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Fabrication and Characterization of Wood Fiber Reinforced Polymer Composites

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ORIGINAL STUDY

Fabrication and Characterization of Wood Fiber Reinforced Polymer Composites

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Abstract

Wood-polymer composites (WPCs) combine the properties of wood and polymers. Creating composites involves adding plant or wood fibers as fillers to a polymer matrix. This study used mahogany and mango wood sawdust as reinforcement materials, while high-density polyethylene (HDPE) and polyvinyl chloride (PVC) were used as matrices. The investigated data in this study comprises four different (10, 20, 30, and 40) weight percentages (wt%) of mahogany and mango sawdust paired with corresponding wt% (90, 80, 70, and60) of HDPE and PVC matrices. The extrusion method produced composites with different amounts of sawdust and polymer matrices. Wood polymer composites were characterized by examining their mechanical properties, and scanning electron microscopy (SEM) was employed to analyze their morphology. The results showed that the maximum tensile strength was obtained from the 20% for both sawdust composites. The ultimate tensile strength was recorded at 15.28 MPa for Mahogany sawdust-HDPE (Mh-HDPE) composite, whereas the Mahogany sawdust-PVC (Mh-PVC) exhibited the lowest tensile strength at 2.38 MPa. In addition, HDPE-based composite shows higher tensile strength (11.56 MPa) with Mango sawdust than PVC-based composites (2.28 MPa). Tensile strength, and impact strength of the fabricated composites were also assessed by ASTM standards. The maximum impact strength was obtained at 10wt% of sawdust for all four composites investigated in this study. It was also observed that impact strength significantly decreased with the increase of fiber percentage in the composite. These results demonstrated the highest mechanical properties of the Mh-HDPE than the other composites, which SEM further investigated. The morphological analyses confirmed uniform mixing of sawdust and polymer matrices, evident by the absence of no pores, cavities, or voids in the prepared composites.

Keywords: Wood polymer composite, HDPE, Mechanical properties, Extrution process

1. Introduction

Polymeric materials are broadly used in chemical industries, medical and construction sectors due to their ease of fabrication, lightweight, and exceptional resistance to corrosion and weathering [1–3]. However, the continued growth of plastic pollution has become one of the most concerning issues worldwide. Most plastic polymers are non-biodegradable and persist in the environment for centuries. Furthermore, pure plastic materials often possess low impact strength, hardness, and low dimensional stability [4,5]. In contrast, wood is one of the ancient environmentally friendly construction materials with high impact strength, hardness, and mechanical properties [6,7]. However, they are susceptible to cracking, warping, and degradation by biological and weathering factors [8]. This restricts some specific exterior applications of pure wood-based materials.

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To mitigate these limitations, wood-polymer composites (WPCs) are suggested, which combine the properties of wood and polymers. WPC is historically a broad term that includes all wood-containing composites in a thermoset or a thermoplastic matrix. These composites are made by adding wood or plant fibers as filler in a polymer matrix and then pressing or molding at high temperatures and pressure. Incorporating wood-based fillers (e.g., fibers, veneer, lumber, or particles) into the polymeric matrix improves the strength, durability, weather resistance, flexural, and other mechanical properties of the resulting composites8. Furthermore, the degradability of the material by weathering and biological factors can also be modulated. Some additives such as coupling agents [9], blowing agents [10], foaming agents [11], reinforcing agents [12], lubricants [13], stabilizers [14], and colorants are used to tailor various physical and mechanical properties of the composites according to the target area of application. WPCs have become a world-class polymer developing over the past few decades because of their high-performance application and market demand [15]. While the other composites materials require complex handling processes with high production costs, production of WPC is straightforward and inexpensive [16].

The first WPC was synthesized about a century ago when the phenol-formaldehyde resin was used as the matrix of wood floors [17]. That composite was used as a gearshift knob for automobiles. Another earlier study of the 1950s" addressed the fabrication of WPCs by incorporating wood sawdust in thermoplastic resin by extrusion method [18]. Since then, several research efforts have been introduced by researchers to test and improve the mechanical properties of various WPCs. Among different thermosetting and thermoplastic polymers, polyethylene (PE), polypropylene (PP), and poly-(vinyl chloride) (PVC) are broadly used, and at present, they are widespread in furniture, construction, and automobile products [19]. The reason of using HDPE and PVC to fabricate a WPC is well investigated in elsewhere [40,44]. In addition, HDPE is a semi-crystalline polymeric material with both crystalline and amorphous phases which elevate its hardness and high temperature resistance (>120 °C) [40,45]. Ge et al. [20] recently studied the mechanical and thermal properties of fresh and decayed wood flour/PVC composites as part of the current research trends. The effects of aging of the filler wood materials, adding preservatives (chitosan) and activated carbon were studied. Zhang et al. [21] examined the effects of reinforcing fiber types and their amounts on the impact strength, tensile strength, ad flexural properties of poplar wood flour/HDPE composites. Carvalho et al. [22] investigated the effect of the HDPE matrix'smatrix's melt flow index (MFI) on the impact strength and tensile and flexural properties of waste fiberboard-derived wood/HDPE composites. In another study, Gama et al. [23] evaluated the mechanical properties of crude glycerol-treated eucalyptus wood/HDPE composites. The surface treatment of wood fibers improved their surface morphology and, consequently, the tensile strength and rigidity of the WPCs. To choose Mahogany and Mango sawdust as a reinforce materials are three folds i) extensive availability in Bangladesh and cheap in price, ii) high carbon content (60% and 57% cellulose in Mahogany and Mango Saw dust, respectively) [38,39], and hardness properties of those two sawdust is widely investigated elsewhere [37]. Koffi et al. [24] reported the effect of a fabrication method of WPCs on the mechanical properties of birch fiber/HDPE composites. The elastic modulus and tensile strength of the end product obtained by compression molding were proved superior compared to the effects of the injection molding process in that study.

In addition to the fabrication process, there are several other factors that may influence the mechanical properties of the composites, such as particle size of the filler [25], molecular weight and functionality of the coupling agents [26], binding agents [27] etc. It is broadly accepted that the percentage of fillers and matrix elements significantly affect the strength, stiffness, fracture behavior and flexural properties of the composites. A study from Sombatsompop group [28] revealed that, the hardness, impact and tensile strength of wood sawdust/PVC composites are significantly varied upon the variation of sawdust content in the WPCs. Rozman et al. [29] found that, the tensile, impact and flexural properties of rice husk/polyester composites decreased with the increase of filler content. Most recently, Redhwi et al. [30] have shown that, the tensile strength and elastic modulus of Fir wood fiber/HDPE and PP composites increases apparently with the increasing percentage of HDPE and PP content (from 0 to 36 wt%).

So, WPCs can be synthesized using different wood fibers and polymeric matrix compositions; their mechanical properties depend on their constituents, design, fabrication process, and other additives. Several scientific works have been reported to date describing the synthesis and characterization of different compositional WPCs. Among them, some prominent mechanical properties have been obtained from the mango wood and mahogany wood-based WPCs, where they were combined with monomers and polymers such as polypropylene [31–34], styrene, acrylamide [35], etc. Recently, Arthur et al. [36] studied the mechanical properties of mahogany wood fiber/PVC composites. However, to the best of the authors' knowledge, there is no such comparative study in the literature where the combination of mahogany sawdust, mango wood sawdust, PVC, and HDPE has been investigated to synthesize WPCs.

In this study, we have prepared WPCs using mahogany (*Swietenia mahagoni*) and mango (*Mangifera indica*) wood sawdust as filler and HDPE and PVC as polymer matrices. Several suggested sawdust formulations were proposed, and extrusion compounding and compression molding in a hot press were used to create the composite samples. The different mechanical properties (tensile strength, impact strength, maximum load capacity, elongation, and elastic modulus) of four different types of samples labeled Mh-HDPE (made of mahogany wood sawdust and HDPE polymer matrix), Mg-HDPE (made of mango wood sawdust and HDPE polymer matrix), Mh-PVC (made of mahogany wood sawdust and PVC polymer matrix), and Mg-PVC (made of mango wood sawdust These composites were tested to quantify the material's performance according to the standard methods outlined in American Standard Testing and Materials (ASTM). For the comparative study, several WPC samples of HDPE and PVC polymers were made using similar formulations. The mechanical properties, dimensional stability, and interface bonding properties were assessed based on the composite formulations.

2. Materials and methods

2.1. Materials

The HDPE with a melt flow index of 0.50 g/8 min (measured according to ASTM D 1238) and a density of 0.950 g/cc was purchased from Chevron Phillips Chemical Company LP, Al Jubail, Kingdom of Saudi Arabia (Fig. 1a). Sony Plastic Complex in Dhaka, Bangladesh, supplied the PVC (Fig. 1b). The sawdust of mahogany and mango tree with mesh no. of 14 was collected from the sawmill in Katakhali, Rajshahi (Fig. 1c-d).

2.2. Methods: screening of sawdust and moisture removal

The sawdust sample was first screened using the USA standard testing sieve (no. 16) with a mesh number of 14 to ensure a uniform particle size. Afterward, the piece was placed in a hot air oven (model #DSO-300D) at 105 °C for 5 h to ensure that there was no moisture present.

*Fig. 1. Raw materials used for the preparation of composite materials **(a)** HDPE pellets **(b)** PVC pellets **(c)** Mahogany wood sawdust, and **(d)** Mango wood sawdust.*

2.3. Extrusion process

An electrically operated extrusion machine with a customized three-coil extruder was used to accomplish the extrusion of the composite sample. In the first step, each composite sample was slowly poured into the extruder's hopper in a modest amount to avoid any spillage. The model subsequently came into contact with the revolving shaft of the extruder, which resulted in the polymer and fiber content being mixed. The three-heating coil is supplied with heat to facilitate mixing and is located on the top of the shaft. The temperature of the coils is maintained in the range of 100–250 °C, depending on the composite sample. The motor (7.50HP, 1450 rpm) maintained the shaft speed, which helped to squeeze out the mixture through a nozzle. A uniform nozzle pressure of 150 bar was maintained during the squeezing out the composite mixture. In the subsequent step of the extrusion process, prepared composites were discharged by the extruder's nozzle, taken into a mold, and then cooled into water. The mold size was 7cm × 4cm × 1 cm, polished with excellent emery paper to remove dirt and maintain its proper shape and size. A schematic diagram of the extrusion process has been provided in Fig. 2.

3. Heating and cooling process

The heating process was accomplished using a batch-type Weber-Pressen Hydraulic Press machine.

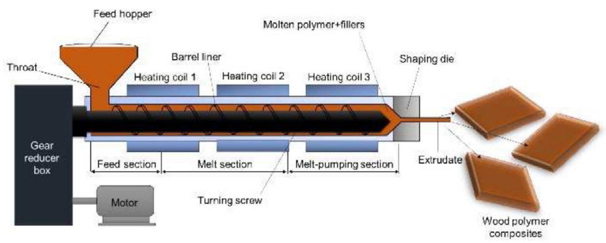

Fig. 2. Schematic diagram of the extrusion process for the synthesis of WPCs.

The pressure gauge range of the hot press machine was 1000Kg/cm2 with a plate heating capacity of 30 °C–600 °C. At first, the sawdust and the polymer were thoroughly mixed to ensure a uniform mixture, and then the prepared mold in the extrusion process was filled with the mixture. The sample was then placed on the heating plates and melted. The molten composites were placed under desired pressure in the hot press machine for shaping. After completing the shaping, the sample was cooled using a cooling system, and the composite was separated from the mold. The temperature was set higher than the matrix's boiling point. A specific size of hot-pressed samples was required for a tensile and impact strength test with the UTM machine. To achieve this, the hot press machine cut 15 cm × 3 cm x 1.5 cm composites. A summary diagram of the composite preparation is given in Fig. 3.

3.1. Tensile strength test

The tensile test was performed using the universal testing machine (UTM). The Hounsfield UTM (H5OKS) device was used to evaluate the samples' tensile and flexural properties, compression shear, and other mechanical and physical properties. The specimen dimensions were 15 cm long, width of 1.5 cm, and 0.2 cm thick. Tensile strength test was carried out according to the American Society for Testing and materials (ASTM-D3379) standards. Tensile strength test was performed on the five different set of samples for ensuring accurate results. The standard deviations of the five experimental runs were recorded ±1.02N.

3.2. Impact strength test

Impact testing gives information about the objects' capacity to withstand the maximum load, and it is commonly used to determine the service life of a part or material. A pendulum impact tester (Hung Ta, model no. 7408) was employed to evaluate the impact properties of the samples. Impact strength test was carried out according to the ASTM-D3410 standards for ensuring the reproducibility and credibility of the results as well as the quality of the fabricated composites. All experiments were performed on five sets of specimens with a standard deviation of ±0.5N.

3.3. Morphological observation

The microstructure of the fractured surface of specimens tested in tensile is examined using a scanning electron microscope (Model No. Evo 18, Company Curl Zeiss). Samples containing 20 wt% sawdust content and 80 wt% polymer matrices were taken for morphological study.

4. Result and discussion

4.1. Tensile strength test

The universal testing machine was used to conduct the tensile test to determine the tensile strength of each sample of the polymer sawdust mixture. Tensile strength measurements were made on specimens, and the mean value for each sample served as the basis for the results.

The tensile strength of composites made of Mh-HDPE, Mh-PVC, Mg-HDPE, and Mg-PVC at various fiber-matrix compositions is shown in Fig. 4. It was observed that the tensile properties of composites decreased with an increase in sawdust content (Fig. 4a). The highest tensile strength, 15.28 MPa, was recorded for Mh-HDPE composites containing 20wt % sawdust. A similar trend was noticed for the Mh-PVC composites with a comparatively lower tensile strength (2.4 MPa) than Mh-HDPE. The maximum tensile strength was obtained from Mh-PVC composites when the fiber content mixture was at 20 wt%. However, the tensile properties of Mh-PVC

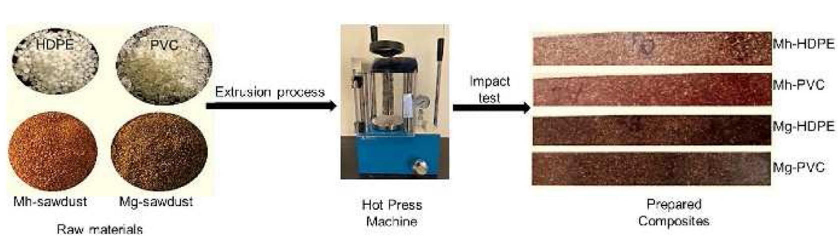

Fig. 3. Overall summary diagram of the fabrication process of WPCs.

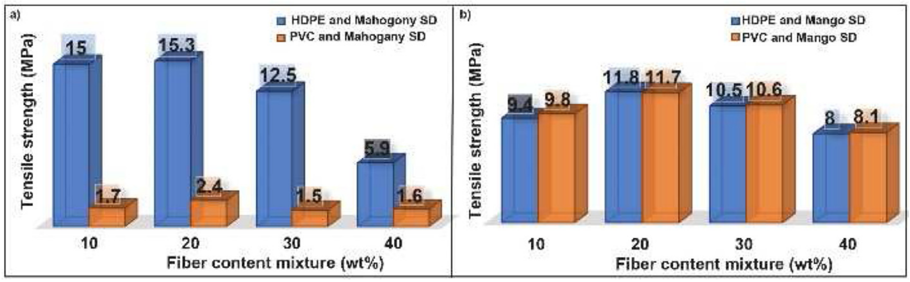

Fig. 4. Effect of reinforcement fiber loading on the tensile strength of ***a)*** *Mahogany wood sawdust,* ***b)*** *Mango sawdust composites, respectively.*

composites were much lower than the Mh-HDPE composites at any fiber-matrix composition, as reported in Table 1. The tensile strength values for sawdust composites with fiber loadings of 30 wt% and 40 wt% decreased significantly.

The Mg-HDPE and Mg-PVC types of mango wood-based composites showed the highest tensile strength at a 20wt% wood fiber composition (Fig. 4b). The tensile strengths of the Mg-HDPE and Mg-PVC composites with 10wt% fiber content were lower, coming in at 9.46 MPa and 1.61 MPa, respectively. For the composition of 20wt% sawdust content, the corresponding samples attained their maximum tensile strength with a value of 11.56 and 2.28 MPa, respectively. Further, an increase in the percentage of fiber loading to 30wt% and 40wt% caused a gradual reduction of the tensile strength of the composites (Fig. 4b).

The highest tensile strength was recorded in composites containing 20wt% sawdust in each composite type, as depicted in Fig. 4. This behavior can be primarily attributed to the reinforcing effect imparted by the sawdust, which allowed a uniform stress distribution from a continuous polymer matrix to a dispersed reinforcing phase. This result is bolstered by the investigations has been done by the Ayyanar et al. (2023) research group where they used Norfolk pine tree leaf as reinforcement materials [40]. This study [40] found 30wt% of the reinforced material has shown the highest tensile strength where they investigated 10-50wt% of reinforced materials with the HDPE polymer. Another study of the same research group shows that the increasing polymer content than the reinforced materials displayed higher tensile strength where they used Poly lactic acid/zeolite/hydroxyapatite composites [41]. However, a significantly lower tensile strength was obtained in the case of a 10wt% sawdust composite. This result indicates the transfer failure of the applied force from the matrix to reinforcement (sawdust) due to inadequate interfacial adhesion. This phenomenon likely occurs because the sawdust starts reinforcing the matrix at a particular sawdust loading. At 20wt% sawdust, there is a reinforcing effect observed in this study.

In contrast, 10wt% sawdust may not be sufficient to reinforce the strength of the matrix, and insufficient stress transfer might have led to a reduction in strength. Additionally, it consistently recorded reduced tensile strength in the case of 30wt% and at 40wt% of fiber content. The potential reason for this result could be the hydrophilic nature of the sawdust materials. The nature of sawdust is hydrophilic, whereas the polymer used in this study is hydrophobic 37. Hence, chemical bond formation between the sawdust and polymer matrices is less. This may be another reason which caused the gradual decrease of composite tensile strength with the increase of fiber content from the optimum composition. The tensile stress–strain curves for four different types of composites at 20wt% are displayed in Fig. 5a-d.

Figure 5 shows the tensile stress–strain curves for 20wt% sawdust of Mh-HDPE, Mh-PVC, Mg-HDPE, and Mg-PVC composites, respectively. Each of the curves comprises two regions, including elastic and plastic areas. The initial region (up to the peak point) typically represents the elastic region, and the later part (peak to the end) indicates the plastic region of the curve. Similar stress vs. strain was recorded for 10wt %, 30wt%, and 40wt% (not shown) sawdust

Table 1. Tabular comparison of the mechanical characteristics of several composites with a sample of 20wt% sawdust and 80wt% polymer matrix. These are the mean average values of four models for each composite.

Polymer type	Sawdust type	Tensile strength (MPa)	Elongation (%)	Elastic modulus (MPa)	Max. load (N)	Break (mm)
HDPE	Mh	15.28	24.31	391.65	235.7	4.31
	Mg	11.55	17.75	385.2	241.9	3.13
PVC	Mh	2.38	135.0	7.14	86.8	26.90
	Mg	2.48	399.9	1.47	93.9	87.9

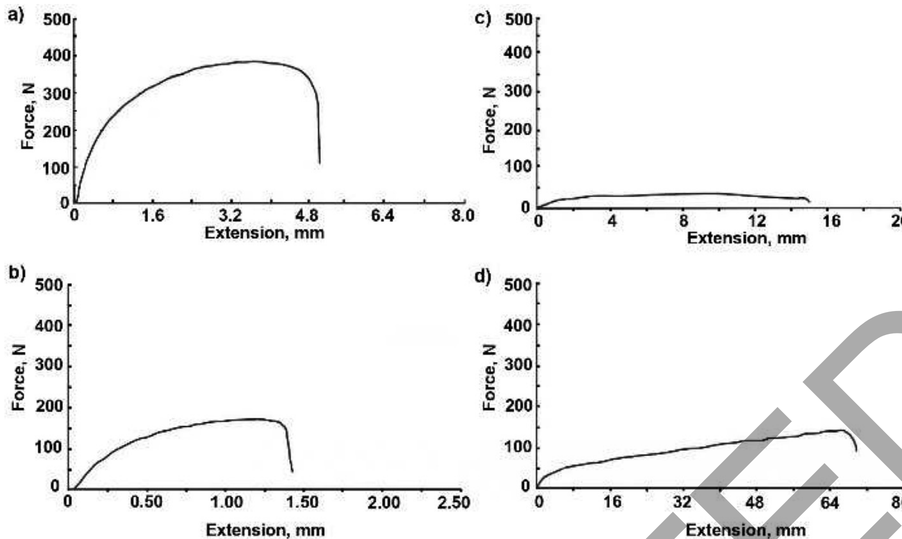

*Fig. 5. The graphical representation of tensile stress vs strain curve of 20wt% of **a)** Mh-HDPE, **b)** Mg-HDPE, **c)** Mg-PVC, and **d)** Mh-PVC composites.*

composites. We recorded an identical stress vs. strain trend where stress increased proportionally with strain in all sixteen trials for all earlier mentioned wt% (10, 20, 30, and 40) of sawdust composites. After reaching the maximum stress value, the curve fell in the plastic region. It is worth mentioning that 20wt% sawdust composites show the highest tensile properties compared to the other percentages of sawdust composites. The result indicates that Mh-composites show higher elongation (Fig. 5a and d) than the Mg-composites (Figs. 5b and c). Therefore, the Mh-PVC shows higher tensile properties than other composites, as shown in Fig. 5d. An overall summary of different mechanical properties of each preprepared composite is reported in Table 1.

4.2. Impact strength test

Impact strength exhumes the ability of a material to capture energy until its fractures under a high-speed collision. The impact strength test result obtained from the pendulum impact tester is reported in Table 2. The results showed that impact strength was maximum in the composition of the 10wt% sawdust composites, with the highest polymer percentage (90%). In the case of fiber loadings of 20wt %, 30wt%, and 40 wt% sawdust composites, impact strength gradually decreased. This result indicates that the impact strength of the composite largely depends on the polymer percentage, where composites with HDPE show the highest impact strength in both cases. A possible reason could be the increasing porosity and roughness inside the composite structure with an increase in sawdust [42,43]. In a critical review of wood-based polymer composites, Ramesh et al. [37] revealed that the impact strength of WPC increases with increasing fiber content percentage up to a certain percentage of the reinforce material (~30wt%), with this phenomenon being more pronounced in the case of hardwoods like mahogany and mango wood. It is also noticed that the Mh-HDPE shows the maximum impact strength among all other composites, which indicates this specific type of composite could be the most hardened and stable compared to other composites.

4.3. Morphological observation

SEM was performed on a scale of 20 μm and at two special magnifications, including 500× and 100KX, for the morphological investigation of prepared composites, as shown in Fig. 6. In this study, samples comprised of 20wt% sawdust polymer matrix were

Table 2. Effect of percentage composition of polymers and wood fiber on the impact strength of composites.

Polymer (%)	Fiber content (%)	Impact strength (kg/cm^2)			
		Mh-HDPE	Mh-PVC	Mg-HDPE	Mg-PVC
90	10	12.962	10.881	8.088	6.891
80	20	5.231	8.093	5.672	5.803
70	30	4.502	5.830	4.971	4.607
60	40	3.880	4.607	4.804	3.788

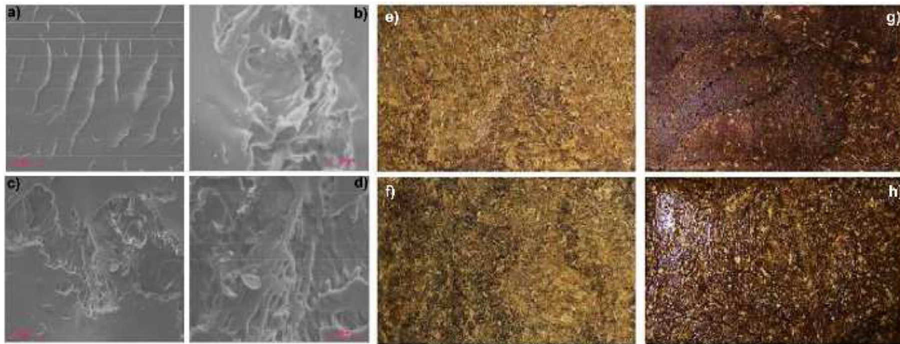

*Fig. 6. The SEM micrographs of tensile fractured surface at 20wt% of fiber content — **a)** Mg-HDPE at 500× magnification, **b)** Mg-HDPE at 100KX magnification, **c)** Mh-PVC at 500× magnification, and **d)** Mh-PVC at 100KX magnification on the scale of 20 μm. Textural view of the synthesized e) Mh-HDPE, f) Mh-PVC, g) Mg-HDPE and h) Mg-PVC composites with naked eye.*

analyzed using SEM based on the results of previous experiments. SEM micrographs were used to investigate composite materials' microstructure and physical and mechanical properties. From the SEM image, it was evident that the qualities of every reinforced plastic containing fiber particles rely on the type of reinforcing material, the arrangement of the particles, and how the particles are connected to the polymeric phase. The morphology of the tensile fractured surface of the Mg-HDPE and Mh-PVC composites at 20wt% fiber contents is illustrated in Fig. 6a–b and 6c–d, respectively.

Figure 6 displayed that the sawdust was embedded in the matrix without a discernible gap in the interfacial area. In addition, the surfaces of both composites were enclosed with polymer matrices. It is also noticed that the interfaces between sawdust and polymer are well bonded (marked spots in Fig. 6), confirming the composites' tensile solid characteristics. Strong adhesion at the interface between fiber and matrix polymer improved their mechanical properties. The absence of holes, cavities, and voids in composites, as detected by SEM, also suggests their high elongation rate and load capacity. This result is more pronounced in Mh-PVC (Fig. 6d) composites than in Mg-HDPE (Fig. 6b). The potential reason could be that the Mh-sawdust mixed more uniformly into the polymer matrices than the Mg-sawdust. Consequently, it was observed that matrix and reinforcement composites with strong adhesion led to important congenital properties with multifunctional textures. The "naked-eye" textural view of the prepared composites is shown in Fig. 6e-h.

5. Conclusion

The four categories of WPCs based on mahogany and mango sawdust have been fabricated and characterized. Sawdust was used as reinforced materials, whereas HDPE and PVC were used as polymer matrices. Composites were prepared using different weight percentages of sawdust and polymer with a percentage range of 10–40wt% with an increment of 10wt%. Extrusion molding and hot press techniques were used for composite fabrication. The study successfully developed a new class of polymer-based composites using mahogany and mango sawdust. The weight percentage of sawdust significantly influenced the mechanical properties of the composites, including tensile strength, load-bearing capacity, and impact strength. Results showed that composites with 20wt% sawdust had the highest tensile strength, while those with 10wt% sawdust exhibited the maximum impact strength. The morphological study demonstrated a uniform distribution of matrix reinforcement without any voids, cavities, or pores in the composites. The prepared composites can be used for household furniture, decking, flooring, lightweight car components, sports equipment, and small industrial applications.

Overall, wood polymer composites are rapidly evolving green materials with numerous advantages, such as production flexibility and recycled materials. This study can be further extended by using a variety of polymer plastics and examining their impact and tensile strength, particularly for residential decking, outdoor floors, railing, park benches, fences, landscaping timbers, cladding, and siding, and are expected to be utilized for a more comprehensive array of applications in the future.

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