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Research Article

Characterization of Physical and Mechanical Properties, and Morphology of Wood Composites Derived from Milk Bottles and Teak Sawdust Powder

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ABSTRACT

This study aims to develop recycled high-density polyethylene (rHDPE) composites reinforced with teak sawdust (TS) and evaluate their mechanical properties to determine the optimal composition for furniture applications. The composites were fabricated through internal mixing followed by compression molding, utilizing maleic anhydride (MA) as a coupling agent to enhance interfacial adhesion between TS and the rHDPE matrix. While this improves impact strength, it simultaneously reduces the overall strength of the composite. The results revealed that incorporating TS significantly enhanced the mechanical properties of the composite. At 50 wt%, TS increased the tensile modulus by 120.79% and Shore D hardness by 10.65% compared to pure rHDPE, while the maximum improvement in flexural strength (15.29%) was observed at 30 wt%. Conversely, higher TS content led to an increase in the composite's density and water absorption while reducing its impact strength. Despite this trade-off, the enhanced stiffness, strength, and cost-effectiveness make these composites promising for sustainable, low-cost furniture applications. A cost analysis revealed that the production cost of these composites is approximately 191 THB/m^2, significantly lower than that of conventional wood-plastic composites (WPCs), which range from 400 to 800 THB/m^2. This study lies in utilizing TS, an underutilized wood waste, as a reinforcing agent for rHDPE derived from recycled milk bottles. This approach not only improves the mechanical performance of rHDPE but also promotes a circular economy by repurposing two types of waste materials into functional composite materials.

1. Introduction

Currently, the consumption of ready-to-drink milk products is on the rise, leading to a significant increase in the use of plastic packaging, particularly in the form of milk bottles. This surge in plastic waste presents a critical environmental issue, as plastic does not decompose naturally in a short time [1]. Consequently, conventional disposal methods, such as incineration or landfilling, contribute to pollution, including the release of greenhouse

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gases and the intensification of global warming [2]. Milk bottles are typically made from high-density polyethylene (HDPE), a commonly used thermoplastic. Recycling used packaging into new products can help mitigate environmental impacts and promote sustainability in the dairy industry. According to the African Development Bank, recycling 50% of Nigeria's plastic waste could save up to 2.4 million barrels of crude oil and significantly reduce greenhouse gas emissions, highlighting the potential benefits of plastic waste recycling [3]. Additionally, HDPE is widely produced by major manufacturers in Thailand [4]. This widespread availability makes HDPE recycling a viable approach for reducing plastic waste while supporting a circular economy. Previous studies have demonstrated that recycled high-density polyethylene (rHDPE) can retain or even enhance its material properties when processed appropriately. For instance, D.A. Tolcha and D.E. Woldemichael [5] found that using short glass fibers as a reinforcing agent significantly enhanced the mechanical properties of blends of rHDPE with recycled polyethylene terephthalate (rPET) compared to virgin rHDPE. Similarly, A.N. Gaduan et al. [6] reported that rHDPE blended with virgin HDPE (vHDPE) at different ratios exhibited no significant differences in melt rheology and tensile strength when compared to vHDPE. In addition, studies have shown that HDPE can be remelted and processed through extrusion up to 10 times without significantly reducing its melt viscosity or tensile strength [7, 8], demonstrating its durability and recyclability. These findings highlight the potential of rHDPE to reduce plastic waste while maintaining performance in various applications.

Although rHDPE is recyclable, using 100% rHDPE remains challenging due to its reduced mechanical performance compared to virgin HDPE. This limitation can lead to reduced durability and performance in many applications. Therefore, rHDPE is often blended or reinforced with other materials to form composite materials that enhance its properties and make it suitable for various applications. One practical approach is to create composite materials by incorporating natural fibers or other sustainable reinforcements [9], which can improve both the mechanical and thermal properties of rHDPE. The use of natural resources, such as plant fibers or agricultural byproducts, as reinforcing agents has gained popularity due to their renewability, biodegradability, and potential to reduce environmental impact [10]. By incorporating these natural reinforcements, the resulting composites offer a sustainable, high-performance alternative that supports waste reduction and promotes the circular economy.

Teak sawdust (TS), a byproduct of sawmills and furniture factories, is generated in large quantities, posing challenges in its disposal due to its volume and the environmental impact of waste management. Improper disposal methods, such as burning or landfilling, can lead to air pollution, resource wastage, and harmful effects on ecosystems. To address these issues, recent studies have explored the potential of utilizing wood sawdust in various applications. For example, it has been investigated as an alternative fuel due to its high energy content, making it suitable for biomass energy production [11]. Additionally, wood sawdust has been utilized in the development of eco-friendly composite materials, serving as a natural reinforcement in polymers to enhance their mechanical properties. H. Jaya et al. [12] demonstrated that incorporating wood sawdust into unsaturated polyester (UP) enhanced the mechanical properties, with further improvements observed as sawdust content increased. Similarly, E. Ferede [13] found that using wood sawdust as reinforcement with polypropylene improved mechanical properties, with the best performance achieved at a sawdust content of up to 40%, after which the properties began to decline. Furthermore, S. Murugapoopathi et al. [14] discovered that wood sawdust reinforced both vHDPE and low-density polyethylene (LDPE) polymers, with HDPE composites showing superior mechanical properties compared to LDPE composites. At an 80% HDPE and 20% sawdust ratio, the tensile strength of the composite showed a notable increase. However, the use of sawdust may increase water absorption due to its natural cellulose and hemicellulose content, which are polar substances that absorb water. A study by A. Kuzmin et al. [15] demonstrated that HDPE/barley straw composites exhibited water absorption of less than 12%, with a gradual increase over time, but this does not pose significant issues for most applications. Compared to solid wood, which tends to absorb higher amounts of water, sawdust-based composites show comparable or even lower water absorption rates. For example, A. Rani et al. [16] found that teak wood had 50% water absorption within 20 hrs, whereas composites made from natural fibers like sawdust absorbed considerably less water, making them suitable for furniture applications without being significantly affected by water absorption.

This study investigated the preparation of composites from recycled milk bottles and teak sawdust powder, examining the impact of teak sawdust content on the mechanical properties of the composites. These wood-plastic composite materials were developed to help mitigate

environmental issues caused by waste, offering an alternative solution for repurposing plastic waste into functional materials, such as plastic wood.

2. Materials and Methods

2.1. Materials

Recycled high-density polyethylene plastic was sourced from Dutch mill milk bottles. The rHDPE was washed to remove impurities and dried at 50°C for 24 hrs. Teak sawdust, a byproduct from Siam Furniture Ltd. in Pathum Thani province, Thailand, was sieved using a stainless-steel sieve to obtain particles smaller than 300 µm. Figure 1 illustrates the morphology and dispersion of the obtained TS from SEM and the Image J program, respectively. The average diameter and length of TS were 31.74 ± 12.71 µm and 88.59 ± 45.26 µm, respectively. Maleic anhydride (MA) in an analytical grade (99%, ACROS) was used as a coupling agent.

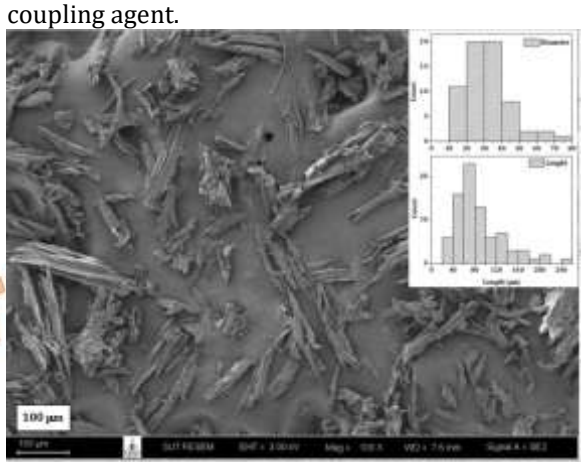

Fig. 1. The morphology and dispersion of the obtained TS from SEM and the Image J program

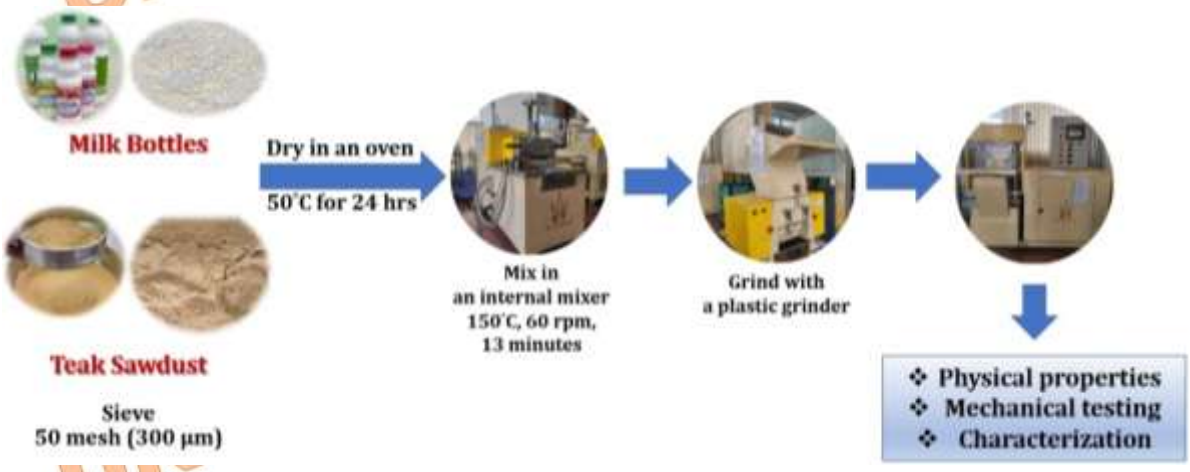

Fig. 2. Fabrication process of rHDPE:TS: MA composites

2.2. Composite Preparation

During the mixing process, the rHDPE:TS: MA composites were combined in an internal mixer (MX500–D75L90, Chareon Tut Co., Ltd., Thailand) at 150°C with a rotor speed of 60 rpm for 13 minutes. After thorough mixing, the composites were ground into small pieces using a plastic grinder. The weight ratios of rHDPE:TS: MA composites were 100:0:0, 97:0:3, 67:30:3, 57:40:3, and 47:50:3. The amount of 3% by weight of MA was fixed according to the previous study [17]. The schematic fabrication process is shown in Fig. 2.

2.3. Sample Preparation

The composites were formed using a stainless-steel mold under hot-compression molding (PR2D-W300L350 PM-WCL-HMI, Chareon Tut Co., Ltd., Thailand) at 150˚C. The process involved preheating for 5 minutes, pressing for 5 minutes, and cooling for 3 minutes. An example of rHDPE:TS: MA composites is shown in Fig. 3. The rHDPE:TS: MA composites with compositions of 100:0:0 and 97:0:3 appeared white, while the other composites exhibited a brown color.

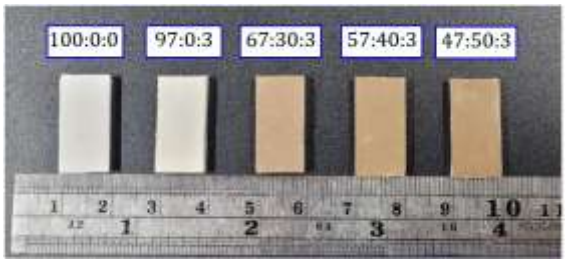

Fig. 3. Sample of rHDPE:TS: MA composites

2.4. Sample Analysis

The density of composites was measured using the Archimedes method [18] and calculated according to Equation (1). In this process, the sample was first weighed in the air (W_1) and then submerged in ethanol to measure its weight in the ethanol (W_2). The density of ethanol, used in this measurement, was taken as 0.789 g/cm^3.

$$\rho = \frac{W_1}{W_1 - W_2} \times 0.789 \quad (1)$$

The water absorption (*W.A.*) of composites was explored and calculated using Equation (2). The sample sizes of 20 mm × 10 mm × 3 mm in a period at 2, 4, 6, 12, and 24 hrs were investigated. The sample was dried at 50˚C for 24 hrs and weighed (W_i). After soaking in deionized water for each interval time, the sample was taped with the towel tissue and weighed (W_f). Each ratio used at least five samples.

$$W.A.(\%) = \frac{W_f - W_i}{W_i} \times 100 \quad (2)$$

The functional groups of all composites were investigated using the FT-IR technique, specifically with the Bruker Tensor 27 model, in transmittance mode with a wavenumber range of 4000 – 400 cm^{-1}.

2.5. Mechanical Testing

The composite hardness was conducted according to ASTM D2240 using a durometer (GS-612, TECLOCK Co., Ltd., Nagano, Japan). Five positions were explored for Shore D hardness.

The three-point bending test was investigated along with ASTM D790 using a universal testing machine (LS Plus Series, Lloyd Instruments, West Sussex, UK). The support span of 48 mm and a crosshead speed of 1.28 mm/min were used. At least five specimens were evaluated.

A tensile test was conducted according to ASTM D638 using a universal testing machine (LS Plus Series, Lloyd Instruments, West Sussex, UK). The conducting speed of 50 mm/min was used at room temperature. Quantities were taken from five specimens for each sample.

For the notched Izod impact test, at least five specimens were evaluated using an impact tester (Ceast 9050, INSTRON) according to ASTM D256. The number of samples was at least five specimens.

2.6. Morphology

The morphology of the impact-fractured surface of the rHDPE:TS: MA composite was investigated by the field emission scanning electron microscopy technique (FESEM, Zeiss, AURIGA FE-SEM/FIB/EDX). The specimens were coated with gold prior to analysis.

3. Results and Discussion

3.1. Physical Properties

The density of wood-plastic composites is a crucial property because it directly affects their mechanical performance, including strength and stiffness. Figure 4 illustrates the density of rHDPE:TS: MA composites, showing that an increase in TS content results in a corresponding increase in density. The highest density, 1.195 ± 0.001 g/cm^3, was achieved with 50 phr of TS, representing a 17.6% increase compared to unfilled rHDPE. This trend is consistent with the study by K. Bhaskar et al. [19], which demonstrated that increasing sawdust content in PP/HDPE blends also resulted in higher composite densities. The denser structure arises from the incorporation of wood particles, which are generally denser than polymers, thus increasing the overall composite density.

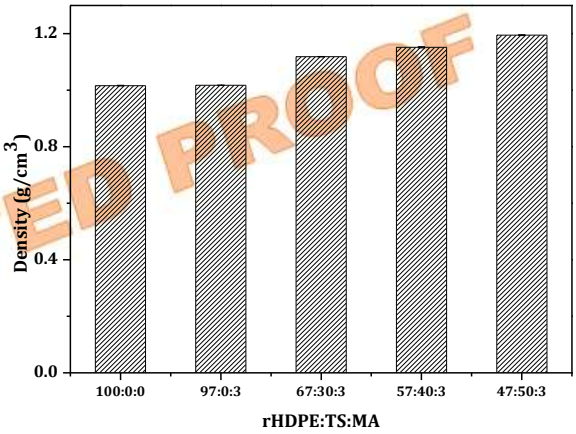

Fig. 4. Density of rHDPE:TS: MA composites

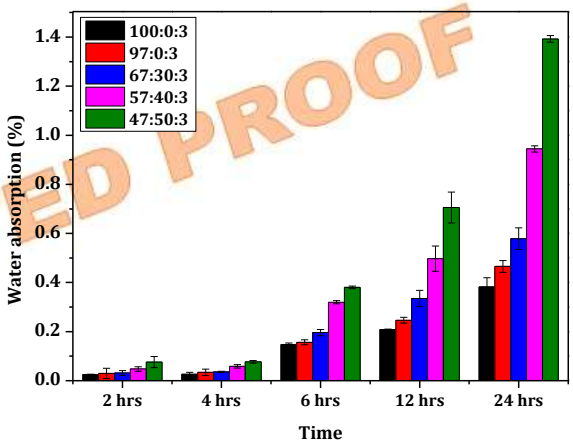

Fig. 5. Water absorption of rHDPE:TS: MA composites

Figure 5 illustrates the water absorption of the composites. The result indicates that water absorption increases with the rising TS content. This phenomenon can be attributed to the intrinsic properties of sawdust, which is capable

of absorbing water due to its fibrous structure. Natural fibers, such as those in TS, contain hydroxyl groups, which are hydrophilic, leading to higher water absorption as their content increases [20]. During the initial 2 to 4 hrs, the water absorption of the composites remained relatively stable, suggesting that the rHDPE:TS: MA composites exhibited some degree of water resistance. However, after 6 hrs, a noticeable increase in water absorption was observed. This sharp rise could be attributed to the saturation of the polymer matrix, which allows more water to be absorbed by the fibers, thereby contributing to the overall water uptake [21]. Despite the increased water absorption with higher TS content, the rHDPE:TS: MA composites exhibited lower water uptake compared to HDPE/barley straw composites, which showed a high water absorption rate of 12–13% [15]. Additionally, the water absorption of the prepared composites was lower than that of wood composites made from Radiata pine sawdust and thermoplastics [22], further highlighting the effectiveness of rHDPE:TS: MA composites in limiting moisture ingress.

The FT-IR spectra of the rHDPE:TS: MA composites, as shown in Fig. 6, reveal several characteristic absorbance bands. The leading absorbance bands of polyethylene were observed at 2914 cm^{-1}, 2847 cm^{-1}, 1470 cm^{-1}, and 718 cm^{-1}. Specifically, the peaks at 1470 cm^{-1} and 718 cm^{-1} confirm the presence of polyethylene in the composite [23, 24]. The absorbance between 2970 cm^{-1} and 2850 cm^{-1} indicates the presence of a methyl functional group, while peaks around 1600 cm−1 to 700 cm−1 correspond to methylene functional groups [25]. The peak of around 720 cm^{-1} is due to CH_2 rocking vibrations [26], confirming the polyethylene structure in the composite.

Additionally, the absorption band at 1372 cm^{-1} is associated with CH bending vibrations in cellulose, and the peak at 1051 cm^{-1} indicates the presence of cellulose in the composite, confirming the incorporation of TS. These findings are consistent with previous studies, such as those by S. Cheng et al. [27], which identified similar functional groups and structural elements of wood. Moreover, the increase in absorbance in the 1160 cm^{-1} and 1105 cm^{-1} regions is attributed to the formation of C–O linkages, which are characteristic of TS constituents [28].

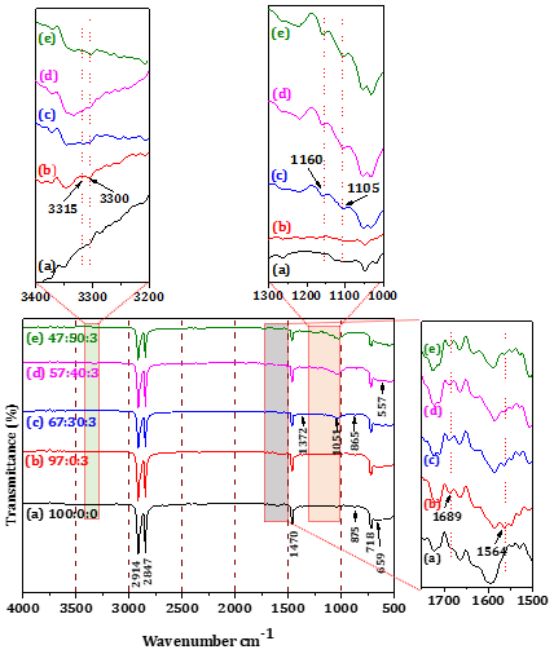

Fig. 6. FT-IR of rHDPE:TS: MA composites

In the hydroxyl region, the appearance of absorption bands at 3315 cm^{-1} and 3300 cm^{-1} upon the incorporation of maleic anhydride suggests interactions between MA and the composite components [28]. Furthermore, the presence of the absorption band at 1684 cm−1, characteristic of C=O stretches, and at 1564 cm^{-1}, corresponding to the C=C double bond of MA in rHDPE [28, 29], may indicate that the grafting reaction was incomplete or that weak interactions between TS and the composite limited the effectiveness of MA. This could potentially impact the mechanical properties of the composite.

3.2. Mechanical Properties

Figure 7 depicts the Shore hardness (Shore D) of the rHDPE:TS: MA composites. The results indicate that the hardness of rHDPE slightly increases with the addition of TS, and the overall hardness of the composite tends to increase as the TS content increases. This finding is consistent with a study by A. Koffi et al. [30], who reported that incorporating birch fiber into HDPE/birch fiber composites improved the hardness, with the hardness increasing as the birch fiber content increased. The increase in hardness can be attributed to the stiffness provided by the TS, which enhances the overall rigidity of the composites. This added rigidity restricts the movement of polymer chains, thereby leading to improved hardness [31]. The highest hardness was observed in the rHDPE:TS: MA composite with a 47:50:3 ratio, showing a 10.65% increase compared to unfilled rHDPE. In contrast, the study by R.C.V. Fletes and D. Rodrigue [32] reported that rHDPE reinforced

with 45% maple fiber showed only a 7.49% increase in hardness compared to virgin rHDPE.

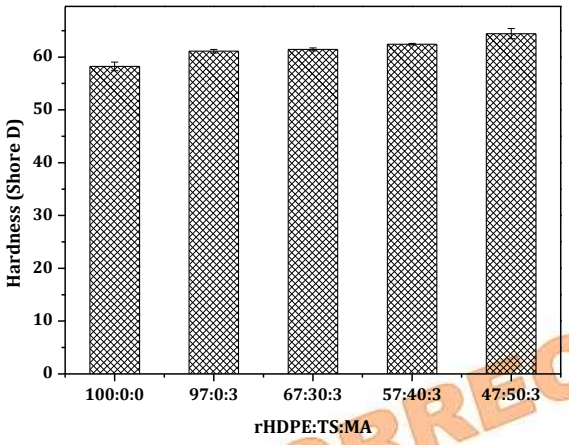

Fig. 7. Hardness of rHDPE:TS: MA composites

The flexural strength of the composites, determined by the three-point bending test, is presented in Fig. 8. The results show that the addition of TS enhances the flexural strength of rHDPE, with the 67:30:3 ratio exhibiting the highest flexural strength of 15.03 ± 0.38 MPa, representing a 15% improvement compared to unfilled rHDPE. This enhancement is attributed to the presence of TS, which strengthens and improves dispersion in the rHDPE matrix. This agrees with the addition of palm microfibers in a polypropylene matrix [33]. However, further increasing the TS content led to a decrease in flexural strength. This reduction may be attributed to the higher TS content, which can cause increased void formation or weakened interfacial bonding between the wood fibers and the polymer matrix [34]. This trend is consistent with the findings of K.B. Adhikary et al. [35], where adding sawdust initially improved flexural strength, but further increases in sawdust content resulted in a decline in strength.

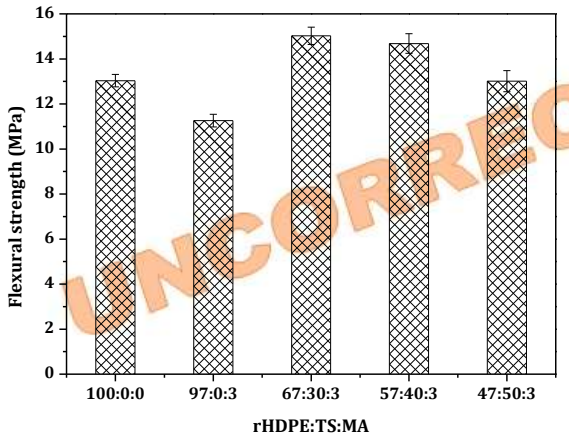

Fig. 8. Flexural strength of rHDPE:TS: MA composites

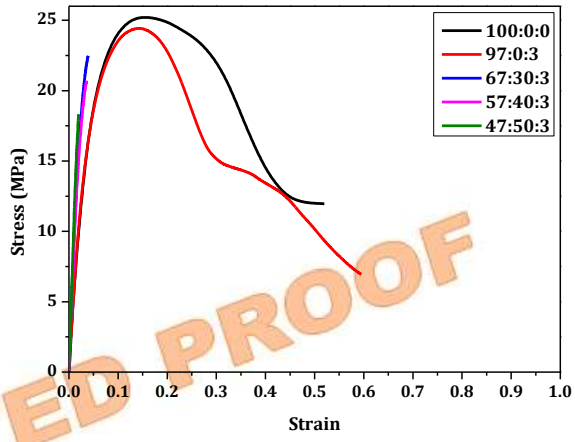

Fig. 9. Stress-strain curve of rHDPE:TS: MA composites

The stress-strain curves of the composites are shown in Fig. 9. As the TS content increased, both maximum stress and strain decreased, while the slope of the stress-strain curve increased, indicating a more brittle behavior of the composites. This can be attributed to the intrinsic rigidity of TS, which restricts the mobility of the polymer chains and reduces the composite's ability to undergo plastic deformation. Similar trends have been observed in other natural fiber-reinforced polymer composites, where an increase in filler content enhances stiffness but compromises ductility [29]. Notably, the composite with an rHDPE:TS: MA ratio of 47:50:3 exhibited the steepest slope, which can be attributed to the high TS content contributing to increased stiffness. Additionally, the presence of MA slightly enhanced the slope of the stress-strain curve. This effect may be due to improved interfacial adhesion between the hydrophilic TS and the hydrophobic rHDPE matrix, facilitated by the compatibilizing effect of MA, which is consistent with previously reported research [36].

Figure 10 illustrates the tensile properties of the composites, including tensile strength and tensile modulus, as seen in Fig. 10 (a) and Fig. 10 (b), respectively. The tensile strength of the composites tends to decrease as the TS content increases. This reduction could be attributed to the reduced interaction between the polymer matrix and the filler, leading to poor stress transfer under tensile loading. The presence of TS agglomerates and interfacial voids, as observed in SEM images (Fig. 12), further contributes to the deterioration of tensile strength, as these defects act as stress concentrators that facilitate crack propagation [37]. On the other hand, the tensile modulus of the composites increased with higher TS content. This increase in stiffness can be attributed to the rigid and fibrous nature of TS, which restricts the mobility of the rHDPE chains and enhances the composite's overall structural rigidity [12]. The reinforcing effect becomes

more pronounced at higher TS loadings, as a more rigid filler is incorporated into the matrix. This trend is consistent with previous studies, which have shown that the inclusion of lignocellulosic fillers, such as wood flour and natural fibers, enhances the modulus of thermoplastic composites due to the higher stiffness of the filler compared to the polymer matrix [38].

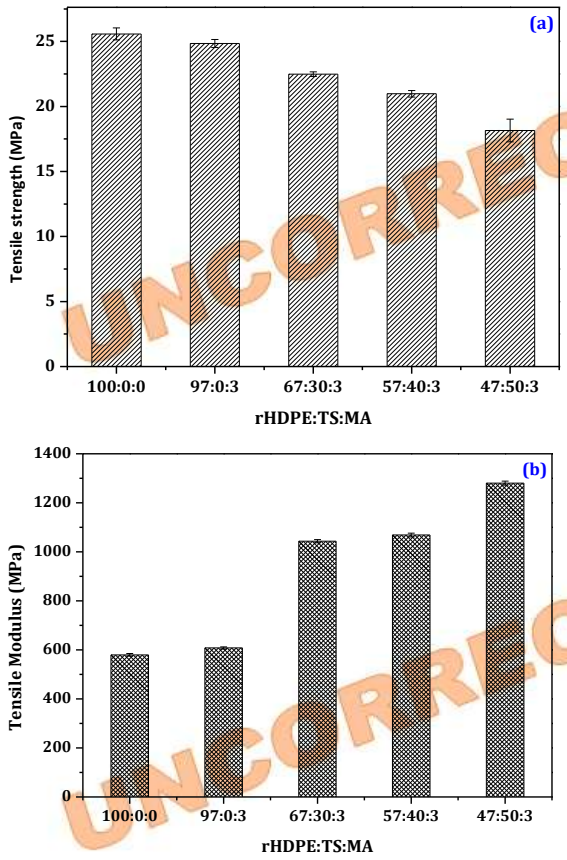

Fig. 10. Tensile properties of rHDPE:TS: MA composites; (a) tensile strength and (b) Tensile modulus

Figure 11 shows the impact strength of the composites. The results indicate that adding MA improved the impact strength due to its plasticizing effect, which enhances the energy absorption capability of the polymer matrix [17]. However, the impact strength tended to decrease with the addition of TS. This reduction could be attributed to TS particles acting as stress concentrators, promoting the initiation and propagation of cracks under impact loading, thereby reducing the composite's ability to absorb energy [39]. These results are consistent with the study by T. Amornsakchai and S. Duangsuwan [40], which demonstrated that the impact strength of HDPE milk bottle composites filled with pineapple leaf powder and short fiber decreased with increasing filler content. Notably, the rHDPE:TS: MA (97:0:3) composite exhibited the highest impact strength of 13.08 ± 0.34 kJ/m^2, showing a significant 192.6% increase compared to virgin rHDPE. This improvement is likely due to the introduction of polar functional groups by MA, which enhance the polymer's compatibility and bonding within its structure. This enhanced bonding results in improved energy absorption and increased resistance to impact loading, thereby improving the toughness of the rHDPE/MA blend [41].

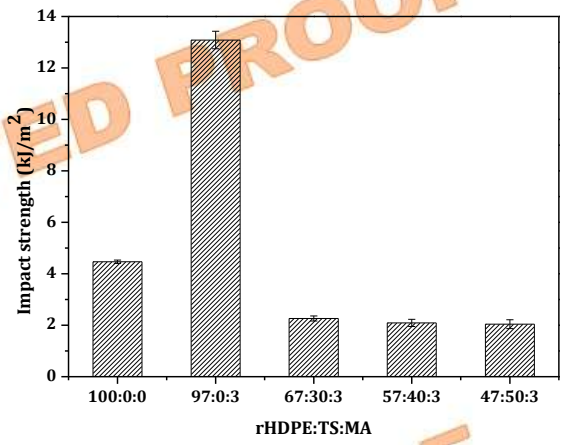

Fig. 11. Impact strength of rHDPE:TS: MA composites

3.3. Morphology

Figure 12 presents the fracture surface of the composites. The virgin rHDPE exhibited a relatively rough surface (Fig. 12(a)), indicative of a rigid material. When MA was added (Fig. 12(b)), the surface roughness increased, suggesting enhanced energy absorption, which correlates with the improved impact strength shown in Fig. 11. However, this also resulted in a decrease in flexural and tensile strength due to the plasticizing effect of MA [17].

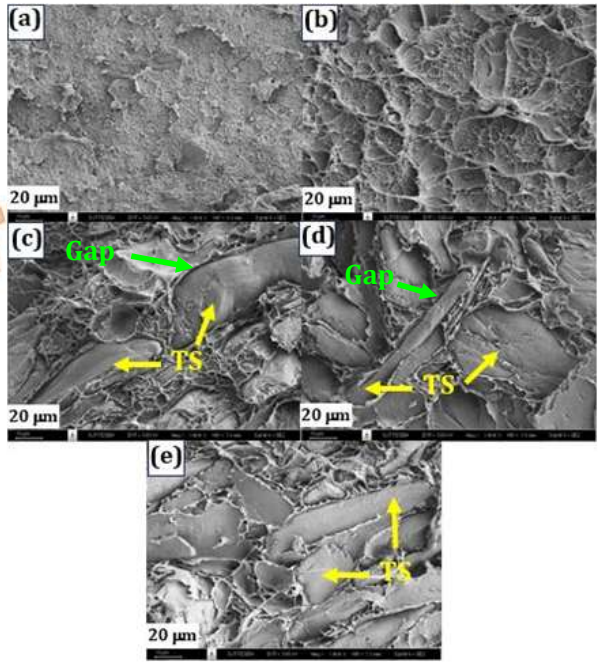

Fig. 12. SEM morphology of rHDPE:TS: MA composites; (a) 100:0:0, (b) 97:0:3, (c) 67:30:3,

(d) 57:40:3, and (e) 47:50:3

In Fig. 12(c)–(e), the addition of TS shows that the particles are embedded and well distributed within the rHDPE matrix, as indicated by the yellow arrows. However, gaps were found between the TS and the rHDPE matrix, highlighted by green arrows, indicating poor interfacial compatibility, which is consistent with a previous study [42]. At lower TS content (Fig. 12(c)), the distribution appears relatively uniform, contributing to improved stiffness. Conversely, at higher TS content (Fig. 12(e)), agglomeration and interfacial gaps become more pronounced, potentially acting as stress concentrators and reducing impact strength. These findings align with previous studies [43], which reported that increasing filler content can lead to reduced impact performance due to weak interfacial adhesion.

4. Conclusion

In the current study, teak sawdust (TS) was utilized as a reinforcement to produce plastic wood composites from recycled high-density polyethylene (rHDPE) obtained from milk bottles. The composites were fabricated using an internal mixer followed by compression molding, with TS content set at 30, 40, and 50 wt%. The rHDPE:TS: MA composite, with a ratio of 47:50:3, demonstrated high performance, exhibiting improved mechanical properties, including a tensile modulus of 1280.31 MPa, a hardness of 64.44 Shore D, and a flexural strength of 13.01 MPa. However, the incompatibility between TS and rHDPE resulted in a reduced impact strength. In contrast, the rHDPE blend with MA exhibited the highest impact strength. This finding is supported by morphological analysis, which confirmed improved interfacial bonding between rHDPE and MA. Future research should investigate the effects of TS particle size and various coupling agents to further enhance the interaction between the polymer matrix and the reinforcing agent.

Nomenclature

rHDPE	Recycled high-density polyethylene
TS	Teak sawdust
MA	Maleic anhydride
%wt	Percent by weight
˚C	Degree Celsius
mm	Millimetre
min	Minute
hrs	Hours
cm	Centimeter
MPa	Megapascal
FT-IR	Fourier transform infrared spectroscopy.
SEM	Scanning electron microscopy

Acknowledgments

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Conflicts of Interest

The authors declare no competing interests.

Appendixes

Appendixes appear after Conflicts of Interest.

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