

PREPARATION AND CHARACTERIZATION OF NANO-TITANIA-SILICA BINARY MIXED OXIDE AND PLA COMPOSITE ON MECHANICAL, THERMAL AND MORPHOLOGICAL PROPERTIES

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Abstract

This paper presents the preparation and characterization of titania-silica binary mixed oxide (Ti_xSi_y) and PLA composite on mechanical, thermal and morphological properties. Ti_xSi_y was prepared via sol-gel method to be used as nucleating agent for PLA with 1:1 molar ratio of Ti/Si. Ti_x-Si_y Titanium(IV) isopropoxide (TTIP) and tetraethylorthosilicate (TEOS) were used as Ti and Si precursor, respectively. The structural and chemical properties of TiO_2-SiO_2 were characterized by Fourier transform infrared spectroscopy (FTIR), field emission scanning electron microscope (FE-SEM) and powder X-ray diffraction (XRD). In addition, the chemical compositions were analyzed by energy dispersive X-ray fluorescence (XRF). The FTIR spectra showed the band at 949 cm^{-1} of $Ti_{50}Si_{50}$ mixed oxide associated with Ti-O-Si vibration indicating the forming of chemical bond between TiO_2 and SiO_2 . PLA nanocomposite films were prepared by solvent film casting method at various contents of mixed oxide (1, 3, and 5 wt%). The incorporation of $Ti_{50}Si_{50}$ decreased cold crystallization temperature (T_{cc}) of PLA and increased degree of crystallinity of neat PLA. Thermal stability of PLA was enhanced with the incorporating of TiO_2 and SiO_2 . The addition of 3wt% of $Ti_{50}Si_{50}$ into PLA film exhibited the best tensile strength and Young's modulus comparing to PLA and other PLA composites but low %elongation at break.

Keywords: Mixed oxide, Sol-gel method, Titania, silica, nanocomposites

Introduction

Over the last decade, there has been a continuous research interest on environmental friendly polymers derived from renewable sources as one of the solution to moderate the plastic pollution problem (Lim *et al.*, 2008). Poly (lactic acid) (PLA) is one of the most important biocompatible and biodegradable polymers and it is a sustainable

alternative to petrochemical-derived products. It could be used as the traditional commodity plastic aliphatic polyester that can derived from renewable resources like corn and sugar cane and decomposes through simple hydrolysis into water and carbon dioxide (Chandra and Rustgi, 1998; Madhavan Nampoothiri *et al.*, 2010). PLA has been viewed as

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one of the most promising materials because of its excellent biodegradability, biocompatibility, compostability, renewability, transparency, high strength, and high modulus. Hence, PLA has attracted more attention in various applications especially biomedical applications (Athanasίου *et al.*, 1996). However, its brittleness, poor toughness, slow crystallization rate, low degree of crystallinity, poor thermal stability, low degradation rate, and hydrophobicity are major drawbacks of PLA and limit its application (Burg *et al.*, 1999; Yeh *et al.*, 2009; Rasal *et al.*, 2010). Several modifications such as copolymerization, plasticization, polymer blending and polymer composites have been applied for improving some PLA properties. Nowadays, the addition of selected nanofillers into PLA such as organomodified layered silicates (OMLS) (Huang *et al.*, 2010), carbon nanotubes (CNTs) (Tang *et al.*, 2012), zinc oxide (Murariu *et al.*, 2015), silica nanofillers (SiO_2) (Wu *et al.*, 2016; Hakim *et al.*, 2017), titanium dioxide (TiO_2) (Xiu *et al.*, 2017), can improve PLA characteristic features. TiO_2 or titania is well recognized as a valuable material used in applications such as paints or as filler in paper, polymer, textile, photocatalysis, etc. Nano- TiO_2 particles hold many good properties such as good chemical resistance, high chemical stability (Zapata *et al.*, 2013), attractive photocatalytic activity, excellent photostability, biocompatibility, antimicrobial activity (Fonseca *et al.*, 2015). Another interesting filler is silicon dioxide (SiO_2) or silica, is a chemical compound that contains oxygen and silicon. It has good thermal stability, low cost and high density of silanol groups (Si-OH) on the surface. As a result, it has been widely used in wide applications such as drug delivery (Wang *et al.*, 2006). Moreover, the crystallization properties of PLA can be improved by SiO_2 (Ge *et al.*, 2014). The binary oxides are prepared for many purposes: to expand the chemical properties, to develop a specific textural properties, or to produce a particle with a personalized composition that known to present unique characteristics (large surface areas, thermal stability, etc.) (Galindo *et al.*, 2007). The use of nano-titania-silica binary mixed oxide ($\text{Ti}_x\text{-Si}_y$) as a nucleating agent for PLA composites was studied in this work. Moreover, the effect of Ti_xSi_y , TiO_2 , SiO_2 and $\text{TiO}_2\text{-SiO}_2$ on mechanical, thermal and morphological properties of PLA composites were investigated.

Experimental

Materials

Poly (lactic acid) (PLA, grade 4043D) was supplied from Nature Works LLC. This PLA is the

commercial grade for 3D printing and film applications. Tetraethylorthosilicate (TEOS, 98%, AR grade) and Titanium(IV) isopropoxide (TTIP, 98%, AR grade) were purchased from Acros. Absolute ethanol ($\text{C}_2\text{H}_5\text{OH}$, AR grade) and ammonium hydroxide (NH_4OH , AR grade), and hydrochloric acid (HCl , AR grade) were supplied from Carlo Erba Reagents.

Synthesis of Titania-Silica Binary Mixed Oxide ($\text{Ti}_{50}\text{Si}_{50}$)

Titania-silica mixed oxide was prepared using sol-gel methods (Kim *et al.*, 2000). TEOS and TTIP were used without purification. The mole ratio of alkoxide precursors: NH_4OH : $\text{C}_2\text{H}_5\text{OH}$: H_2O was 2:1:31:8. Total moles of the two alkoxide precursors were fixed at 0.22 mol. The mixture of two alkoxides was added into a 500 cm^3 five-neck flask containing 150 cm^3 ethanol for 1h for pre-hydrolysis. A condenser was attached to prevent the solvent from vaporizing. The reactor temperature was increased to 75-80°C while stirring. TTIP and ethanol (25 ml) was slowly added to reactor drop by drop for 1h and then yellowish transparent sol was obtained after an hour of further mixing. Additional distilled water was added in the sol and aged at 80°C for 2 h at room temperature. Then, the aged gel was further refined for 6,000 rpm for 10 min in centrifugal separator. Finally, the obtained solid particles was calcined at 550°C for 4h. A referenced pure SiO_2 sample was prepared in NH_4OH with the same way described above without the addition of TTIP (Kim *et al.*, 2017). In addition, referenced pure TiO_2 was prepared in acid condition at the same way with mixed oxide (Karkare, 2014).

Preparation of PLA Nanocomposite Films

PLA and nanocomposites were prepared by solvent film casting method. $\text{Ti}_{50}\text{Si}_{50}$, SiO_2 , and TiO_2 was dispersed in chloroform and then PLA were added into this solution. The suspensions were stirred and dispersed for 3 days with ultrasound for 30 min so that the particles could disperse in PLA solution uniformly. At last, the nanocomposites were casted on glass petri dishes. Then the prepared films were kept at room temperature for 12 h and kept in oven at 40°C for 4 h.

Characterization of Titania-Silica Binary Mixed Oxide

Infrared spectra of TiO_2 , SiO_2 , and $\text{Ti}_{50}\text{Si}_{50}$ was determined by Fourier transform infrared spectroscopy using attenuated total reflectance (FTIR-ATR, Bruker, TENSOR 27). The spectra were recorded within the wavenumber of 400-4,000 cm^{-1} with 4 cm^{-1} resolution through the accumulation of 64 scans. Field-emission scanning electron

microscope (FESEM-EDS, Carl Zeiss Auriga) was applied to determine the morphologies of TiO_2 , SiO_2 , and $\text{Ti}_{50}\text{Si}_{50}$. The crystal structure of TiO_2 , SiO_2 , and $\text{Ti}_{50}\text{Si}_{50}$ was determined by powder X-ray diffraction (Bruker, Model D2 phaser, Germany), with $\text{CuK}\alpha$ radiations scanning from 10 - 80° at a rate of $0.05^\circ/\text{s}$ with current 35 mA and powder X-ray diffraction (XRD). In addition, the chemical compositions were analyzed by energy dispersive X-ray fluorescence (XRF) (EDS Oxford Instrument ED 2000) with Rh X-ray tube and a vacuum medium.

Characterization of PLA and PLA Nanocomposites

The tensile properties of PLA and PLA nanocomposites films were obtained using an Instron universal testing machine (UTM, model 5565) with a load cell of 5 kN according to the ASTM standard method D882-88. Initial grip separation and crosshead speed were set at 10 cm and 50 cm/min , respectively.

Thermal properties of PLA and PLA nanocomposites films were carried out using a differential scanning calorimeter (DSC204F1, Netzsch) equipped with a liquid nitrogen cooling system. The sample was heated from room temperature to 200°C at a heating rate of 10°C , and kept for 5 min to erase the thermal history. Then it was cooled to room temperature (25°C) at a cooling rate of 10°C/min . Finally, it was heated again to 200°C at heating rate 10°C/min . The degree of crystallinity (X_c) of PLA and PLA nanocomposites was estimated using the follow equation:

$$X_c = \frac{\Delta H_m}{\Delta H_m^0 \left(1 - \frac{\%wt\ filler}{100}\right)} \times 100$$

where ΔH_m are the melting enthalpy in the second heating process and ΔH_m^0 , which is the melting enthalpy of an infinitely large crystal, was taken as 93.6 J/g (Tang *et al.*, 2012).

Thermogravimetric analysis of PLA and PLA nanocomposite films were examined using thermogravimetric analyzer (TGA/DSC1, Mettler Toledo). The temperature was raised from the room temperature to 650°C under nitrogen and then heated to 800°C under air atmosphere at heating rate of 10°C/min . The weight change was recorded as a function of temperature.

Morphological properties of the film were examined by a scanning electron microscope (JEOL, JSM-6010LV). Acceleration voltage 9 - 12 kV was used to collect SEM images of sample. The cross-sections of the films after tensile test and the

freeze-fractured films in liquid nitrogen were sputtered with gold.

Results and Discussion

Characteristics of $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides, TiO_2 , and SiO_2

Fourier transform infrared (FTIR) spectrum of the $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides, TiO_2 , and SiO_2 nanoparticles were shown in Figure 1. The FTIR spectrum of the $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides showed three main peaks with the wavenumbers of 801 , 949 , and $1,052\text{ cm}^{-1}$. The peak with the wavenumber of 801 and $1,052$ were assigned to the symmetric and asymmetric stretching vibration of Si-O-Si of silica, respectively (Sahu *et al.*, 2009). The peak with the wavenumber of 949 cm^{-1} was commonly attributed to Ti-O-Si vibrations indicating the existence of Ti-O-Si linkages (Yamashita *et al.*, 1998). The Ti-O-Ti bond of the mixed oxides may be too weak to be detected at $1,400\text{ cm}^{-1}$ (Chiahung *et al.*, 2012). The FE-SEM images of $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides, TiO_2 , and SiO_2 were shown in Figure 2. The powders of $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides, TiO_2 , and SiO_2 show a homogeneous spherical morphology with size of 20 - 250 nm . The chemical compositions of $\text{Ti}_{50}\text{Si}_{50}$

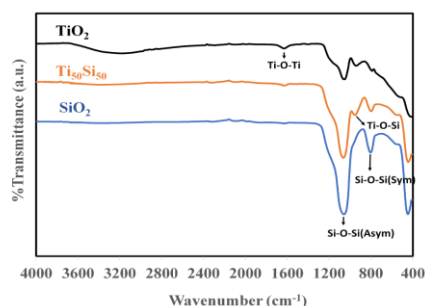


Figure 1. FTIR spectra of $\text{Ti}_{50}\text{Si}_{50}$, TiO_2 , and SiO_2

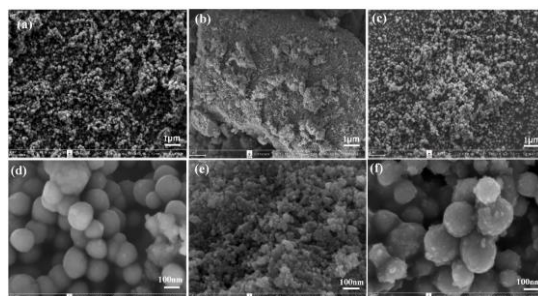


Figure 2. FE-SEM image of (a) $\text{Ti}_{50}\text{Si}_{50}$ ($\times 10\text{k}$), (b) TiO_2 ($\times 10\text{k}$), (c) SiO_2 ($\times 10\text{k}$), (d) $\text{Ti}_{50}\text{Si}_{50}$ ($\times 100\text{k}$), (e) TiO_2 ($\times 100\text{k}$), (f) SiO_2 ($\times 100\text{k}$)

Table 1. The molar content of metal oxides $\text{Ti}_{50}\text{Si}_{50}$, TiO_2 , and SiO_2 by XRF

Compound	TiO_2 (mol.%)	SiO_2 (mol.%)
$\text{Ti}_{50}\text{Si}_{50}$	50.19	49.80
TiO_2	99.91	-
SiO_2	-	99.94

Table 2. Tensile properties of PLA and PLA nanocomposites

Sample	Tensile strength (MPa)	Elongation at break (%)	Young's Modulus (GPa)
PLA	33.94±1.38	19.62±8.64	0.98±0.23
99PLA/1 $\text{Ti}_{50}\text{Si}_{50}$	29.16±1.78	9.08±2.75	1.13±0.10
97PLA/3 $\text{Ti}_{50}\text{Si}_{50}$	35.64±3.21	9.61±2.57	1.29±0.12
95PLA/5 $\text{Ti}_{50}\text{Si}_{50}$	34.25±0.61	7.44±2.19	1.21±0.10
97PLA/3 TiO_2	28.22±1.47	18.1±4.24	1.01±0.04
97PLA/3 SiO_2	29.75±1.38	11.8±4.96	1.07±0.10
97PLA/3 TiO_2SiO_2	29.00±1.42	58.37±5.00	0.96±0.07

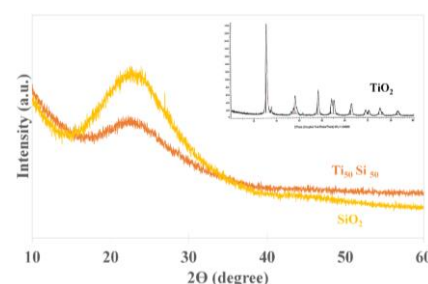
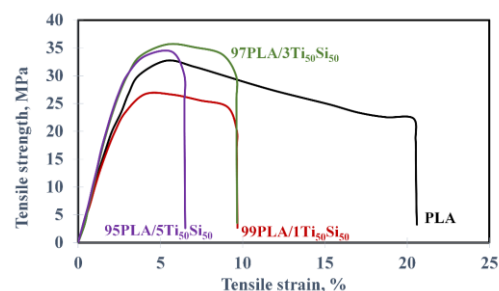
mixed oxide, TiO_2 , and SiO_2 were analyzed by XRF as shown in Table 1. The XRF analysis showed the content of TiO_2 and SiO_2 were 50.19% and 49.80%, respectively. This result confirmed the content of Ti and Si in $\text{Ti}_{50}\text{Si}_{50}$ mixed oxide.

The crystalline structure of $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides, TiO_2 , and SiO_2 was determined by X-ray diffraction (XRD) analysis. The X-ray diffraction patterns of $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides, TiO_2 , and SiO_2 were shown in Figure 3. TiO_2 showed the diffraction peak at 25° (101) and 48° (200), which correspond to the crystalline phase (anatase) of TiO_2 (Sahu *et al.*, 2009; Yamashita *et al.*, 1998). SiO_2 showed only diffraction peak at 23° , which was attributed to a typical pattern of amorphous silica (Pabón *et al.*, 2007). $\text{Ti}_{50}\text{Si}_{50}$ mixed oxides exhibited a broad diffraction peak within 2θ range of $10\text{--}40^\circ$ corresponding to the characteristic of amorphous silica. This indicates that titanium is highly dispersed in silica matrix. However, its crystal size may be too small to be detected by XRD (Ren *et al.*, 2008).

Characterization of PLA nanocomposites

From Figure 4, all of the composite films showed lower transparency than PLA. The transparency of PLA/ $\text{Ti}_{50}\text{Si}_{50}$ decreased with increasing $\text{Ti}_{50}\text{Si}_{50}$ content. The film of 97PLA/3 SiO_2 showed the highest transparency compared with 97PLA/3 $\text{Ti}_{50}\text{Si}_{50}$, 97PLA/3 TiO_2SiO_2 and 97PLA/3 TiO_2 .

Tensile stress-strain curves of pure PLA and PLA/ $\text{Ti}_{50}\text{Si}_{50}$ were shown in Figure 5. Tensile properties of PLA and PLA nanocomposites were listed in Table 2 and Figure 6. The addition of 3wt%

**Figure 3. XRD pattern of $\text{Ti}_{50}\text{Si}_{50}$, TiO_2 , and SiO_2** **Figure 4. Photographs of films prepared from PLA and PLAnanocomposites (250-300 μm thickness)****Figure 5. Stress-strain curves of PLA and PLA nanocomposites**

of $\text{Ti}_{50}\text{Si}_{50}$ slightly increased tensile strength and Young's modulus and decreased %elongation at break of nanocomposites films compared to neat PLA (Figure 6(a)). The addition of nanoparticles to polymer matrix was also found to result in a decrease in ductile properties (Chu *et al.*, 2017). With increasing $\text{Ti}_{50}\text{Si}_{50}$ content from 3 to 5wt%, the tensile strength and Young's modulus slightly decreased. This may be due to the agglomeration of $\text{Ti}_{50}\text{Si}_{50}$ mixed oxide. This result was corresponded to SEM observation. The agglomeration of nanoparticle may act as stress concentrating center in the matrix and adversely affect the mechanical properties of PLA (Shirkavand and Moslehifard, 2014). With the different nanoparticle, 97PLA/3 $\text{Ti}_{50}\text{Si}_{50}$ exhibited higher tensile strength, Young's modulus and lower %elongation at break than

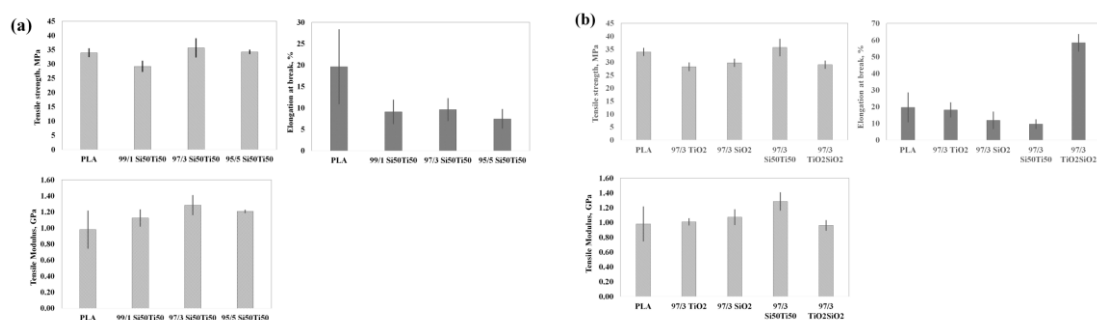


Figure 6. Tensile properties of PLA and PLA nanocomposites (a) various $\text{Ti}_{50}\text{Si}_{50}$ contents (b) different types of nanoparticles

Table 3. Thermal characteristics of PLA and PLA nanocomposites (the second heating, heating rate $10^\circ\text{C}/\text{min}$)

Samples	$T_g, ^\circ\text{C}$	$T_{cc}, ^\circ\text{C}$	$\Delta H_c, \text{J/g}$	$T_{m1}, ^\circ\text{C}$	$T_{m2}, ^\circ\text{C}$	$\Delta H_m, \text{J/g}$	$X_c, \%$
PLA	46.6	103.1	30.14	137.3	146.3	28.59	30.50
99PLA/1 $\text{Ti}_{50}\text{Si}_{50}$	46.4	100.6	31.93	135.8	145.0	32.99	35.56
97PLA/3 $\text{Ti}_{50}\text{Si}_{50}$	46.3	95.2	32.37	133.8	145.0	34.11	37.53
95PLA/5 $\text{Ti}_{50}\text{Si}_{50}$	46.7	95.4	32.16	135.8	145.0	32.75	36.79
97PLA/3 TiO_2	46.8	106.5	24.08	140.0	147.2	28.17	30.99
97PLA/3 SiO_2	46.8	105.0	28.78	138.8	146.7	29.03	31.94
97PLA/3 TiO_2SiO_2	46.7	104.2	24.43	138.9	146.9	23.71	26.09

97PLA/3 TiO_2 , 97PLA/3 SiO_2 , and 97PLA/3 TiO_2SiO_2 as shown in Figure 6(b). This may be due to better dispersion of 3 $\text{Ti}_{50}\text{Si}_{50}$ in PLA than the others.

DSC thermograms of PLA and PLA nanocomposites were shown in Figure 7. Thermal properties of all samples were listed in Table 3. Glass transition temperature (T_g), cold crystallization temperature (T_{cc}), and melting temperature (T_m) of PLA nanocomposites were observed. The double melting endotherms of neat PLA was explained by the melting and recrystallization. The peak at low temperature was attributed to the melting of the crystals formed during the nonisothermal melt crystallization, while the peak at high temperature was corresponded to re-melting of newly formed crystallite during melting and recrystallization during DSC heating scans (Sarasua *et al.*, 1998).

T_g of PLA/ $\text{Ti}_{50}\text{Si}_{50}$ nanocomposites did not change with varying $\text{Ti}_{50}\text{Si}_{50}$ content. In this work, the T_{cc} of the nanocomposites shifted to lower temperature approximately $3\text{--}8^\circ\text{C}$ with increasing $\text{Ti}_{50}\text{Si}_{50}$ mixed oxide contents up to 5 wt%. This indicated that crystallization ability of composite was enhanced. While 97PLA/3 TiO_2 , 97PLA/3 SiO_2 , and 97PLA/3 TiO_2SiO_2 composites showed an increase of the T_{cc} of PLA. This result can be explained by the agglomeration of TiO_2 and SiO_2 . The T_m of nanocomposites was decreased with addition of $\text{Ti}_{50}\text{Si}_{50}$. This may due to the heterogeneous nucleation effect of $\text{Ti}_{50}\text{Si}_{50}$

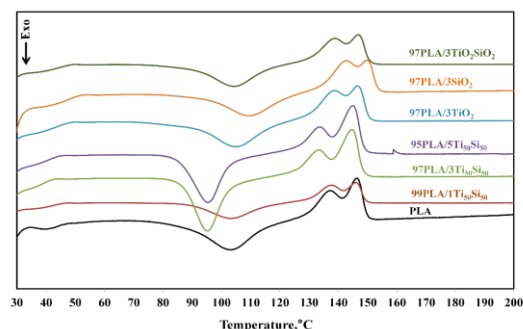


Figure 7. DSC thermograms of PLA and PLA nanocomposites (the second heating, heating rate $10^\circ\text{C}/\text{min}$)

nanoparticles on PLA during the crystallization process. The lamella formation of PLA was hindered by $\text{Ti}_{50}\text{Si}_{50}$ nanoparticles and led to less perfect crystals of PLA (Chen *et al.*, 2014). The degree of crystallinity (X_c), of neat PLA significant increases with increasing $\text{Ti}_{50}\text{Si}_{50}$ content. This implies that $\text{Ti}_{50}\text{Si}_{50}$ nanoparticles can act as a nucleating agent for PLA. However, adding TiO_2 , SiO_2 and TiO_2SiO_2 at 3wt% into PLA showed insignificant effect on T_g and X_c .

TGA curves of neat PLA and PLA nanocomposites were shown in Figure 8. The presence of $\text{Ti}_{50}\text{Si}_{50}$, TiO_2 , SiO_2 and TiO_2SiO_2 did not change the thermal decomposition behavior of PLA. First, there was an initial mass loss between

80-170°C, attributed to the loss of water and moisture. After that, a significantly mass loss between 250-360°C was observed, which corresponded to the decomposition of PLA. Finally, from 360 to 600°C thermal analysis curves slow down to complete the decomposition of PLA matrix until a constant mass was reached. The onset decomposition temperature (T_{onset}), decomposition temperature (T_d) and final decomposition temperature (T_f) were listed in Table 4. With the addition of nanoparticles, the degradation begins at slightly higher temperature. This suggested that thermal stability of PLA was slightly enhanced with the incorporating of TiO_2 and SiO_2 . Moreover, when 1, 3, and 5 wt% Ti_50Si_{50} mixed oxides were added into PLA, the composites left the char residual of nanoparticle at 1.61, 3.67, and 5.22%, respectively for PLA/ Ti_50Si_{50} . The char residual generally depends on the amount of added nanoparticles (Buzarovska, 2013).

The surface morphology of prepared films was investigated by SEM analysis. The cross-section of PLA and PLA composites films were presented in Figure 9. PLA showed relative brittle and smooth fracture surface morphology. At low Ti_50Si_{50} content, well dispersion of nanoparticles in PLA matrix was observed. Moreover, 97PLA/3 SiO_2 and PLA/3 TiO_2SiO_2 showed more agglomeration of SiO_2 , and TiO_2SiO_2 leading to PLA composites with poor mechanical properties. In addition, the micrographs of the fracture surface after tensile tests for PLA and PLA nanocomposites films with a magnification of 1500x were shown in Figure 10. PLA/ Ti_50Si_{50} nanocomposite showed many small cavities on the fracture surface of the nanocomposite due to the removal of agglomerate of nanoparticles during the tensile test. However, PLA/ TiO_2 , PLA/ SiO_2 , and PLA/ TiO_2SiO_2 nanocomposites presented more cavities and fibril on the fracture surface than PLA/ Ti_50Si_{50} nanocomposite indicating poor interfacial interaction between particles of TiO_2 or SiO_2 and PLA matrix.

Table 4. Thermal degradation of PLA and PLA nanocomposites

Samples	T_{onset} , °C	T_d , °C	T_f , °C	Residual, %
PLA	344.86	358.83	424.64	0.7053
99PLA/1 $Ti_{50}Si_{50}$	345.30	350.26	420.69	1.6108
97PLA/3 $Ti_{50}Si_{50}$	346.24	356.67	425.49	3.6729
95PLA/5 $Ti_{50}Si_{50}$	347.09	356.33	418.93	5.2243
97PLA/3 TiO_2	351.16	362.17	429.22	4.0747
97PLA/3 SiO_2	346.04	359.50	427.27	4.1432
97PLA/3 TiO_2SiO_2	348.66	360.17	418.69	3.7922

Conclusions

In this study, $Ti_{50}Si_{50}$ mixed oxide was synthesized using TTIP and TEOS as precursors. A combination of FTIR, FE-SEM, XRD and XRF have been used to characterize morphologies and structures of the mixed oxide. $Ti-O-Si$ vibration of $Ti_{50}Si_{50}$ mixed oxide was confirmed by FTIR at 949 cm^{-1} indicating the forming of chemical bond between TiO_2 and SiO_2 . The powders of $Ti_{50}Si_{50}$ mixed oxides, TiO_2 , and SiO_2 show a homogeneous spherical morphology with size of 20-25 nm. XRD results of $Ti_{50}Si_{50}$ mixed oxides presented a broad diffraction peak within the 2θ range 10-40 corresponding to

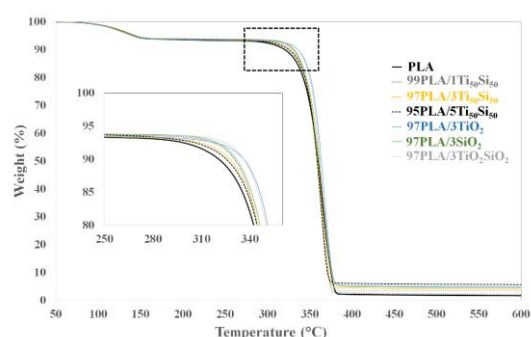


Figure 8. TGA curves of PLA and PLA nanocomposites at a heating rate of 10°C/min

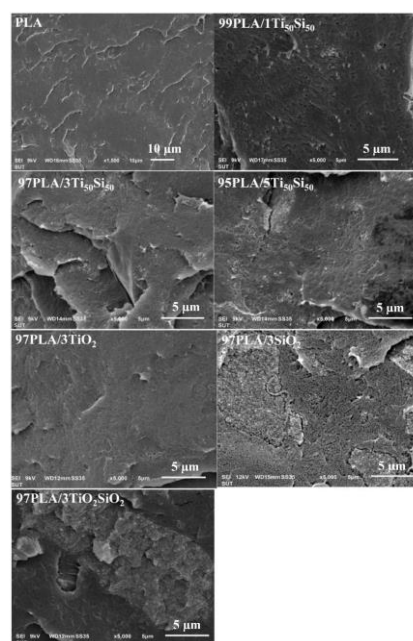


Figure 9. SEM micrographs at 5000x magnification of PLA and PLA nanocomposites

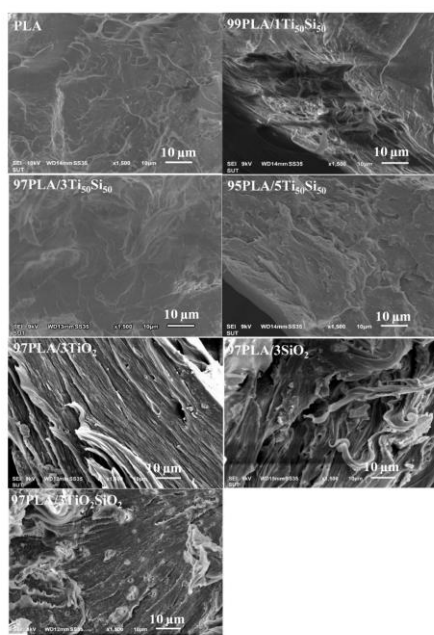


Figure 10. SEM micrographs after tensile testing at 1,500x magnification of PLA and PLA nanocomposites

characteristic of amorphous silica. This indicates that the titanium is highly dispersed in the silica matrix. The addition of 3 wt% of $\text{Ti}_{50}\text{Si}_{50}$ into PLA film improved the tensile strength and Young's modulus of PLA. The incorporation of $\text{Ti}_{50}\text{Si}_{50}$ decreased the cold crystallization temperature and increased degree of crystallinity of PLA. It may be concluded that $\text{Ti}_{50}\text{Si}_{50}$ nanoparticles can act as a nucleating agent for PLA. Thermal stability of PLA was enhanced with the incorporation of TiO_2 and SiO_2 .

Acknowledgments

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