Properties of Wood Plastic Composite Boards Made from Selected Hardwood Species in Oyo State, Nigeria

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ABSTRACT

This study investigated the effects of wood–plastic mixing ratio and wood particle size on the physical and mechanical properties of wood plastic composite (WPC) boards produced from three hardwood species (*Tectona grandis*, *Gmelina arborea*, and *Cassia sieberiana*) purposely selected for the study. Fresh sawdust from each species was processed and mixed with recycled polyethylene plastic at wood plastic ratios of 40:60, 50:50, and 60:40 using two particle sizes (1.00 mm and 2.00 mm). Composite boards were manufactured using extrusion and hot-pressing techniques. Physical and mechanical properties were determined using standard test methods. Data was analyzed using factorial analysis of variance at $p < 0.05$. The results showed that wood–plastic ratio and particle size significantly influenced the physical and mechanical performance of the WPC boards. Boards produced at a 50:50 ratio exhibited the highest density and lowest volumetric change, indicating superior dimensional stability, while the 60:40 ratio resulted in the lowest water absorption. The 40:60 ratio produced the highest tensile and flexural modulus of rupture, demonstrating improved strength performance. Particle size also affected board properties, with 1.00 mm particles producing higher density, whereas 2.00 mm particles enhanced stiffness, as reflected by higher tensile and flexural modules of elasticity values and reduced volumetric change. Overall, the study demonstrates that WPC formulation parameters, particularly wood–plastic ratio and particle size, are critical determinants of composite performance, while wood species plays a secondary role. The properties obtained indicate that WPC boards produced from locally available hardwood sawdust and recycled polyethylene plastic are suitable for various non-structural wood-based applications and offer a sustainable alternative to solid wood materials.

Keywords: Wood plastic composite, Wood plastic ratio, Particle size, Physical properties, Mechanical properties, Recycled polyethylene and Hardwood sawdust

INTRODUCTION

Wood panel materials in the form of plywood, particle board, flake board and wood-cement board among others has consistently been on the increase in demand in Nigeria. The decline in supply of wood raw materials has also affected its production leaving no option than to seek for alternate raw materials for wood-based industries. According to Kehinde *et al.* (2014) and Chaudemanche *et al.* (2018),

wood residues from sawmills and other wood-processing factories are poorly disposed into the environments. Similarly, plastic water bottles and related materials are either discharged into streams, ditches, canals and rivers or used for land filling and in some cases incinerated causing flooding, land degradation and also contributing to global warming. These wastes can be recycled to

form new and value-added products especially where alternatives are being sought for virgin materials (Winnandy *et al.*, 2004; Akinfiresoye *et al.*, 2018; Olufemi and Armando, 2017; Taufiq *et al.*, 2018). According to Keskisaari and Kärki, (2018) utilizing wood fibers as part of WPC is usually done in order to replace the more expensive wood raw materials (Schwarzkopf and Burnard, 2016). The advantage of using recycled materials is not only the lower price, but it is also more eco-effective to recycle materials instead of disposing them. Ratanawilai and Taneerat, (2018) opined that pollution also results from the overuse of plastic; moreover, it is the main cause of plastic pollution as it is cheap, widely available and an item people frequently dispose of, additionally and just as important, they do not decompose and they release an incredible amount of toxins into the air when they are burned. Regular everyday trash is one of the biggest contributors to plastic pollution. There are already a wide range and large number of different kinds of products made from WPC (Partanen and Carus, 2016). Using recycled materials as a part of WPC offers more options for the composition of composites and as one of the solutions to environmental pollutions by both sawdust and plastic. According to Taufiq *et al.* (2018) the aforementioned residues can be used in the manufacture of wood plastic composite (WPC). These boards are considered among the most resistant forest industry materials in relation to conventional boards used in construction and have a very significant environmental, ecological and sustainable value. In addition, they have a great acceptance in the market due to their properties and natural durability, which allows them to replace the wood in external environment.

Wood Plastic Composite (WPC) is a mixture of polymer and wood residue and it has advantages which include low moisture absorption, inability to splinter, high dimensional stability, low wet/dry traction, good workability, high resistance to decay, termite attack, and ultra violet (UV) radiation

(Effah, *et al.*, 2018). Due to these properties, WPCs market in Europe and United State has witnessed significant growth over the last decades (Keskisaari and Kärki (2018). WPCs are commonly used in exterior and aboveground applications where the possibility of attack by physical and bio deteriorating agents are high. The introduction of the WPC in residential applications as an alternative to copper chromate arsenate (CCA) treated lumber has resulted in a more appealing price for the composite products. According to Akinfiresoye *et al.*, (2018) WPCs can be produced from hardwood species such as *Milicia excelsa*, *Ceiba pentandra* and *Cola gigantia*, in Nigeria, elsewhere orange trees, walnut trees, yellow poplar, hickory, Utah juniper, salt cedar and emerald ash borer-infested ash are being used to produce WPC, (Kim *et al.*, 2008).

From environmental point of view, plastic waste has several impacts on the health of ecosystems and humans being non-biodegradable and a large amount of woodresidues is generated from wood industry at different stages of wood processing in Nigeria. disposal is mostly in dump sites or set on fire around the sawmills. According to Kehinde *et al.*, (2014), poor management and burning of wood residues causes environmental and air pollution through the emission of toxic and non-toxic particulates and smoke. Wood and plastic wastes can therefore be recycled to produce value-added products thereby eliminating environmental pollution (Akinfiresoye *et al.*, 2017). Previous research works on the effect of wood species showed that WPC made from hardwood sawdust has improved tensile strength with high heat deflection temperature (the temperature at which a plastic deforms under a specified load) over softwood sawdust (Effah, *et al.*, 2018). Properties of the WPCs depend on several factors like physical and mechanical characteristics of the plastic matrix, chemical composition of the wood particles, and chemical interactions between the plastic and wood (Yudhi *et al.*, 2017). These factors have been noted to have

influence on the processing attributes and mechanical properties of the WPCs (Yadav and Yusoh, 2015; Schwarzkopf and Burnard, 2016)

Nigeria is currently experiencing scarcity and inadequate supply of round logs to wood-based industries. The present shortfall of supply of the prime timber species as well as the prevalence of the supply in small diameter sizes log have been predicted (Badejo, 1999). The identification of wastes from suitable indigenous species to produce WPC would assist in reducing the problems associated with greenhouse gases emission.

This study was designed to investigate the physical and mechanical properties of WPC produced from three different hardwood species at varying ratios in Oyo state. Growing production and consumption of plastics worldwide has resulted in significant contribution to municipal solid waste, thereby causing environmental menace. Plastics are discarded unto the street and drainage thereby blocking free flow of rainwater which eventually leads to flooding. A number of reclamation techniques have been developed to recycled plastics as a substitute for the virgin plastics in many applications (Lightsey *et al.*, 1977). Recycled high density polyethylene pellets and flakes are 31 - 34% less expensive than the virgin high density polyethylene (Powel 1999). About 40% of all recycled plastics products were used in distribution products such as film and bags, and ~30% were used in building applications such as pipes, windows and tiles in Western Europe (APM; 2004). There is a greater potential to use recycled plastics to produce WPC products in low cost without reduced properties.

In spite of all its good attributes, the drawback to WPC production lies in the wood and plastic raw materials used. WPC boards are commonly produced from wood species such as Pines, oaks and Maple; preference in selection of wood species for the production of WPCs are based on factors such as regional availability and cost (Kim *et al.*, 2008). WPCs production is usually done from wood species that have been tested and confirmed suitable

for both structural and domestic application. It has been reported that wood species like Ponderosa pines provides better mechanical property enhancements compared with other species like loblloy pine, maple and oak (Berger and Stark, 1997). As the production of WPCs is being intensified using temperate wood species, the restriction on logging of wood species in temperate region has increased tempo on investigating other wood species from other regions.

Previous studies have shown that WPC could be produced in Nigeria using readily available and locally sourced materials [Aina *et al.*, (2013), Aina and Fuwape (2008), Aina and Ajayi (2008), Ajigbon and Fuwape (2005)]. These authors have shown that variability exists in properties of the WPCs produced from different indigenous hardwood species (Aina *et al.*, 2013). There is need to more research efforts aimed at providing information on physical and mechanical properties and utilization potentials of the composite. The issues of the WPC usage for outdoor and indoor application in Nigeria are long overdue since other countries of the world have shifted their attention towards WPC products as alternative to solid wood for structural applications. This study was carried out at Forestry Research Institute (FRIN) Ibadan, Oyo State.

MATERIALS AND METHODS

Study Area

Onigambari Forest Reserve is located about 17 km South-east of Ibadan on the Idi-Ayunre-Ijebu-Ode Road, Oyo state. It lies between latitude $7^{\circ} 4' - 7^{\circ} 14' N$ and longitude $3^{\circ} 42' - 3^{\circ} 56' E$ of the equator (Salami *et al.*, 2016). The Forest Reserve was declared from Ibadan Forest Reserve by a resolution of the Ibadan city council passed in September 1899 (Ajibode, 2002). A month later, the Mamu portion was added and to the government by deed of gift. Both sections were consolidated to form Gambari Forest Reserve 1953 making a total area of 125.62 km² (Ajibode, 2002).

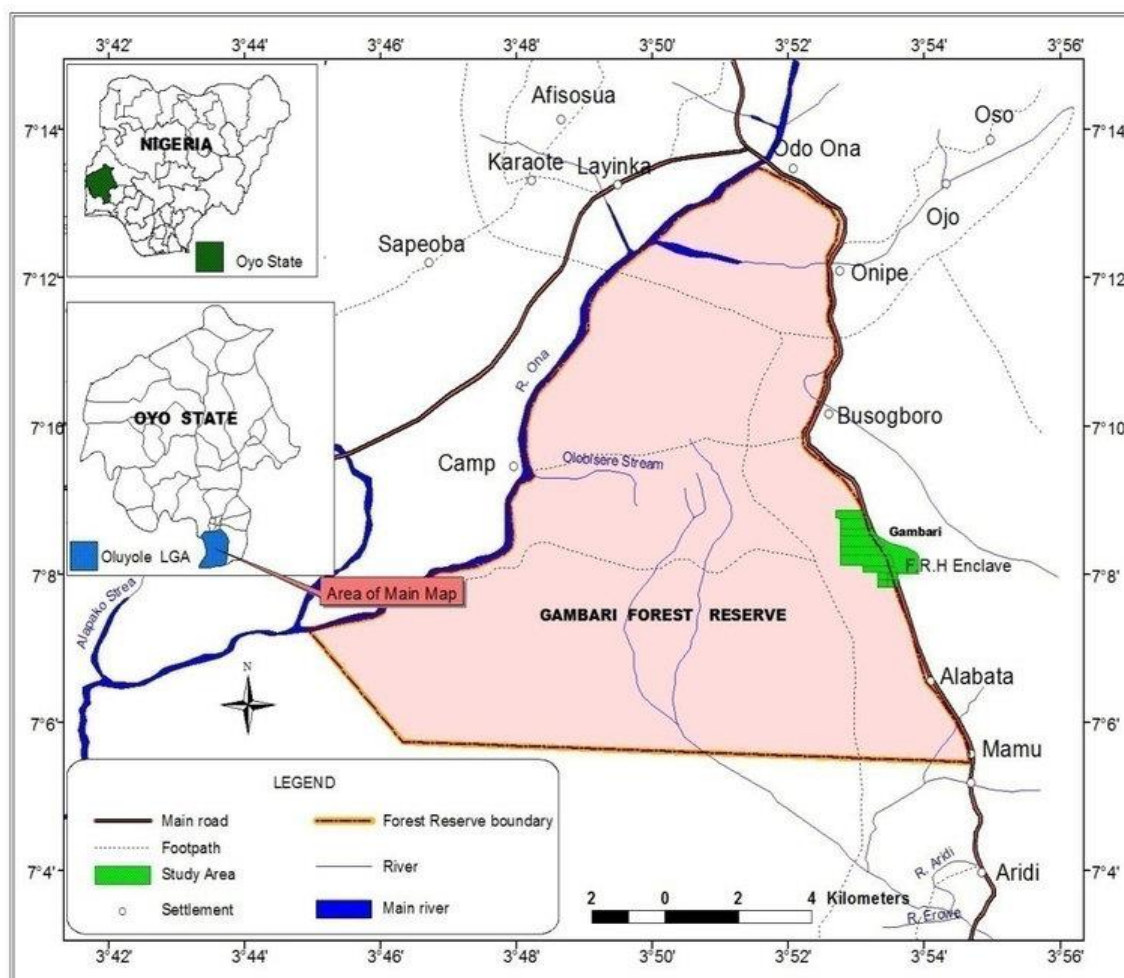


Figure 1: The map of Onigambari Forest Reserve
Source: Salami et al. (2016)

Hence tree like Teak (*Tectonia grandis*), Mahogany (*Khaya ivorences*), and other Agricultural crops like Cocoa (*Theobroma cacao*), Cassava (*Manihot esculata*) with exotic trees and crops are cultivated. The inhabitants of the area are predominantly farmers with relatively low number of hunters. Some of the forestry practice includes: Planting production of trees for both timber and fuel wood, Collection and sales of non-wood products such as leaves and bark for herbs, rattan (cane) etc. The noticeable surrounding areas are Idi Ayunre, Adebayo, Ibusogboro and Mamu. These areas are along the same equatorial belt with the study area. Onigambari area which was bounded up with the following villages; Aba-Igbagbo, gbale-asun, Ajibodu, Lagunju, Akintola, Okeseyi, Akinogbun, Amosun, Olonde ige, Olaya, Onipede. The distance between these areas

is about 200 m to 500 m and altitude if 147 m depends on the undulating nature of the areas with a total number of people of 600 as at 1996 (Salawu,2002; Salami et al., 2016).

Experimental Design

The study utilized a factorial experimental design to investigate the effects of wood species, wood/plastic mixing ratio, and particle size on the physical and mechanical properties of wood-plastic composite (WPC) boards. The blocks were wood species, mixing ratio, and particle sizes while the treatments were the *Tectona grandis* (Teak), *Gmelina arborea* and *Cassia seiberiana* for wood species; 40:60, 50:50 and 60:40 for mixing ratio and 1-00 mm and 2.00 mm for particle size. Each treatment was replicated 3 times to ensure statistical validity (Tables 1 and 2).

Table 1: Experimental Treatment Structure for Wood–Plastic Composite (WPC) Boards

Factor	Level	Description
Wood species (S)	3	<i>Tectona grandis</i> , <i>Gmelina arborea</i> , <i>Cassia sieberiana</i>
Wood–plastic ratio (R)	3	40:60, 50:50, 60:40 (wood: plastic, % by weight)
Particle size (P)	2	1.00 mm, 2.00 mm
Experimental design	—	3 × 3 × 2 factorial in Randomize Complete Block Design (RCBD)
Number of treatments	18	All combinations of S × R × P
Replication	3	Each treatment replicated 3 times
Total number of boards	18 × 3	Determined by number of replications

Note: Table 1a presents the full factorial treatment structure used in this study, showing all combinations of wood species, wood–plastic ratios, and particle sizes evaluated for WPC board production.

Table 2: Treatment Combinations Used for WPC Board Production

S/N	Wood Species	Wood–Plastic Ratio	Particle Size	Wood Species	Wood–Plastic Ratio	Particle Size	Wood Species	Wood–Plastic Ratio	Particle Size
1.	<i>T. grandis</i>	40:60	1.00 mm	<i>G. arborea</i>	40:60	1.00 mm	<i>C. sieberiana</i>	40:60	1.00 mm
2.	<i>T. grandis</i>	40:60	2.00 mm	<i>G. arborea</i>	40:60	2.00 mm	<i>C. sieberiana</i>	40:60	2.00 mm
3.	<i>T. grandis</i>	50:50	1.00 mm	<i>G. arborea</i>	50:50	1.00 mm	<i>C. sieberiana</i>	50:50	1.00 mm
4.	<i>T. grandis</i>	50:50	2.00 mm	<i>G. arborea</i>	50:50	2.00 mm	<i>C. sieberiana</i>	50:50	2.00 mm
5.	<i>T. grandis</i>	60:40	1.00 mm	<i>G. arborea</i>	60:40	1.00 mm	<i>C. sieberiana</i>	60:40	1.00 mm
6.	<i>T. grandis</i>	60:40	2.00 mm	<i>G. arborea</i>	60:40	2.00 mm	<i>C. sieberiana</i>	60:40	2.00 mm

Sample and Sampling Techniques

Three species namely, *Tectona grandis* (Teak); *Gmelina arborea* and *Cassia sieberiana* were purposely obtained from the arboretum of Forestry Research Institute of Nigeria (FRIN) plantation at Onigambari Town, Ibadan, Oyo State of Nigeria. These species were selected because of their availability and were found in the same locality to remove the bias of location variability. Plastic wastes from packaged sachets made of polyethylene were randomly collected from dump sites around Aleshinloye Market, Jericho, Ibadan, Oyo State, Nigeria. For each species, sawdust was mixed with recycled polyethylene plastic at three ratios by weight: 40:60, 50:50, and 60:40 (wood: plastic). Two particle sizes (1.00 mm and 2.00 mm) were used.

Sample Preparation

Fresh sawdust from each wood species was oven-dried and sieved to the desired particle sizes. The sawdust and plastic particles were thoroughly hand-mixed according to the specified ratios and processed using a single-screw extruder. The extruded material was hot-pressed into boards, cooled, and cut into test specimens.

Laboratory Procedures

Physical properties measured included density, water absorption, and volumetric shrinkage, following ASTM D2395 and D792 standards. Mechanical properties (modulus of rupture [MOR] and modulus of elasticity [MOE]) were determined using three-point bending tests on a universal testing machine, following ASTM D7031-11 and D790-84a.

Statistical Analysis

Data was analyzed using one-way and two-way analysis of variance (ANOVA) to assess the effects of wood species, mixing ratio, and particle size, as well as their interactions, on the measured properties. For factors with only two levels (e.g., particle size), independent samples t-tests were used instead of ANOVA. Where significant differences were detected by ANOVA, mean separation was performed using Duncan's Multiple Range Test (DMRT) for factors with more than two levels. All statistical analyses were conducted using [insert software, SPSS version X. The significance level was set at $p < 0.05$.

The equation used in the study were:

$$\text{Modulus of Rupture (MOR)} = \frac{3PL}{2HB^2} \quad 1$$

Where:

P = Maximum load applied before failure

L = Span length between supports

B = Width of the specimen

H = Height (or depth) of the specimen

Purpose:

According to Jones and Ashby (2019), MOR measures the *maximum stress* a material can withstand before it breaks during a bending test. It reflects the material's bending strength.

$$\text{Modulus of Elasticity (MOE)} = \frac{PL^3}{4BHD_3} \quad 2$$

Where:

P = Load applied

L = Span length

B = Width

H = Height

D = Deflection at the center of the span

MOE quantifies the *stiffness* of a material—how much it resists deformation under load. A higher MOE means the material is stiffer and less likely to bend. MOR and MOE were calculated within the linear limit in accordance with ASTM D198

Data Analysis

The data obtained for the appraisal of the study variables employed in this study included analysis of variance and graphical analysis which provided an easy means of observing the trend of the relationship which might exist between the study variable and a specific board property. Analyses of variance were conducted to estimate the relative importance of various sources of variations on boards' density, water absorption, volumetric shrinkage, modulus of rupture and elasticity. The main effects considered were those due to differences among the wood species, plastic/wood ratios and locations of exposure. In addition, the interaction effects between the main effects were also considered.

RESULTS AND DISCUSSION

Effects of Wood-Plastic Ratio on Physical Properties

Table 3 and Figure 2 revealed that the boards produced at 50:50 had the highest mean density (1.18 g/cm^3), while 40:60 and 60:40 produced lower densities of 0.85 and 0.82 g/cm^3 , respectively. This means that the wood-plastic ratio significantly affected density, which serves as an indication of a balanced mix that can enhance compaction/packing and reduce voids, thereby increasing density.

The increase in density of the WPC boards was primarily influenced by the wood-plastic mixing ratio and wood particle size rather than wood species alone, a phenomenon supported by findings that formulation controls matrix continuity and particle packing (Nukala et al., 2022). Boards produced at the 50:50 wood-plastic ratio recorded the highest mean density (1.18 g/cm^3), which can be attributed to improved particle encapsulation, enhanced compaction, and reduced internal void spaces at balanced wood-plastic proportions. Increasing

plastic content beyond this level to 40:60 reduced density; while literature generally observes that higher plastic matrix concentration increases composite density when filling porous wood structures, a decrease at excessive polymer ratios can occur depending on the specific weight fractions and composite compaction mechanics under compression molding (Oladejo, 2019).

The 60:40 treatment recorded the lowest water absorption (0.23%), followed by 40:60 (0.53%), whereas 50:50 showed the highest (1.59%) (Figure 3). Water absorption varied significantly with the mixing ratio. The reduced water uptake at 60:40 is consistent with higher plastic content limiting moisture pathways within the composite structure due to the hydrophobic nature of the polymer matrix (Xu *et al.*, 2024). This is further corroborated by established trends showing that water absorption and thickness swelling drop drastically as the volume fraction of the hydrophobic plastic matrix increases (Gulitah and Liew, 2019; Nukala *et al.*, 2022). Conversely, the 50:50 boards recorded the lowest volumetric change (3.61%), compared with 60:40 (4.45%) and 40:60 (5.76%). This suggests that dimensional stability improved most at the balanced ratio under the production conditions used, indicating that a synchronized structural packing network at an even 50:50 formulation resists elastic swelling deformations better than unbalanced compositions (Endesha, 2026).

Effects of Particle Size on Physical Properties

The results of particle size influence on density in Table 3 revealed that 1.00 mm particle boards produced with 1.00 mm particles exhibited higher density (0.99

g/cm³) than those produced with 2.00 mm particles (0.91 g/cm³). This outcome is consistent with finer particles packing more efficiently and reducing internal voids, aligning with established composite processing dynamics where reduced filler size minimizes void formation and facilitates enhanced compaction within the polymer matrix (Izekor *et al.*, 2013). These findings demonstrate that density development in WPC boards is governed mainly by formulation parameters specifically the wood-plastic ratio and particle size which control particle packing, matrix continuity, and void distribution within the composite structure which agrees with the study by Chen *et al.* (2005).

The water absorption of the composite did not differ strongly between particle sizes in the mean table (0.75% for 1.00 mm and 0.82% for 2.00 mm) (Table 3), which demonstrates that at these localized dimensions, total filler exposure remains statistically comparable. However, the volumetric change was lower at 2.00 mm (4.19%) compared with 1.00 mm (5.01%) (Figure 4), indicating improved dimensional stability at the larger particle size in this dataset. While some literature notes that larger particle networks can provide long-path resistance to baseline structural buckling, this specific dimensional trend presents an interesting contrast to standard WPC behaviors, as smaller geometric particles are conventionally documented to yield lower overall thickness swelling and reduced volumetric distortion due to more uniform polymer encapsulation and isolated moisture pathways (Izekor *et al.*, 2013).

Table 3: Mean Physical Properties of WPC Boards as Influenced by Wood–Plastic Ratio and Particle Size

Factor	Level	Density (g/cm ³)	Water Absorption (%)	Volumetric Change (%)
Wood–Plastic Ratio	40:60	0.85 ^b	0.53 ^b	5.76 ^c
	50:50	1.18 ^a	1.59 ^c	3.61 ^a
	60:40	0.82 ^b	0.23 ^a	4.45 ^b
Particle Size	1.00 mm	0.99 ^a	0.75 ^a	5.01 ^a
	2.00 mm	0.91 ^b	0.82 ^a	4.19 ^b

Mean values with the same superscript letter within a column are not significantly different at $p \leq 0.05$.

Density by Wood Species

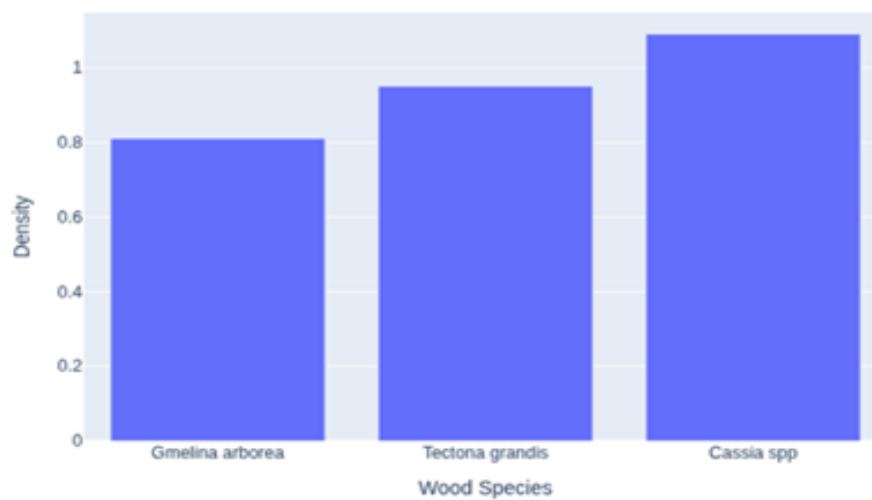


Figure 2: Mean density of WPC boards produced at different wood–plastic ratios (40:60, 50:50, and 60:40) and two particle sizes (1.00 mm and 2.00 mm)

Water Absorption by Wood Species

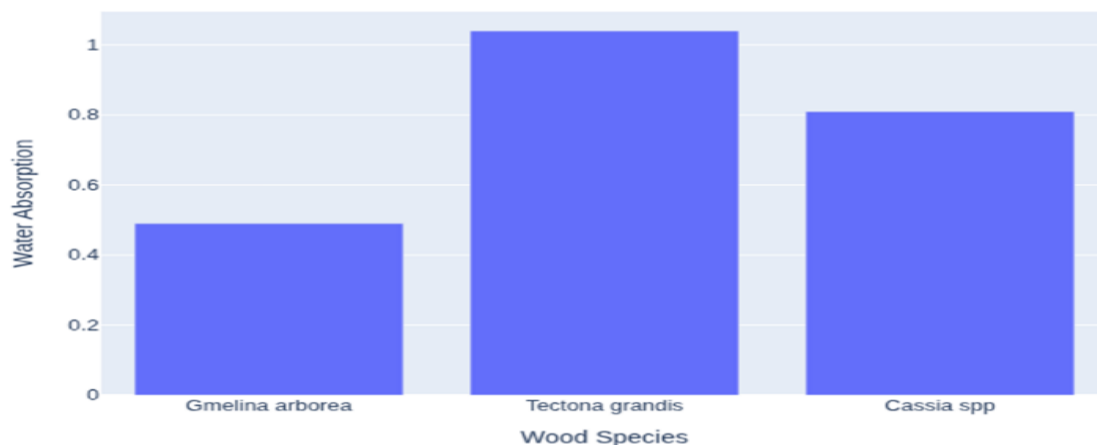


Figure 3: Water absorption of WPC boards after one week of immersion as influenced by wood–plastic ratio and particle size

Volumetric Change by Wood Species

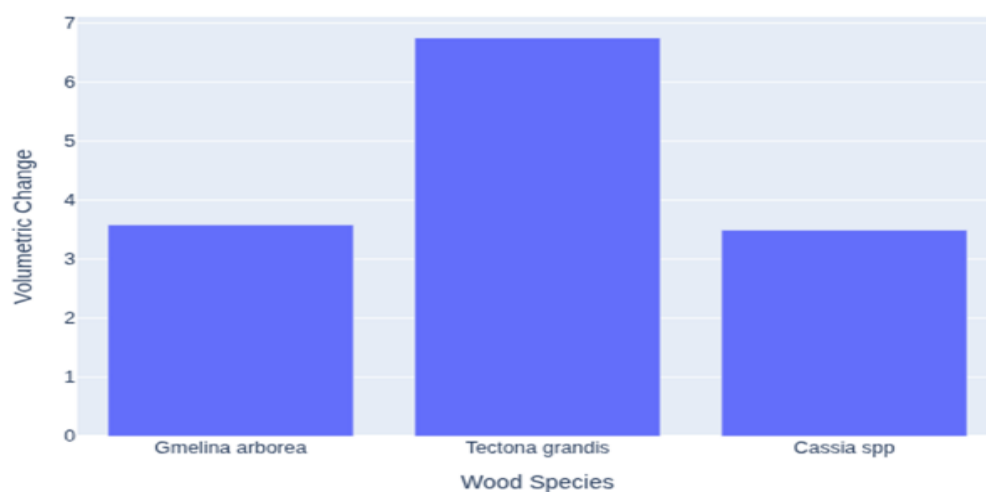


Figure 4: Volumetric change of WPC boards produced at varying wood–plastic ratios and particle sizes following one week of water soaking

Effects of Wood–Plastic Ratio on Mechanical Properties

Effects of Wood–Plastic Ratio on Tensile Properties

The shift from a 60:40 to a 40:60 wood-to-plastic ratio, demonstrates a notable increase of the tensile Modulus of Rupture (MOR) from 115.68 N/mm² to a maximum

value of 132.06 N/mm² (Table 4). This enhancement in ultimate tensile strength is primarily attributed to the continuous encapsulation of the lignocellulosic phase by the hydrophobic polymer matrix (Mitařová *et al.*, 2024). The tensile Modulus of Elasticity (MOE) displayed an entirely inverse behavioral trajectory as

shown on Table 4. The highest structural stiffness (2834.09 N/mm²) was observed at the high-fiber loading of 60:40, while dropping significantly to 2252.13 N/mm² at the 40:60 ratio. This might be attributed to the fact lignocellulosic wood fibers possess intrinsically higher rigidities than virgin or recycled thermoplastics, an increased fiber volume fraction restricts the segmental mobility of the polymer chains under tensile load, driving up the elastic modulus at the expense of maximum load-bearing capability before failure (Gulitah and Liew, 2019).

Effects of Particle Size on Tensile Properties

Altering the filler geometry from a fine powder (1.00 mm) to a coarser particulate fraction (2.00 mm) yields simultaneous improvements in both tensile parameters. The tensile MOR increases significantly from 118.55 N/mm² to 124.94 N/mm² while the tensile MOE jumps sharply from

1935.48 N/mm² to 3038.20 N/mm². This agrees with Hung *et al.* (2017) who reported that larger wood particles typically exhibit higher aspect ratios (length-to-diameter profiles) in particulate-filled polymers that offer greater surface areas for stress distribution, assuming adequate wet-out by the thermoplastic phase. The 1.00 N/mm² particle size behaves more like a low-efficiency filler than a structural reinforcement agent, providing limited structural continuity and higher void generation potential, which manifests as lower rigidity and reduced tensile rupture resistance (Khan, 2025). By expanding the particle size boundary to 2.00 N/mm², the mechanical integrity is elevated because longer structural fiber paths can successfully deflect propagation cracks and carry external tensile loads more efficiently across the composite framework.

Table 4: Tensile Properties

Factor	Level	Tensile MOR (N/mm ²)	Tensile MOE (N/mm ²)
Wood-Plastic Ratio	40:60	132.06 ^a	2252.13 ^c
	50:50	117.50 ^b	2374.29 ^b
	60:40	115.68 ^c	2834.09 ^a
Particle Size	1.00 mm	118.55 ^b	1935.48 ^b
	2.00 mm	124.94 ^a	3038.20 ^a

Mean values with the same superscript letter within a column are not significantly different at $p \leq 0.05$.

In Table 5, the 40:60 ratio yielded the highest flexural strength (30.17 N/mm²), which significantly decreased as the wood content increased to 50:50 (24.49 N/mm²) and reached its lowest value at 60:40 (15.29 N/mm²). This degradation in MOR at higher biomass content is typical for natural fiber-reinforced polymer composites without sufficient coupling agents. This occurrence may be connected to excess of hydrophilic wood particles leads to poor interfacial bonding, insufficient encapsulation by the hydrophobic plastic matrix, and increased void formation, which creates localized stress concentration points that lower the

ultimate bending strength as reported by Yemele *et al.* (2010). Conversely, the flexural MOE behaved non-linearly, peaking drastically at the 50:50 ratio (1002.86 N/mm²) compared to the 40:60 (402.28 N/mm²) and 60:40 (704.19 N/mm²) formulations. Wood fibers possess a significantly higher intrinsic modulus of elasticity than standard thermoplastic resins (Yadav *et al.*, 2021). Increasing the wood-plastic ratio from 40:60 to 50:50 introduces rigid lingo-cellulosic particles that restrict the mobility of the polymer chains, dramatically augmenting the material's overall stiffness. However, when the fiber loading is further accelerated to

60:40, the severe lack of matrix continuity and poor interfacial interactions compromise structural integrity, causing a subsequent drop in stiffness to 704.19 N/mm².

The larger particle size of 2.00 mm resulted in a significantly higher MOE (822.78 N/mm²) compared to the 1.00 mm size (583.44 N/mm²). Various parameters influence the flexural properties of wood plastic composites including the fibre aspect ratio, fibre matrix adhesion, stress transfer at the interface, mixing temperatures as well as the inherent wood property (Madhoushi *et al* 2013). The higher flexural and tension values observed in 2.00 mm particle size for all species may be as a result of the larger surface areas of the sawdust thus fibre polymer adhesion/interaction on the interfacial surface was stronger at this particle size. This behaviour aligns with composite stress-transfer theories. Larger wood particles maintain a higher aspect ratio (length-to-diameter ratio), which provides a more substantial network to intercept and redistribute bending stress across the composite matrix, ultimately yielding superior resistance to elastic deformation under flexural loads (Yemele *et al.*, 2010). Meanwhile, smaller particles (1.00 mm despite offering a larger total surface area for polymer interaction, often yield lower aspect ratios and are more prone to agglomeration, minimizing their capacity to effectively stiffen the polymeric matrix.

Wood particles with wider pore space will absorb more moisture even in wood plastic composites, therefore with the increase in

the sawdust content, there will be more water residence sites thus more water is absorbed. The low water absorption capacity by the 1 mm sized sawdust may be as a result of less surface area for linkage of water with the sawdust. Furthermore, large numbers of porous tubular structures present in fibre accelerates the penetration of water by the so-called capillary action (Madhoushi *et al.*, 2013 and Nourbakhsh and Ashori. 2009). The water absorption obtained for the species in this study were lower than that reported for WPC boards obtained in a previous work with commercial wood flour by Yadama *et al.* 2009; Pelaez-Samaniego *et al* 2013; and Yudhi Arnandha, 2017, for wood polymer composites of formulations containing high density for polyethylene (HDPE). This difference is as a result of the difference in the duration of soaking. The thickness swelling of the wood plastic composites varied with the sawdust content. The densities obtained for the species in this study were lower but comparable with the densities of WPC boards obtained in a previous work with commercial wood flour (1.153 g cm³) by Yadama *et al.* (2009) and Pelaez-Samaniego *et al.* (2013) and Yudhi Arnandha, (2017) for densities of formulations containing HDPE. Furthermore, Table 5 revealed that while the flexural MOR showed no statistically significant variation between 1.00 mm (22.76 N/mm²) and 2.00 mm (23.10 N/mm²), the flexural stiffness (MOE) was profoundly affected.

Table 5: Flexural Properties

Factor	Level	Tensile MOR (N/mm ²)	Flexural MOE (N/mm ²)
Wood-Plastic Ratio	40:60	30.17 ^a	402.28 ^c
	50:50	24.49 ^b	1002.86 ^a
	60:40	15.29 ^c	704.19 ^b
Particle Size	1.00 mm	22.76 ^a	583.44 ^b
	2.00 mm	23.10 ^a	822.78 ^a

Mean values with the same superscript letter within a column are not significantly different at $p \leq 0.05$.

Variation of the Physical Properties

The analysis of variance presented in Table 6 revealed that the physical properties of the fabricated composites (density, water absorption and volumetric change) were profoundly influenced by the raw material characteristics and manufacturing configurations. For density, all main factors (tree species, Particle size, and Mixing ratio) and all of their two-way and three-way interactions were statistically significant at $p < 0.05$. The highly significant effect of the mixing ratio ($F = 560.989$, $p < 0.00$) suggests that the volumetric proportions of the raw components dictate the compaction behaviour, void spaces and specific gravity of the resulting boards. Furthermore, the significant three-way interaction ($F = 144.044$, $p < 0.00$) showed that the density achieved is not merely an additive function of independent variables, but depends dynamically on how a specific anatomical species structure interacts with a given particle size distribution under different blending ratios. This aligns with the findings by Dialnet (2026), who reported that the inter-particle contact and consolidation behavior of particulate composites are heavily driven by the co-dependence of mesh size and raw material mass distribution.

The dimensional and hygroscopic stability of the composites were evaluated through water absorption and volumetric change tests. For water absorption, tree species ($F = 5.483$, $p = 0.01$) and mixing ratio ($F = 38.002$, $p < 0.00$) emerged as highly significant main effects, whereas Particle

size alone did not significantly alter water uptake ($F = 0.291$, $p = 0.59$). This lack of main effect significance for particle size implies that the ultimate volume of water absorbed is primarily governed by the chemical composition or inherent hydrophilicity of the specific species used, alongside the relative volume of binder or matrix shielding the particles, rather than the raw grain dimension alone. However, the interaction of tree species and particle size ($F = 10.650$, $p < 0.00$) and the three-way interaction ($F = 8.320$, $p < 0.00$) were significant. This indicates that while particle size alone may not shift water absorption uniformly, it acts conditionally; finer or coarser particles change the total exposure surface area and aggregate layout depending on the anatomical density of the species and the fullness of the binder matrix (Aguda and Plastic, 2021).

In contrast, the volumetric change of the boards was significantly affected by every single independent factor and interaction tested. The mixing ratio ($F = 96.592$, $p < 0.00$) and the two-way interaction of particle size and mixing ratio ($F = 204.632$, $p < 0.00$) showed exceptionally strong influences on dimensional swelling. The intense interaction between particle size and mixing ratio highlights that a lack of adequate binder content combined with unfavourable particle surface areas drastically compromises the interior bonding network, causing major structural shifting when exposed to moisture. Castro (2018) reported that optimized blending ratio is critical to encapsulate raw particles thoroughly; when the matrix material is

insufficient to coat variable grain sizes, the composite suffers from high void accumulation, facilitating excessive linear and thickness expansion. Ultimately, the significant three-way interaction across all three physical properties confirms that

achieving high-density, dimensionally stable composite materials requires a carefully tailored equilibrium between the chosen biomass species, its screened particle dimension, and its precise formulation layout.

Table 6: Result of Analysis of Variance Conducted for Physical Properties

Physical properties	Source of variance	Type III Sum of Squares	df	Mean Square	F	Sig.
Density	Species	0.739	2	0.369	294.035	0.00*
	Particle size	0.106	1	0.106	84.461	0.00*
	Mixing ratio	1.409	2	0.705	560.989	0.00*
	Specie * Particle size	0.048	2	0.024	19.189	0.00*
	Specie * Mixing ratio	1.268	4	0.317	252.390	0.00*
	Particle size * Mixing ratio	0.450	2	0.225	179.322	0.00*
	Species * Particle size * Mixing ratio	0.724	4	0.181	144.044	0.00*
	Error	0.045	36	0.001		
	Total	4.858	53			
Water absorption	Species	2.769	2	1.384	5.483	0.01*
	Particle size	0.073	1	0.073	0.291	0.59 ^{ns}
	Mixing ratio	19.189	2	9.595	38.002	0.00*
	Specie * Particle size	5.378	2	2.689	10.650	0.00*
	Specie * Mixing ratio	5.893	4	1.473	5.835	0.00*
	Particle size * Mixing ratio	1.089	2	0.544	2.156	0.13 ^{ns}
	Species* Particle size * Mixing ratio	8.402	4	2.101	8.320	0.00*
	Error	9.089	36	0.252		
	Total	50.972	53			
Volumetric change	Species	119.570	2	59.785	252.544	0.00*
	Particle size	10.912	1	10.912	46.095	0.00*
	Mixing ratio	45.733	2	22.866	96.592	0.00*
	Specie * Particle size	34.957	2	17.478	73.832	0.00*
	Specie * Mixing ratio	51.980	4	12.995	54.893	0.00*
	Particle size * Mixing ratio	96.886	2	48.443	204.632	0.00*
	Specie * Particle size * Mixing ratio	73.778	4	18.444	77.913	0.00*
	Error	8.522	36	.237		
	Total	444.624	53			

* = means significant, ns = no significant at 0.05

Variation of Mechanical Properties

Table 7 revealed that the tensile (MOR and MOE), all individual main effects (tree species, particle size, mixing ratio) and all of their two-way and three-way interactions were highly significant ($p < 0.01$). Tree species exhibited the highest influence on tensile strength. This could be attributed to inherent differences in density, cellular structure, and chemical composition (such as cellulose and lignin ratios) across different tree species reported by Jian *et al.* (2022). Furthermore, particle size significantly alters the surface area available for

interfacial adhesion with the polymer matrix. This implies that variations in particle sizes directly shift how stresses are transferred through the composite framework (Gulitah and Liew, 2019). The significance of the mixing ratio highlights how the volume fraction of the lignocellulosic filler dictates the continuous polymer matrix density, with higher filler loading generally improving structural stiffness (MOE) but risking brittle failure if inadequate matrix is present to encapsulate the fibers (Gulitah and Liew, 2019).

Similarly, all main effects of the flexural properties (tree species, particle size, mixing ratio) and their interactions significantly influenced tensile MOR and MOE ($p < 0.01$). While particle size remains a highly significant main effect for Flexural MOE ($F = 9041.716$, $p < 0.01$), it fails to achieve statistical significance as

an independent main effect for flexural MOR ($F = 0.084$, $p = 0.77$). This reveals that while the independent variation of particle size alters the bending stiffness (elastic deformation), it does not directly determine the ultimate bending strength (rupture point) on its own.

Table 7: Result of Analysis of Variance Conducted for Mechanical Properties

Variable	Source of variance	Type III Sum of Squares	df	Mean Square	F	Sig.
Tensile MOR	Species (S)	24250.803	2	12125.402	178.811	0.00*
	Particle size (P)	809.166	1	809.166	11.933	0.00*
	Mixing ratio (M)	2013.096	2	1006.548	14.843	0.00*
	Specie * Particle size	50493.414	2	25246.707	372.309	0.00*
	Specie * Mixing ratio	10618.834	4	2654.709	39.149	0.00*
	Particle size * Mixing ratio	2300.039	2	1150.020	16.959	0.00*
	S * P * M	21254.644	4	5313.661	78.360	0.00*
	Error	2441.202	36	67.811		
	Total	115900.461	53			
Tensile MOE	Species (S)	5.519E7	2	2.760E7	4876.782	0.00*
	Particle size (P)	1.581E7	1	1.581E7	2794.675	0.00*
	Mixing ratio (M)	3184396.343	2	1592198.172	281.384	0.00*
	Specie * Particle size	1.300E7	2	6500319.844	1148.782	0.00*
	Specie * Mixing ratio	7610186.533	4	1902546.633	336.231	0.00*
	Particle size * Mixing ratio	5817956.735	2	2908978.368	514.095	0.00*
	S * P * M	6895706.053	4	1723926.513	304.664	0.00*
	Error	203704.083	36	5658.447		
	Total	1.094E8	53			
Flexural MOR	Species (S)	8965.383	2	4482.691	234.243	0.00*
	Particle size (P)	1.610	1	1.610	0.084	0.77 ^{ns}
	Mixing ratio (M)	1731.944	2	865.972	45.251	0.00*
	Specie * Particle size	515.353	2	257.677	13.465	0.00*
	Specie * Mixing ratio	3478.413	4	869.603	45.441	0.00*
	Particle size * Mixing ratio	20.168	2	10.084	0.527	0.59 ^{ns}
	S * P * M	1024.393	4	256.098	13.382	0.00*
	Error	688.929	36	19.137		
	Total	16680.222	53			
Flexural MOE	Species (S)	3.492E7	2	1.746E7	204390.203	0.00*
	Particle size (P)	772419.807	1	772419.807	9041.716	0.00*
	Mixing ratio (M)	3205188.547	2	1602594.274	18759.490	0.00*
	Specie * Particle size	1508647.896	2	754323.948	8829.891	0.00*
	Specie * Mixing ratio	5994361.397	4	1498590.349	17542.051	0.00*
	Particle size * Mixing ratio	327484.045	2	163742.023	1916.715	0.00*
	S * P * M	566692.756	4	141673.189	1658.384	0.00*
	Error	3075.424	36	85.428		
	Total	4.765E7	53			

* = means significant, ns = no significant at 0.01

CONCLUSION

This study assessed the influence of wood–plastic mixing ratio and wood particle size on the physical and mechanical properties of wood–plastic composite (WPC) boards produced from selected hardwood species. The results clearly show that variations in WPC formulation parameters exert a stronger influence on board performance than wood species alone, confirming the central objective of the study. The wood–plastic ratio significantly affected all measured properties. Boards produced at a 50:50 ratio exhibited the highest density and lowest volumetric change, indicating superior dimensional stability. In contrast, the 60:40 ratio resulted in the lowest water absorption, reflecting the increased influence of plastic in limiting moisture uptake. The 40:60 ratio consistently produced the highest tensile and flexural modulus of rupture, demonstrating that higher plastic content enhances load-bearing capacity and strength characteristics of WPC boards. Wood particle size also influenced composite performance. Boards manufactured with 1.00 mm particles achieved higher density due to improved packing efficiency, while 2.00 mm particles enhanced stiffness, as evidenced by higher tensile and flexural modulus of elasticity values and reduced volumetric change. This indicates that particle size selection plays a critical role in balancing density, dimensional stability, and mechanical stiffness.

Overall, the interaction between wood–plastic ratio and particle size governed the observed trends in physical and mechanical properties. The properties obtained in this study fall within acceptable ranges for several wood-based applications, particularly for non-structural construction elements and interior products. The findings demonstrate that recycled polyethylene plastic combined with locally available hardwood sawdust

can be effectively utilized for WPC production, thereby reducing dependence on solid wood resources and contributing to sustainable waste management and material utilization. The physical (density, water absorption, volumetric change), tensile, and flexural properties of the fabricated composites are not dictated by individual factors alone, but are dynamically driven by a highly significant interaction between tree species anatomy, particle size distribution and the precise mixing ratio.

RECOMMENDATIONS

Manufacturers should utilize a 50:50 or 40:60 wood-to-plastic formulation with a 2.00 mm particle size for applications requiring high structural rigidity and load-bearing capacity. This is to ensure maximum encapsulation and efficient stress transfer across the composite matrix. To manufacture high-density, dimensionally stable, and structurally sound composites, producers must avoid an additive approach and instead optimize the specific blending ratio to ensure adequate binder encapsulation based on the unique anatomical density of the chosen biomass species and its screened particle surface area.

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