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Properties of wood-plastic composites based on PVC/PLA/PBAT ternary blend

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Abstract

The objective of this work was to improve mechanical properties, thermal resistance, and biodegradability of poly(vinyl chloride) (PVC) by the addition of poly(lactic acid) (PLA), poly(butylene adipate-*co*-terephthalate) (PBAT), and wood flour (WF). The samples made from a mixture of PVC/PBAT exhibited the highest impact and tensile properties, while properties of the samples made from PVC/PLA had the highest flexural and thermal properties, PVC/PLA/PBAT mixed samples exhibited average mechanical properties. The addition of WF to all the blends increased impact strength, flexural properties, Young's modulus, thermal resistance, and biodegradability of the samples in comparison to those of the neat PVC and its blends. Composite samples of PVC/PBAT/WF showed the highest impact strength, while PVC/PLA/WF composite had the highest flexural and thermal resistance. The samples manufactured from a mixture of PVC/PLA/PBAT/WF had the highest tensile strength and Young's modulus. The overall results in this work suggested that the enhanced properties of PVC samples were strongly influenced by the compatibility between polymer blend matrix and WF particles.

1. Introduction

Wood-plastic composites (WPCs) are usually a combination of plastics and wood flour (WF) or wood fibers, which refer to a matrix and a reinforcing filler, respectively [1-3]. In the area of construction materials, WPCs are widely used for decking, furniture, interior, exterior owning to their advantages such as lightweight, inexpensive, non-abrasive, acceptable specific strength, biodegradability, non-toxic, excellent insulating, acoustic properties, and mold resistance [4-6]. WPCs are typically made of thermoplastics such as polyethylene (PE), polypropylene (PP), and poly(vinyl chloride) (PVC) [3]. PVC is mainly used as a raw material because of its advantages that are stiffness, high flame retardancy, high chemical resistance, and inexpensiveness [3,4,7]. However, the addition of heat stabilizer, lubricant, and plasticizer is needed for PVC due to its high brittleness and low thermal stability [7,8]. Thus, some methods were used to improve PVC drawbacks, such as blending, modification, and grafting [7,9-11]. In general, polymer blending is one of the effective methods to enhance PVC properties because it is an economical and efficient way. Previous works investigated properties of PVC blended with biodegradable polymers such as poly(lactic acid) (PLA), poly(butylene adipate-*co*-terephthalate) (PBAT), poly(butylene succinate) (PBS) to improve their mechanical properties, thermal properties, and biodegradability [7-10,12-14]. PLA and PBAT are biodegradable polymers chosen for blending with PVC in this work. PLA is an aliphatic polyester which can be obtained from renewable resources such as corn starch, tapioca roots, sugar cane via fermentation [15,16]. This biopolymer has excellent mechanical properties and biodegradability but poor processability [9,15-17]. In contrast, PBAT is an aliphatic-aromatic copolyester which can be produced from petroleum resources by random co-polymerization of 1,4-butanediol, adipic acid, and dimethyl terephthalate monomers [8,15]. Such copolymer has high flexibility and good processability [7-9,15,18]. Hence, the blending of PVC with PLA and PBAT is expected to enhance mechanical properties and impart biodegradability to the PVC. The aim of this study is to improve the properties of wood-plastic composite based on PVC by blending with PLA and PBAT. The series of binary and ternary of polymer blends and composites were prepared to investigate the effects between fillers. A ternary blend of PVC/PLA/PBAT may also achieve a combination of the desirable properties of each polymer component providing a better efficiency matrix for preparing composites for decking application. Components were fixed amount of PVC, PLA, PBAT, and WF at 100, 20, 20, and 40 parts per hundred of PVC resin (phr),

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respectively. Tensile strength (TS), tensile modulus (E), elongation at break (EB), impact strength (IS), flexural strength at 2% strain (FS@2%), flexural modulus (FM), heat deflection temperature (HDT), Vicat softening temperature (VST), glass transition temperature (Tg,), soil burial, and morphology were investigated.

2. Experimental

2.1 Raw materials

PVC resin with a K value of 58 was produced by SCG Chemicals Co., Ltd. The heat stabilizer, processing aid, external lubricant, and internal lubricant were obtained from Thainam Plastic Company (Thailand). PBAT Ecoflex grade 1200 with a melt flow index of 2.7-4.9 g/10 min (190°C, 2.16 kg), a density of 1.25-1.27 g$\cdot$cm^{-3}, and melt temperature in the range of 110-120°C was manufactured by BASF, Germany. PLA grade 4043D with a melt flow index of 6 g/10 min (210°C, 2.16 kg), a density of 1.24 g$\cdot$cm^{-3} and melt temperature in the range of 145-160°C was manufactured by NatureWorks, USA and WF (Lignocel grade C120) with a bulk density, and grain size of 1-1.35 g$\cdot$cm^{-3} and 70-150 μm was supplied by J. Retenmaier & Sohne Co. (Germany). All materials were used as received without any purification.

2.2 Specimen preparation

Neat PVC, blends, and composites formulas shown in Table 1 were mixed with fix amount of 4 parts per hundred parts of PVC resin (phr) of heat stabilizer, 6 phr of processing aid, 2 phr of external lubricant, and 0.5 phr of internal lubricant and oven-dried at 80°C for 24 h to remove any trace of moisture. Dried-compounds were melt-mixed using a twin-screw extruder (Labtech Engineering L-40, Thailand) following a temperature profile of 175, 180, 180, 180, 180, 175, 170, 165, 160, 155 and 150°C, at screw speed 120 rpm. The extrudates were cooled by air and pelletized at 2.5 mm by length.

The specimens were molded by injection molding machine at 170-172°C for neat PVC, neat PLA, blends and composites, at 110-120°C for neat PBAT.

2.3 Testing and Characterization of the samples

The tensile test was conducted on a standard dumbbell-shaped specimen according to ASTM D638 Type I using a universal testing machine (Tinius Olsen, England) with a load cell capacity of 5000 N, crosshead speed of 50 mm$\cdot$min^{-1}, and a gage length of 50 mm. The average of five measurements of the tensile test was used in calculation.

The notched Izod impact test was performed on a specimen with a dimension of 12.7 mm in width × 63.5 mm in length × 3.2 mm in thickness using an impact tester (Ceast, Resil Impactor 10K, USA) according to ASTM D256. The average of ten measurements of notched Izod impact test was used in calculation.

The flexural test was conducted on five rectangular-shaped specimens with a dimension of 12.7 mm in width × 127 mm in length × 3.2 mm in thickness using a universal testing machine (Tinius Olsen, England) under three-point bending mode according to ASTM D790 with a load cell capacity of 5000 N, crosshead speed of 1.4 mm$\cdot$min^{-1}, and support span length of 50 mm.

One-way ANOVA was applied to analyze statistically significant differences between group means ($p<0.05$) using Origin Pro 9. Multiple comparisons of mean were carried out using Tukey's model. The superscripted letters in Table 2-3 represented statistically significant differences between components.

Heat deflection temperature (HDT) of the samples was determined deflection temperature at 0.25 mm bending of edgewise specimen in silicone oil bath with a load of 0.455 MPa according to ASTM D648 using HDT & Vicat testing machine (Instron HV6X, Italy). Three specimens with dimensions of 127 mm in length × 12.7 mm in depth × 3.2 mm in width were placed at 23°C for 5 min and then heated at the rate of 120°C$\cdot$h^{-1}.

Vicat softening temperature (VST) of the samples was measured at 1 mm penetrated on samples surface which circular indenter with a tip cross-section of 1 mm2 under a standardized loading of 10 N according to ASTM D1525 using HDT & Vicat testing machine (Instron HV6X, Italy). Three specimens with one layer of dimensions of 127 mm in length × 3.2 mm in thickness × 12.7 mm in width were heated at the rate of 120°C$\cdot$h^{-1} in a silicone oil bath.

Glass transition temperature of the samples was analyzed by employing the thermomechanical analyzer (Mettler Toledo TMA/SDTA 2+ LF/1100, Switzerland). The specimens in square-shaped of 7 mm in width and length and 3.2 mm in thickness were heated from room temperature to 90°C. The glass transition temperature of the samples was detected at the point of volume expansion sharply.

Five replicate specimens with a dimension of 12.7 mm in width × 63.5 mm in length × 3.2 mm in thickness were immersed in a water bath at room temperature to determine their water absorption within 30 days. Specimens were taken out of the water bath and wipe out excess water on the surface to weight on balance with a precision of 0.001 g. Water uptake percentage of each sample was calculated following equation (1), where W_0 and W_i represent to the initial weight of dried specimens and the weight of wet samples at different times, respectively.

$$\text{Water uptake (\%)} = [[W_i\text{-}W_0]/W_0]\times 100 \qquad (1)$$

Morphologies of tensile fractured surface and soil burial of the samples after 0, 3, and 6 months were observed by scanning electron microscopy (SEM) (Jeol JSM-6480LV, Japan) at a voltage of 5 kV and a magnification of 500x. The surface was clean, dry, and sputter-coated with a thin layer of gold under vacuum to avoid an electrostatic charge.

Soil burial test was conducted to observe the degradation surface for 90 days. Burying the specimens with a dimension of 12.7 mm in width × 63.5 mm in length × 3.2 mm in thickness deep below the soil surface at least 20 cm. The humidity control was maintained at about 40%. At 3 and 6 months, the buried specimens were removed, cleaned, and dried in an oven at 80°C for 24 h. The SEM technique observed the surface of samples as above.

Table 1. Sample composition.

Composition	PVC (phr)	PLA (phr)	PBAT (phr)	WF (phr)
PVC	100	-	-	-
PLA	-	100	-	-
PBAT	-	-	100	-
PVC/PLA	100	20	-	-
PVC/PBAT	100	-	20	-
PVC/PLA/PBAT	100	20	20	-
PVC/PLA/WF	100	20	-	40
PVC/PBAT/WF	100	-	20	40
PVC/PLA/PBAT/WF	100	20	20	40

Table 2. Mechanical properties of the samples.

Composition	IS ($kJ \cdot m^{-2}$)	FS@2% strain (MPa)	FM (MPa)	TS (MPa)	E (MPa)	EB (%)
PVC	$2.5 \pm 0.02^{a, b}$	$54.0 \pm 0.14^{a, b}$	$2696 \pm 8^{a, b}$	57.8 ± 0.06^{a}	1837 ± 48^{a}	7.4 ± 0.74^{a}
PLA	2.6 ± 0.10^{c}	67.0 ± 0.72^{c}	3348 ± 47^{c}	63.1 ± 0.64^{b}	1803 ± 46^{a}	8.0 ± 0.62^{a}
PBAT	Not break^{d}	2.6 ± 0.10^{d}	115 ± 2^{d}	13.1 ± 0.11^{c}	77 ± 1^{b}	Not break^{b}
PVC/PLA	2.2 ± 0.06^{e}	55.6 ± 0.25^{a}	2814 ± 11^{a}	36.8 ± 0.18^{d}	1856 ± 8^{a}	2.4 ± 0.03^{c}
PVC/PBAT	2.5 ± 0.03^{a}	52.0 ± 1.75^{b}	2593 ± 90^{b}	58.1 ± 0.67^{a}	1557 ± 35^{c}	5.1 ± 0.19^{d}
PVC/PLA/PBAT	$2.3 \pm 0.05^{e, f}$	55.7 ± 1.41^{a}	2787 ± 72^{a}	52.8 ± 0.76^{e}	1631 ± 10^{c}	4.3 ± 0.03^{d}
PVC/PLA/WF	$2.4 \pm 0.05^{b, f, g}$	76.4 ± 2.15^{d}	4758 ± 101^{d}	44.2 ± 0.97^{f}	2027 ± 32^{d}	2.5 ± 0.07^{c}
PVC/PBAT/WF	2.6 ± 0.08^{c}	68.6 ± 1.08^{b}	4106 ± 79^{e}	40.0 ± 0.20^{g}	1848 ± 32^{a}	2.9 ± 0.03^{c}
PVC/PLA/PBAT/WF	$2.5 \pm 0.03^{a, g}$	78.1 ± 1.82^{d}	4466 ± 130^{f}	48.6 ± 0.89^{h}	2279 ± 11^{e}	2.9 ± 0.01^{c}

Different superscript letters represented statistically significant differences at $p<0.05$

Table 3. Thermal properties of the samples.

Composition	HDT (°C)	VST (°C)	$T_{g,\ TMA}$ (°C)
PVC	65.3 ± 0.70^{a}	81.6 ± 0.46^{a}	69.5
PLA	58.2 ± 0.12^{b}	60.6 ± 0.57^{b}	60.4
PBAT	50.4 ± 0.85^{c}	88.5 ± 1.30^{c}	Not detect
PVC/PLA	65.2 ± 0.25^{a}	79.4 ± 0.17^{d}	72.8
PVC/PBAT	52.8 ± 0.15^{d}	71.5 ± 1.01^{e}	60.7
PVC/PLA/PBAT	52.8 ± 0.20^{d}	66.7 ± 0.71^{f}	57.9
PVC/PLA/WF	70.9 ± 0.47^{e}	96.4 ± 0.76^{g}	76.8
PVC/PBAT/WF	56.2 ± 0.82^{f}	91.8 ± 0.12^{h}	52.7
PVC/PLA/PBAT/WF	56.6 ± 0.40^{f}	84.2 ± 0.67^{i}	55.3

Different superscript letters represented statistically significant differences at $p<0.05$

3. Results and discussion

3.1 Mechanical properties of the samples

The mechanical properties in terms of the impact strength (IS), flexural strength at 2% strain (FS@2% strain), flexural modulus (FM), tensile strength (TS), Young's modulus (E), elongation at break (EB) of samples are summarized in Table 2 and illustrated in Figure 1-3. As a hard and brittle plastic, the neat PVC and neat PLA showed low impact strength values of 2.5 and 2.6 kJ/m^2, high flexural strength at 2% strain values of 54 and 67 MPa, and high flexural modulus values of 2696 and 3348 MPa, respectively. The tensile strength value of the neat PVC was determined as 57.8 MPa which was lower than the neat PLA. However, Young's modulus and elongation at break showed no difference from each other. Although the neat PLA exhibited higher mechanical properties than those of the neat PVC, impact strength, tensile strength, elongation at break of PVC/PLA blend were reduced, and flexural properties were not increased due to low interfacial adhesion and immiscible blending [10,17,19-21].

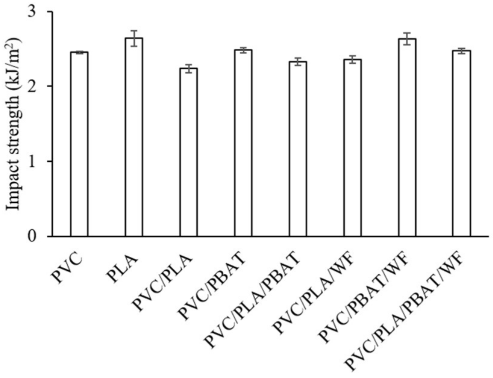

Figure 1. Impact strength (IS) of neat PVC, neat PLA, blends, and composites.

On the other hand, the neat PBAT showed a kind of flexible plastic owing to its unbreakable specimen under impact test, and a low flexural strength at 2% strain of 2.6 MPa and flexural modulus of 115 MPa compared to the neat PVC and the neat PLA [22]. Consequently, the neat PBAT had the highest elongation at break, not breaking at 350% strain, but having the lowest tensile strength of 13.1 MPa and Young's modulus value of 77 MPa. The addition of PBAT to the PVC matrix was not increased the impact strength and elongation at break of PVC/PBAT blend as expected. This might be because PBAT was not dispersed into the PVC matrix as a co-continuous structure which the dual co-continuous interpenetration associated unique combination or improvement of the mechanical properties [23-25]. Flexural properties and Young's modulus of PLA/PBAT mixed samples decreased from the neat PVC owing to the high flexibility of the PBAT phase. However, the tensile strength of the PVC/PBAT blend did not change significantly compared to that of the neat PVC, even though the neat PBAT exhibited very low tensile strength indicating that PVC/PBAT blend had good compatibility [7,8]. It was reported that acidic hydrogen of PVC has polar interaction with the carbonyl group of PBAT [7,8]. A ternary blend of PVC/PLA/PBAT exhibited low impact strength and high flexural properties the same as PVC/PLA blend.

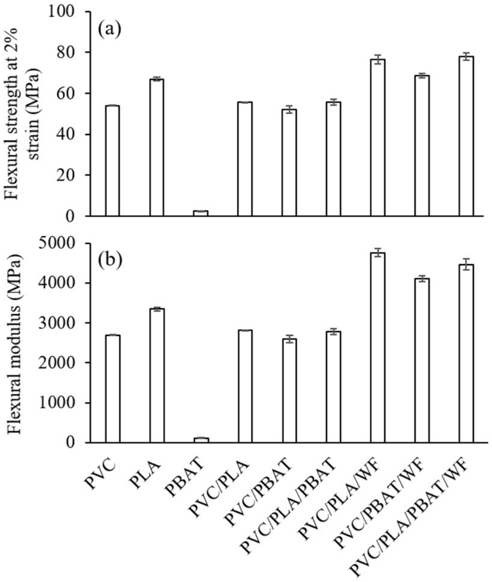

Figure 2. Flexural properties of neat PVC, neat PLA, neat PBAT, blends, and composites: (a) flexural strength at 2% strain (FS@2% Strain) (b) flexural modulus (FM).

The low impact strength of the ternary blend was also influenced by low interfacial adhesion between PVC and PLA while high flexural properties were influenced by high stiffness of the neat PLA [26]. The tensile strength and elongation at break of the ternary blend were all lower than PVC/PBAT blend because PLA reduced the interfacial adhesion as previous mentioned. In contrast, the tensile strength and elongation at break of the ternary blend samples were higher than those of PVC/PLA blend since PBAT in the ternary blend had good compatibility with the PVC matrix. Young's modulus of the ternary blend was lower than the PVC/PLA blend due to the high flexibility of the PBAT phase. All the WF composites exhibited higher flexural properties and Young's modulus than its blends because of the rule of mixtures, as the high modulus of the WF particles is higher than that of the polymer matrix [3,27]. Interestingly, the tensile strength of PVC/PLA/WF composite samples was 44.2 MPa which is higher than that of the PVC/PLA blend indicating that PLA and

WF had good interfacial adhesion. However, the tensile strength and elongation at break of PVC/PBAT/WF and PVC/PLA/PBAT/WF composites were all decreased from its blend. These results indicated that PBAT and WF particles had low wettability [18,28]. The tensile strength of PVC/PLA/PBAT/WF sample was 48.6 MPa higher than PVC/PLA/WF and PVC/PBAT/WF about 4.4 MPa and 8.6 MPa, respectively. These might be influenced by the compatibility of the PVC/PBAT matrix and wettability of PLA/WF [7,18,28].

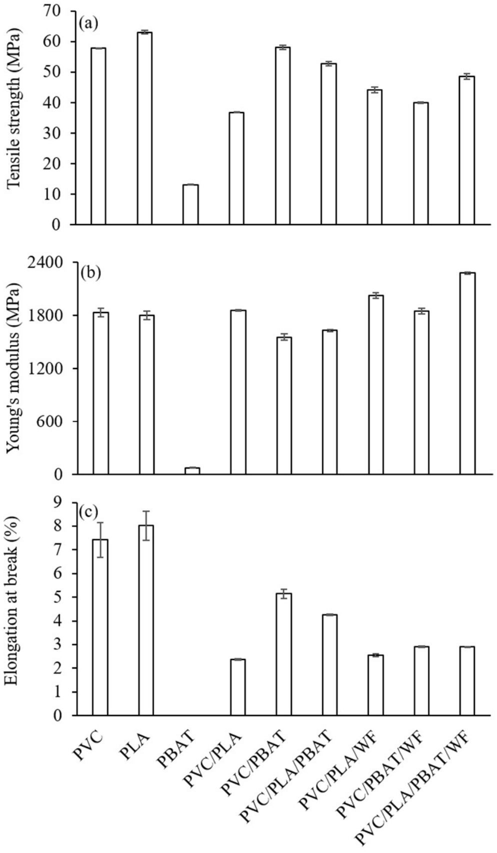

Figure 3. Tensile properties of neat PVC, neat PLA, neat PBAT, blends, and composites: (a) tensile strength (TS) (b) Young's modulus (E) and (c) elongation at break (EB).

3.2 Thermal properties of the samples

Heat resistance of the samples was determined by two standard test methods, which are heat deflection temperature (HDT) and Vicat softening temperature (VST). HDT is a temperature at the point of sample deforms under constant loading to 0.25 mm, while VST is a temperature at the point of sample penetrates by needle-shaped indenter to 1 mm. The HDT and VST results of neat PVC, neat PLA, neat PBAT, blends, and composites are summarized in Table 3 and presented in Figure 4. As can be seen in Figure 4 (a), the HDT of the neat PVC was 65.3°C higher than the neat PLA and PBAT about 7.1 and 14.9°C, respectively. However, the HDT of the PVC/PLA blend was not significantly changed compared to the neat PVC because of the high stiffness of PLA [14,26]. The HDT of PVC/PBAT blend and PVC/PLA/PBAT blend were both 52.8°C, and it was decreased from the neat PVC about 12.5°C due to the low HDT and modulus of the neat PBAT [29]. Moreover, the addition of WF increased the HDT of all the composites compared to its blends due to the high stiffness of WF particles that restricted the mobility of the polymer chains and retarded the deformation temperature of the composites. As can be seen in Figure 4 (b), the VST of the neat PBAT, neat PVC, and neat PLA were 88.5, 81.6, and 60.6°C, respectively. The VST of the PVC/PLA blend slightly decreased from the neat PVC about 2.2°C due to the low VST of the neat PLA. The VST of the PVC/PBAT blend was 71.5°C, and it was lower than the neat PVC about 10.1°C because the PBAT phase increased the free volume of the polymer blend and reduced the deformation temperature. Furthermore, the poor interfacial adhesion between PVC and PLA, as well as the decrease in the modulus of PBAT, also be the reason that reduced the VST of the PVC/PLA/PBAT blend. The addition of WF increased the VST of all the composites compared to the neat PVC and its blends due to the increase of surface hardness by the high stiffness of WF particles.

Table 3 and Figure 5 shows the glass transition temperature (Tg) of neat PVC, neat PLA, and samples, which were analyzed by the TMA technique. The Tg of the neat PVC was 69.5°C, it was higher than those of the neat PLA about 9.1°C due to the high polarity of the PVC side group. The Tg of the neat PBAT did not detect from this TMA machine because it was below 25°C [15,16]. All the blends and composites were observed only one Tg, which could be the Tg characteristic of PVC dominant matrix. The Tg of PVC/PLA blend was shifted to higher temperatures over the neat PVC and PLA about 3.3 and 12.4°C indicating that PVC/PLA blend was immiscible blending [10,14,26]. While the Tg of PVC/PBAT blend was 60.7°C and shifted to lower temperature from the neat PVC about 8.8°C indicating that the addition of PBAT decreased modulus of the sample [16,30]. The Tg of PVC/PLA/PBAT blend was 57.9°C and shifted to a lower temperature than the neat PVC and binary blends because ternary phases provided more free volume, leading to the reduction of modulus [31]. Moreover, the Tg of PVC/PLA/WF composite was shifted to a higher temperature than its blend owing to good interfacial adhesion between PLA and WF that increased stiffness of the sample. On the other hand, the Tg of PVC/PBAT/WF and PVC/PLA/PBAT/WF composites was shifted to lower temperature than its blends about 8°C and 2.6°C owing to poor interfacial adhesion between PBAT and WF that reduced stiffness of the samples.

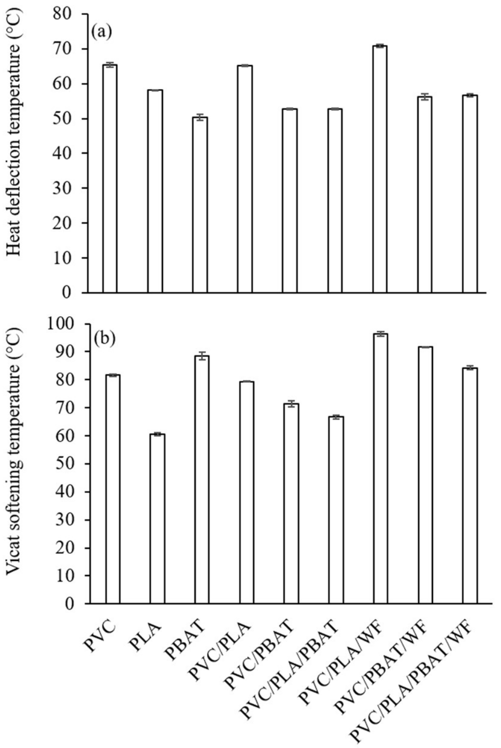

Figure 4. Thermal properties of neat PVC, neat PLA, neat PBAT, blends, and composites: (a) heat deflection temperature (HDT) (b) Vicat softening temperature (VST).

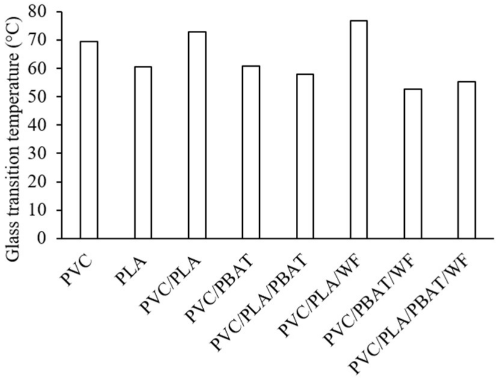

Figure 5. The glass transition temperature of neat PVC, neat PLA, blends, and composites by the thermomechanical analyzer.

3.3 Water uptake of the samples

Figure 6 illustrates the percentage of water uptake of neat PVC, neat PLA, neat PBAT, blends, and composites at different periods of immersion. The water uptake of all the neat and blends was slowly increased for the first seven days and rapidly increased from 9 days and kept rising as a function of immersion time. After 17 days, the water uptake of the samples was slowing down until reaching a saturation point. In contrast, the water uptake of the composites rapidly increased for the first seven days and continue slowly increased until a saturation point. The results show that the lowest water uptake at 30 days of immersion time was the neat PVC owing to its hydrophobicity. The water uptake of the neat PBAT (6 %) was higher than the neat PLA (4 %) due to the low glass transition temperature of PBAT increased the mobility of polymer chain and lead to rising of water absorption [32]. All the blends had increased water uptake value compared to those of neat PVC owing to the addition of PLA and PBAT to the PVC matrix which increased the ability to absorb water. The water uptake of all the composites increased compared to its blends because WF contains a hydrophilic hydroxyl group that interacted with water molecules through hydrogen bonding [4, 6, 9]. The water uptake of PVC/PBAT/WF composite was the highest value compared to the PVC/PLA/WF and PVC/PLA/PBAT/WF composites because low wettability of WF and PBAT provided a loose internal structure and increased the ability of water penetration. Thus, the higher water uptake could accelerate the biodegradation of the samples by allowing the microorganism to penetrate the samples using water as a medium [25, 33].

3.4 Morphology analysis of the samples

Representative SEM images on the tensile-fractured surface of neat PVC, neat PLA, blends, WF, and composites are illustrated in Figures 7 and 8. The neat PVC (Figure 7 (a)) showed a rough surface more than the neat PLA (Figure 7 (b)), indicating that the neat PVC was weaker than the neat PLA. The neat PLA (Figure 7 (b)) showed a relatively flat and smooth surface with a brittle fracture behavior. The blend of PVC/PLA (Figure 7 (c)) exhibited a rough fractured surface with many voids because of their low interfacial adhesion or immiscible between PVC matrix and PLA [34]. In agreement with the reduction of tensile results of PVC/PLA compared to the neat PVC as previous mentioned. The blends of PVC/PBAT (Figure 7 (d)) and PVC/PLA/PBAT (Figure 7 (e)) showed a homogenous fractured surface without any cavities suggesting that interfacial adhesion between polymer and filler was better than the PVC/PLA blend. However, the addition of PBAT to the binary and ternary blends did not observe a kind of ductile fracture behavior due to PBAT was not dispersed as a co-continuous structure [23,24].

Additionally, Figure 8 (a) showed the images of WF particles with different length to diameter ratio. The composites of PVC/PLA/WF (Figure 8 (b)) revealed a strong bond of WF particles on the polymer matrix and increased tensile strength compared to its blend owing to good interfacial adhesion between PLA and WF particles. In contrast, the composites of PVC/PBAT/WF (Figure 8 (c)) showed large cavities of fiber pull-out on their fractured surface indicating that the wettability and interfacial adhesion of PBAT and WF particles were poor, leading to a reduction in tensile strength and elongation at break [35]. Therefore, the composite of PVC/PLA/PBAT/WF (Figure 8 (d)) showed the fiber detach out of the fractured surface due to low interfacial adhesion between PBAT and WF particles, but less gaps space than those of PVC/PBAT/WF composite owing to a good wettability between PLA and WF particles.

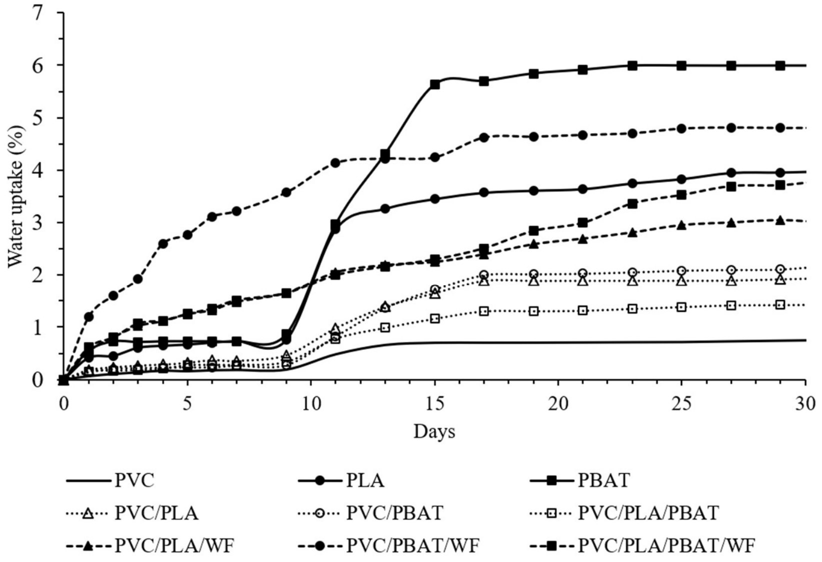

Figure 6. Water uptake during 0-30 days of neat PVC, neat PLA, neat PBAT, blends, and composites.

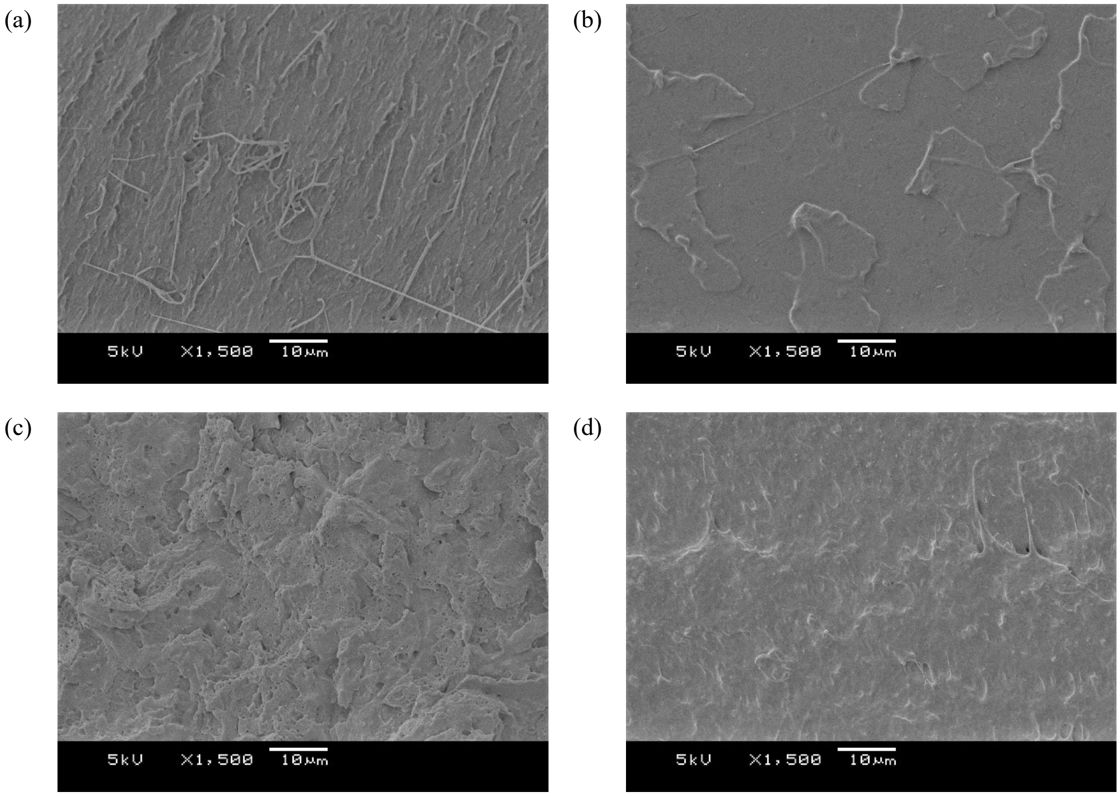

Figure 7. SEM images of tensile fracture surface at 1500x magnification of samples: (a) PVC (b) PLA (c) PVC/PLA (d) PVC/PBAT (e) PVC/PLA/PBAT.

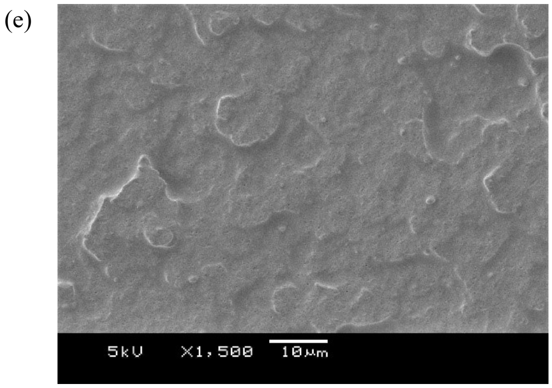

Figure 7. SEM images of tensile fracture surface at 1500x magnification of samples: (a) PVC (b) PLA (c) PVC/PLA (d) PVC/PBAT (e) PVC/PLA/PBAT. (continue)

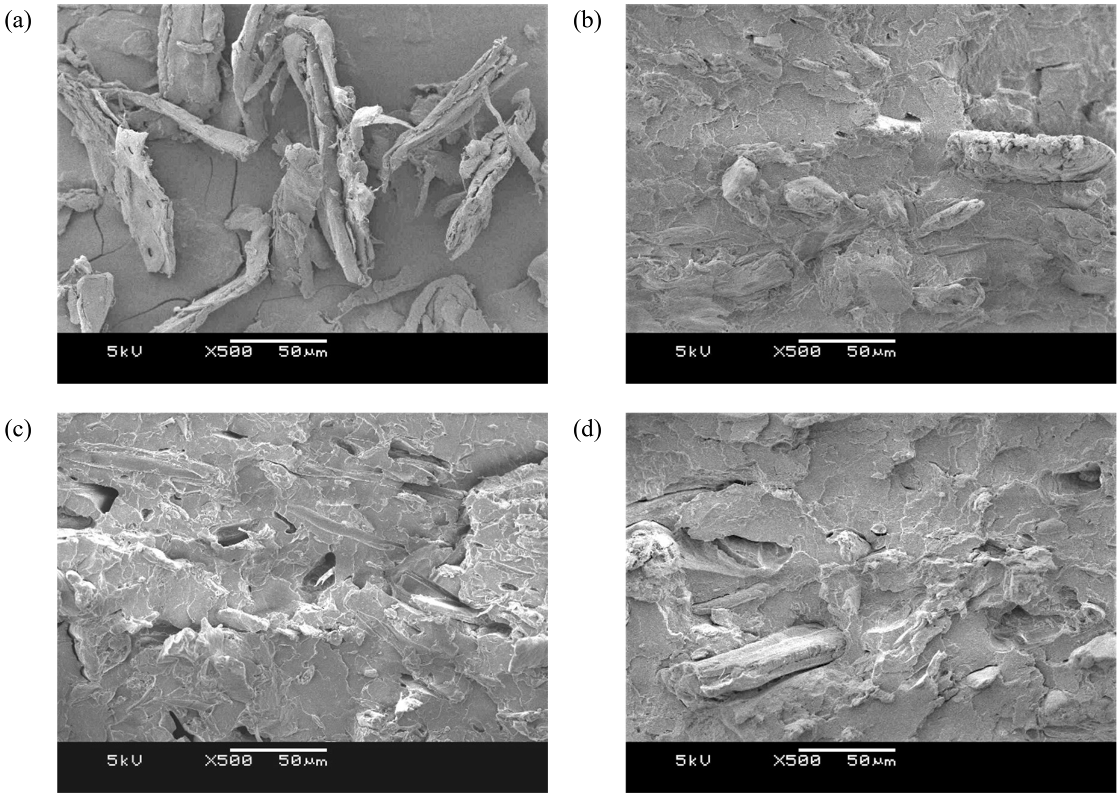

Figure 8. SEM images of tensile fracture surface at 500x magnification of samples: (a) WF particles (b) PVC/PLA/WF (c) PVC/PBAT/WF (d) PVC/PLA/PBAT/WF.

3.5 Soil burial test of the samples

The surface of neat PVC, neat PLA, neat PBAT, blends, and composites as a function of the soil burial time at 0, 3, and 6 months is shown in Figure 9. This experiment was carried out to determine the biodegradability of the samples by observing their surface morphology after soil burial test. The samples were taken out after 3 and 6 months of degradation, respectively. The SEM images in Figure 9 (a) showed that the neat PVC surface at 3 and 6 months did not change because it did not degrade in the soil. The surface of the neat PLA and neat PBAT in Figure 9 (b) and (c) changed after 3 and 6 months owing to their microorganism degradation [19,33,36]. However, the neat PBAT surface exhibited the most deterioration surface compared to the neat PLA in agreement with the water uptake results. In Figure 9 (d) to (f), it is observed that all the blends surface after six months did not change significantly because of the non-biodegradable PVC is the main component. As can be seen in Figure 9 (g) to (i), all the composites exhibited a rupture surface at six months, indicating that WF particles accelerated biodegradation [19].

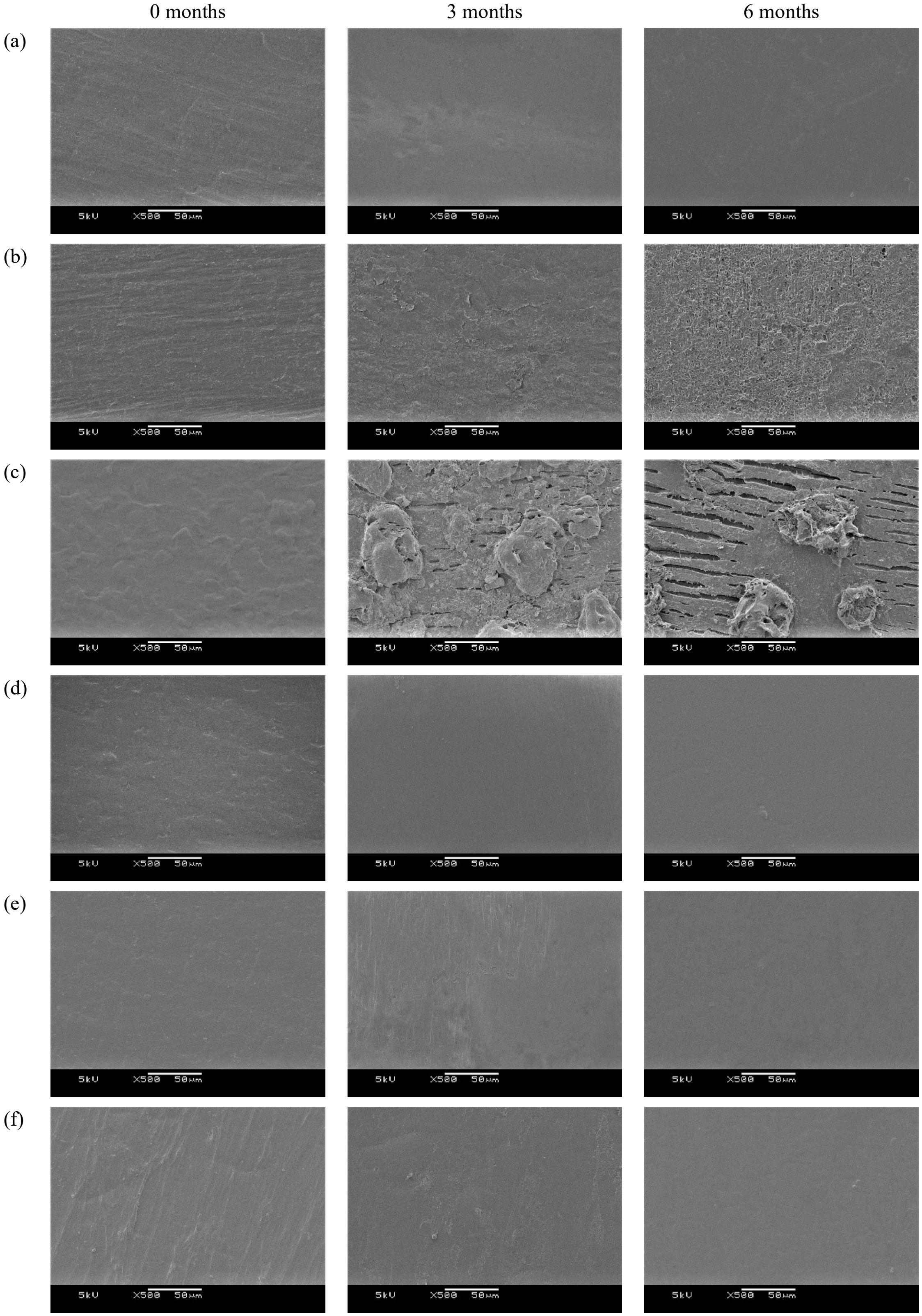

Figure 9. SEM images of soil burial test at 0, 3, 6 months at 500x magnification of samples: (a) PVC, (b) PLA, (c) PBAT, (d) PVC/PLA, (e) PVC/PBAT, (f) PVC/PLA/PBAT, (g) PVC/PLA/WF, (h) PVC/PBAT/WF, and (i) PVC/PLA/PBAT/WF.

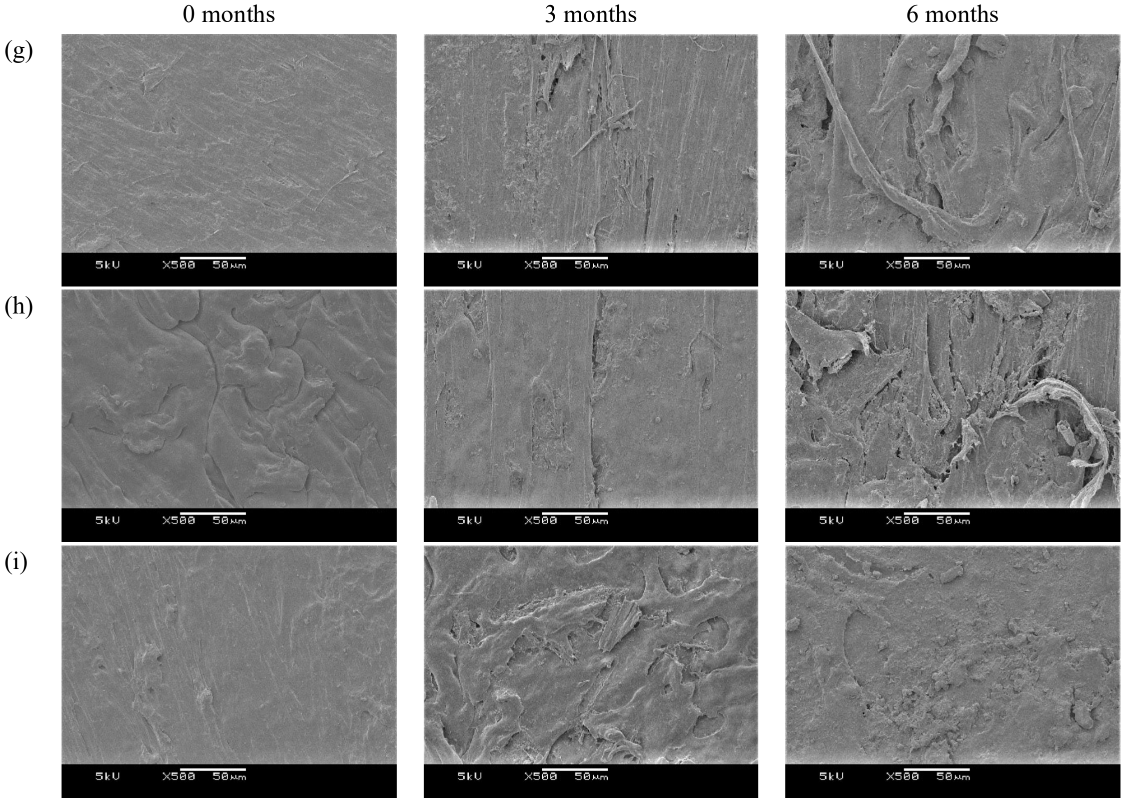

Figure 9. SEM images of soil burial test at 0, 3, 6 months at 500x magnification of samples: (a) PVC, (b) PLA, (c) PBAT, (d) PVC/PLA, (e) PVC/PBAT, (f) PVC/PLA/PBAT, (g) PVC/PLA/WF, (h) PVC/PBAT/WF, and (i) PVC/PLA/PBAT/WF. (continue)

4. Conclusions

Effects of PLA, PBAT, and WF on the mechanical properties including impact, flexural, tensile and thermal properties including HDT, VST, Tg, biodegradability in the form of water uptake, and soil burial test, and morphology of blends and composites based on PVC matrix were examined. The addition of PLA to the PVC matrix increased glass transition temperature and provided high flexural properties and thermal resistance of the samples. In contrast, the addition of PBAT to binary and ternary blends decreased their glass transition temperature and resulted in high impact strength and tensile properties. The addition of WF to all the blends was found to improve the overall impact strength, flexural properties, Young's modulus, thermal resistance, and biodegradability. SEM images of the blends confirmed that PVC was compatible with PBAT. The SEM images of the composites revealed that the bonding of WF particles and PVC/PLA matrix was better than other matrixes. Based on the findings in this work, it can be concluded that the most suitable composite for decking is PVC/PLA/WF due to it provided an excellent thermal resistance, good flexural properties, low water absorption, and acceptable tensile properties and impact strength.

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