


EREM 78/1 Journal of Environmental Research, Engineering and Management Vol. 78 / No. 1 / 2022 pp. 57–69 DOI 10.5755/j01.erem.78.1.29502	Degradation Behavior of Biodegradable Plastics in Thermophilic Landfill Soil and Wastewater Sludge Conditions	
	Received 2021/08	Accepted after revision 2022/02
	 http://dx.doi.org/10.5755/j01.erem.78.1.29502	

Degradation Behavior of Biodegradable Plastics in Thermophilic Landfill Soil and Wastewater Sludge Conditions

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In this study, three common biodegradable plastics, namely, poly(hydroxybutyrate-co-hydroxyvalerate) (PHBV), poly(butylene succinate) (PBS) and poly(butylene adipate-co-terephthalate) (PBAT) were all buried in a mixture of landfill soil and wastewater sludge and incubated under thermophilic (61°C) oxygen-limited conditions. At the end of the 90-day test, the degradation ranking order was PHBV > PBS > PBAT. Only PHBV was completely degraded over the 60 days, while PBS and PBAT displayed 24.04% ± 3.37% and 18.26% ± 3.77% weight loss, respectively. The differences in the degradation and disintegration profiles among these materials were observed. The results showed that PHBV lost its thickness and degraded from the edges of the specimens. Both PBS and PBAT were reduced into small fragile fragments during the degradation process. SEM micrographs revealed that irregular roughness with many holes and cracks was characteristic of PHBV, while slightly smooth surfaces were found on PBS and PBAT. All the materials showed continuous decreases in the thermal stability and the percentage of carbon content in the molecular structures after the degradation test. Fourier transform infrared (FTIR) spectroscopy revealed that the chemical structure of PHBV was changed during the biodegradation test,

while both PBS and PBAT were unchanged under the same test conditions. However, the peak for carboxylate ions was found after the degradation of all the samples. Having a deep understanding of the degradability behavior can contribute to the development of biodegradable plastic waste management in the future.

Keywords: biodegradable plastic, degradation, landfill; weight loss, PHBV.

Introduction

Petroleum-based or conventional plastics are manufactured long-chain polymers with high molecular masses. Because of their favorable chemical and physical properties, petroleum-based plastics have been used to replace many natural materials (Shah et al., 2008). Plastics tend to resist biodegradation because microorganisms in nature are unable to produce the enzymes for biodegradation (Shah et al., 2008). Therefore, nondegradable plastics are not incorporated into the carbon cycle (Hayase et al., 2004). Moreover, these plastics are designed for long-term use over a wide range of applications. In fact, plastics are common in single used applications, especially plastic bags, packaging, and medical materials (Chanprateep, 2010). This use produces a large amount of landfill waste. In recent years, there has been increased concern about environmental problems. One of the largest major problems is the disposal of solid waste, especially nondegradable plastic, which has reached a critical point in the environment (Abdel-Shafy & Mansour, 2018; Quecholac-Piña et al., 2020). Plastics are dangerous to both the physical and biological parts of the environment. Moreover, burning plastic waste releases toxic chemicals, including carcinogens, resulting in air pollution (Shah et al., 2008). To reduce the environmental pollution from plastic waste, biodegradable plastics with similar properties to those of conventional plastics have been developed and released to the market.

Polyhydroxyalkanoates (PHAs) are a group of polymers belonging to the microbial polyesters. Poly(hydroxybutyrate) (PHB) and its copolymer, poly(hydroxybutyrate-co-hydroxyvalerate) (PHBV), are representative polymers of the PHA family that can be accumulated in microbial cells and serve as carbon and energy sources (Weng et al., 2010; Salomez et al., 2019). The PHBV copolymer is stronger and more flexible than PHB, so it is used more frequently

in commercial production (Liu et al., 2019; Tebaldi et al., 2019; Policastro et al., 2021). PHBV, which is one of the best candidate biodegradable plastics, can be degraded by many groups of microorganisms such as *Bacillus* sp. AF3 (Shah et al., 2007) or *Actinomadura* sp. AF-555 (Shah et al., 2010). Previously, the biodegradability of PHBV was demonstrated under composting (Luo & Netravali, 2003; Iggui et al., 2015; Muniyasamy et al., 2019), anaerobic conditions (Abou-Zeid et al., 2001), and soil under tropical conditions (Boyandin et al., 2013).

Poly(butylene succinate) (PBS) and poly(butylene adipate-co-terephthalate) (PBAT) are commercial biodegradable plastics with good mechanical properties. They are chemically synthesized from petroleum resources (Gigli et al., 2016). Although they are petroleum-based products, they have the ability to be biodegradable and environmentally compatible. The degradability of PBS was reported both in compost and under soil conditions (Abe et al., 2010; Phua et al., 2012; Al Hosni et al., 2019). PBAT was degraded by fungal strain NKCM1712, which is closely related to *Isaria fumosorosea*, in medium containing PBAT (Kasuya et al., 2009). The degradation of PBAT was catalyzed by lipase from *Stenotrophomonas* sp. YCJ1 (Jai et al., 2021). Moreover, PBAT degradability was reported in soil burial conditions (Kijchavengkul et al., 2010; Wang et al., 2015).

Biodegradable plastics require suitable conditions for complete degradation. They seem to be preferably degraded under compost conditions (Fojt et al., 2020). However, bioplastic wastes are not only sent to compost, but they are also discarded in landfills in large amounts. Therefore, the degradation of biodegradable plastics under landfill conditions must be investigated. Our study revealed that poly(lactic acid), one of the biodegradable polymers, showed good degradability

under thermophilic oxygen-limited conditions (61°C) (Boonmee et al., 2016a). We define “oxygen-limited conditions” as those in which the amount of dissolved oxygen is at a starvation level. However, both aerobic and anaerobic biological activities occur under these conditions. In this study, the degradability behavior of three commercial biodegradable plastics, namely, PHBV, PBS, and PBAT, was investigated under thermophilic oxygen-limited conditions. A mixture of landfill soil from agricultural soil and anaerobic sludge from the anaerobic digester of a wastewater plant was used as the source of microorganisms.

Materials and Methods

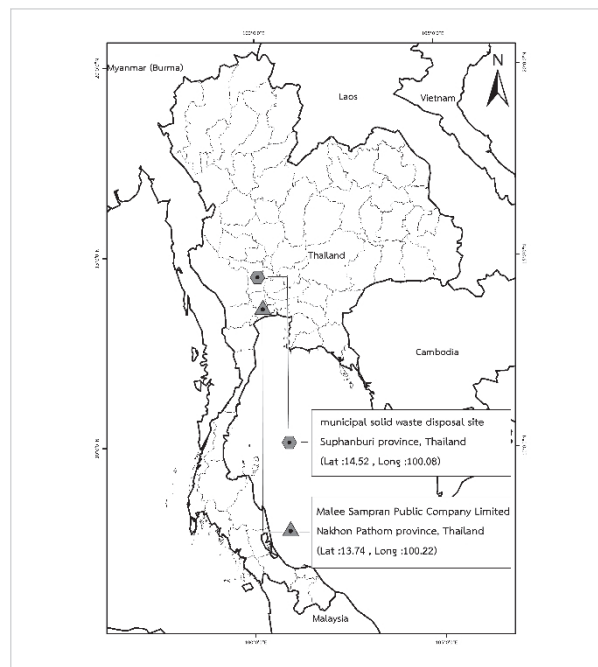
Materials

The homopolymer PBS and two copolymers of biodegradable plastics, PHBV and PBAT, were supplied as granules by the National Metal and Materials Technology Center in Thailand. The PBS and PBAT sheets were prepared using a cast sheet extrusion machine. The PHBV sheet was prepared by hot press compression molding. All the prepared sheets were cut into 2×2 cm pieces.

Medium

A mixture of landfill soil and anaerobic sludge in a 50:50 ratio was used as the inoculum. Soil was collected from a municipal solid waste disposal site in Suphanburi province, Thailand. Anaerobic sludge was obtained from the anaerobic digestion of wastewater from Malee Sampran Public Company Limited, Nakhon Pathom Province, Thailand. The location of these two sites is shown in Fig. 1. The total solid content (%) of landfill soil and anaerobic sludge was 95.70% and 65.40%, respectively, which was determined according to standard methods. The percentages of C, H, and N and the C:N ratio were analyzed by CHNS/O analyzer. The physical and chemical properties of the medium are described in our previous study (Boonmee et al., 2016b). The C:N ratio of landfill soil and anaerobic sludge was 7.48:1 and 7.23:1, respectively. The initial pH of the landfill soil and anaerobic sludge was 7.73 and 7.14, respectively, which is suitable for microbial growth.

Fig. 1. Location of the landfill site and anaerobic digestion plant



Experimental set-up

The degradation tests were conducted in 660 mL glass test vessels containing 330 g of the inoculum. The specimens were put into a net bag at 1.5% weight by weight and buried in the inoculum. Each glass vessel was sealed with a rubber cap to create oxygen-limited conditions and incubated at 61°C in the dark for 90 days. All the tests were performed in triplicate. To investigate the degradation of biodegradable plastic under the test conditions, the recovered specimens were taken out of the glass test vessels at 15, 30, 45, 60, 75, and 90 days and thoroughly washed with distilled water to remove contaminating particles. The specimens were dried and kept in a desiccator until their weights were constant. The dried specimens were used to calculate the percentage of weight lost according to the following equation (1). The weight loss percentage was averaged from three vessels.

$$\text{Weight loss (\%)} = \frac{(w_i - w_f)}{w_i} \times 100 \quad (1)$$

Where: w_i – the original sheet weight; w_f – the weight of the specimen after the degradation test.

pH analysis

After each degradation time, the inoculum pH was monitored by using a pH electrode (C862, Consort, Belgium). The inoculum (10 g) was added to 50 mL of deionized water, mixed for 2 min, and allowed to stand for 1 h at room temperature before the pH measurement.

Visual evaluation and particle size analysis

The effects of the degradation on the physical structural appearance were observed by visual observation. Moreover, a particle size analysis was performed by the sieving method. The fragmented residuals of each tested sample were divided into four fractions, namely greater than 6.73 mm, 6.73–2 mm, 2–1 mm, and less than 1 mm. Each sample fraction size was separately determined to find the weight fraction percentage.

Scanning electron microscopy

A morphological examination of the original samples and the residuals after the degradation test were comparatively observed by using a scanning electron microscope (SEM model JSM-5410LVJEOL, Japan) operating at an acceleration voltage of 10 kV. Each tested sample was coated with gold prior to SEM observation.

Fourier transform infrared (FTIR) spectroscopy

The chemical structures of the samples were analyzed after the degradation test using FTIR spectroscopy over a frequency range from 650 cm^{-1} to 4000 cm^{-1} using a Perkin Elmer FTIR-spectrometer Spectrum One (PerkinElmer, U.S.A.).

Thermal gravimetric analysis

The thermal properties of the original samples and the residuals after the degradation test were analyzed by Thermal Gravimetric Analyzer (NETZSCH Thermos gravimetric balance, model TG 209F3, NETZSCH, Germany). The tests were run using a heating rate of $20^\circ\text{C min}^{-1}$ from 28°C to 600°C under a nitrogen atmosphere.

Elemental analysis

The C, H, and O contents of the samples before and after degradation were analyzed with an elemental analyzer (PerkinElmer model PE2400 Series II, PerkinElmer, USA).

Results and Discussion

Weight loss (%) and degradation rate

The degradation of each biodegradable plastic under thermophilic oxygen-limited conditions was investigated by measuring the weight loss percentage and the rate of degradation (mg/day) as shown in Fig. 2 and Table 1, respectively. The highest weight loss (%) was found for PHBV, which showed complete degradation (100%) over the 60 days of the degradation test. At 30 days, the PHBV showed an $83.27\% \pm 0.97\%$ weight loss and a 154.38 mg/day degradation rate. The PBS displayed a slower degradation than the PHBV. As can be observed from Table 1, the highest degradation rate for PBS was found at approximately days 76–90 at 33.15 mg/day . The weight of PBS was reduced to $24.04\% \pm 3.37\%$ until the end of the testing. Under the test conditions, PBAT showed the slowest degradation. Only $8.13\% \pm 0.87\%$ of the weight loss occurred after the first 60 days. However, the most obvious degradation rate occurred from 61 to 75 days (25.06 mg/day) and there was a $15.53\% \pm 1.97\%$ weight loss at 75 days. At the end of the degradation test, PBAT displayed an $18.26\% \pm 3.77\%$ weight loss with an 8.47 mg/day degradation rate.

Fig. 2. Weight loss percentage of PHBV, PBS, and PBAT as a function of time during a 90-day degradation

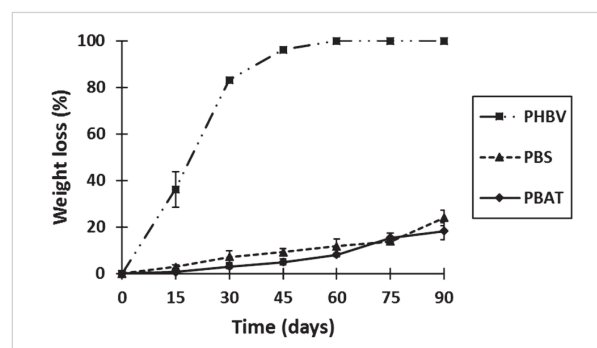


Table 1. Degradation rates of PHBV, PBS, and PBAT

Sample	Rate of degradation (mg/day)					
	0–15	16–30	31–45	46–60	61–75	76–90 days
PHBV	119.25	154.38	42.46	12.91		
PBS	9.66	14.75	6.17	8.69	7.12	33.15
PBAT	2.47	7.85	6.76	10.56	25.06	8.47

The degradation rate of biodegradable plastics is influenced by both abiotic and biotic factors. The abiotic factors include the properties of the polymers and the surrounding environmental factors, while the biotic factors depend on the type of microorganisms and their enzyme activity. Temperature is one of the environmental factors that plays a key role in polymer degradation (Arcos-Hernandez et al., 2012; Dvorackova et al., 2015). In this study, the biodegradability of three different biodegradable plastics was investigated and compared. Over 90 days, PHBV experienced complete degradation, whereas PBS and PBAT were slowly degraded under the test conditions. PHBV displayed the highest degradation. This result occurred because this polymer could be naturally synthesized by bacteria to serve as an energy source. Therefore, the enzyme produced by bacteria could degrade the polymer. By contrast, PBS and PBAT are chemically synthesized petroleum-based plastics. They required longer degradation times than PHBV. According to the literature, PHBV showed good degradability under composting conditions, which are oxygen-requiring conditions (Weng et al., 2010; Luo & Netravali, 2003; Weng et al., 2011). However, in this study, the results revealed that PHBV was also degraded under oxygen-limited conditions.

Along with PBS, this polymer can be degraded under aerobic composting, soil environment and anaerobic environments (Cho et al., 2011; Dvorackova et al., 2015; Hosni et al., 2019). The percentage of PBS weight loss in this study was similar to the result by Dvorackova et al. (2015), who reported that 25.4% of PBS was lost under thermophilic anaerobic conditions. Hosni et al. (2019) reported a moderate reduction in the weight of PBS discs at 50°C in compost and 37°C in soil but there was no significant weight loss at 25°C in compost and soil conditions. Moreover, there was no significant weight loss of buried PBS under uncontrolled soil conditions over a period of 21 months. The biodegradability of PBS is significantly affected by the temperature. Therefore, PBS should be degraded under thermophilic conditions to enhance the degradation rate.

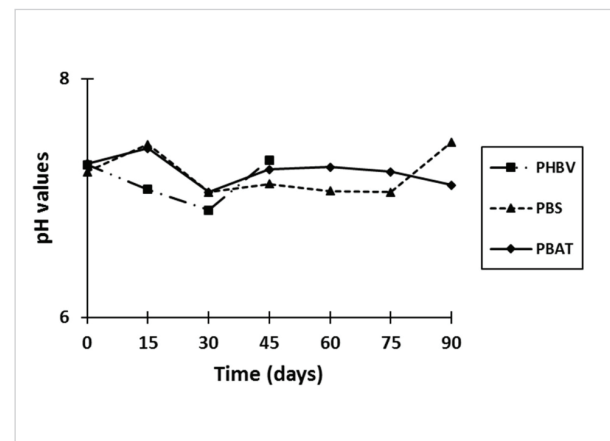
PBAT showed low degradability under the test conditions. According to the literature, PBAT has good composability under aerobic conditions. PBAT could be degraded in a natural soil environment. However, a slow PBAT degradation rate was found in a natural

soil environment (Wang et al., 2015; Saadi et al., 2013). This may have occurred because of the higher microbial population found under the high humidity and temperature of the compost environment. Moreover, the degradation rate of PBAT also depended on the amount and source of microorganisms (Kijchavengkul et al., 2010). Therefore, in the case of PBAT, a more suitable method should be considered to accelerate the waste management of PBAT.

pH variation

The change in the pH of the medium during the degradation test was investigated. The results are shown in Fig. 3. The initial pH of the medium was over a range from 7.22–7.29. During the 30 days of testing, the pH value of PHBV decreased more quickly than the pH values of PBS and PBAT. This result was related to the weight loss percentage and the degradation rate (mg/day). As described in Fig. 2 and Table 1, the highest degradation rate for PHBV was observed at 30 days. At that day, PHBV was degraded and released acidic products, which led to a reduction in the pH. However, after 30 days, the plateau phase of PHBV degradation, the pH value increased to 7.32. This rebound could indicate that the acidic products from the PHBV degradation process were used by microorganisms. This result was in accordance with a study by Weng et al. (2010), who reported that the lowest pH value of PHBV medium was 6.40 at week 6 of testing and the pH increased and then stabilized until the end of the testing. Iggui et al. (2015) reported decreasing pH at early stages in compost

Fig. 3. pH variations in the medium at different test times

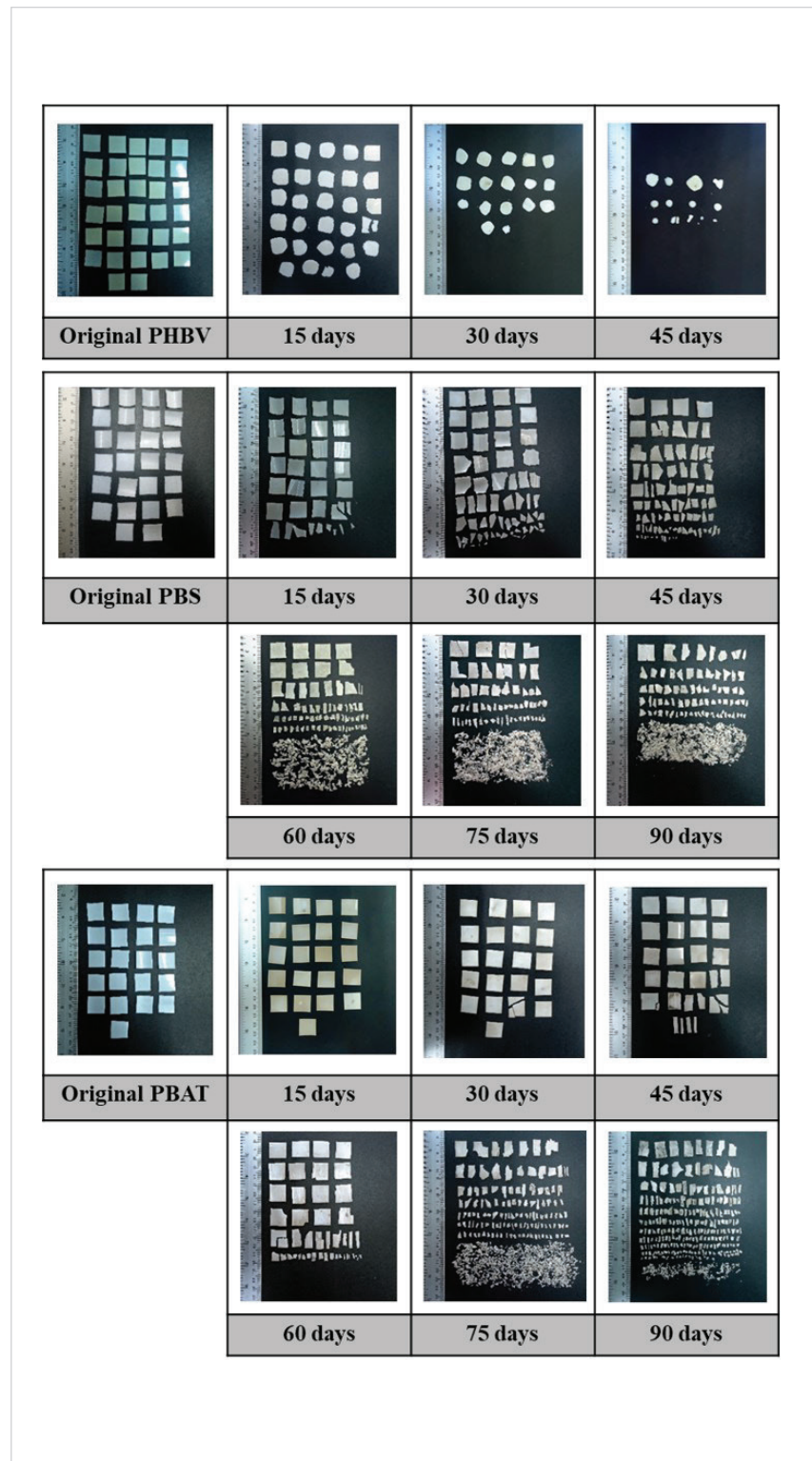


containing cast PHBV; then the pH increased due to the hydrolysis of polymeric material. The pH of the medium was slightly changed in the case of PBS and PBAT. This change probably occurred because PBS and PBAT degraded slowly under these conditions, and therefore, a small number of acidic products leaked out into the medium.

Visual appearance and particle size

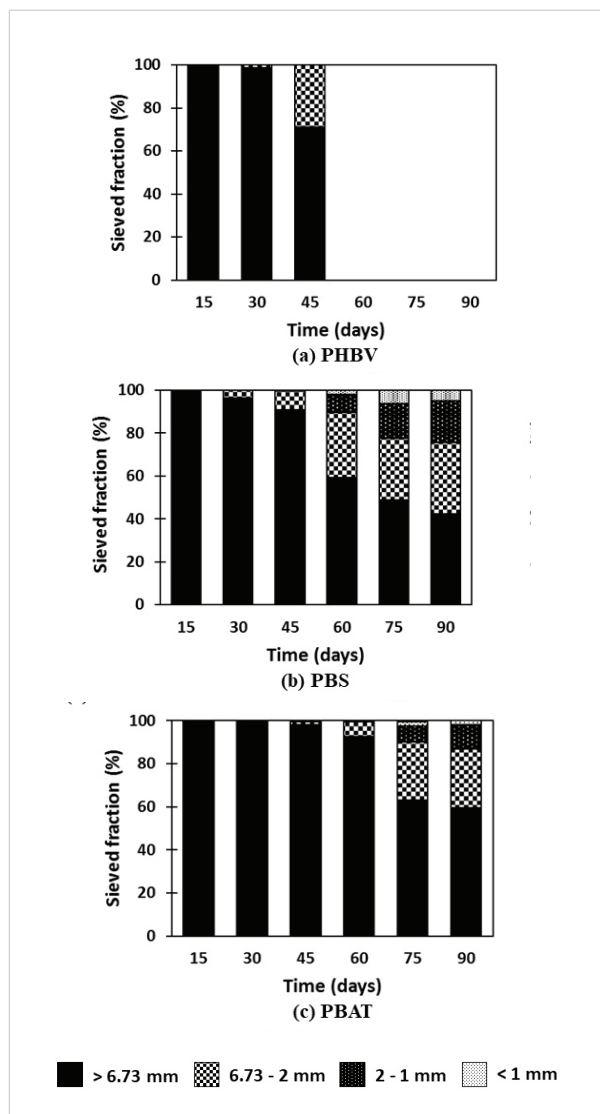
The change in the residual fragment appearance was demonstrated in Fig. 4. PHBV was degraded from the edges of the specimens. The erosion of the surface was also observed, which resulted in the reduction of the sample thickness. After 15 days, reductions in the size and shape alteration were observed. The specimens were continuously degraded into smaller, thinner, and rougher fragments. After 60 days, no residual fragment was found in the PHBV system. The degradation characteristics of PBS and PBAT were different from those of PHBV. Few PBS specimens showed disintegration after 15 days and were smaller, fragile fragments when the degradation time reached 60 days. For PBAT, only one specimen was cracked after 30 days of the incubation time. The smaller residual fragments were found after 75 days of testing. The residual fragments were sieved to specify particle sizes at degradation times of 15, 30, 45, 60, 75 and 90 days. Plots with four size ranges

Fig. 4. Photographs of residual samples at different degradation times



(> 6.73 mm, 6.73–2 mm, 2–1 mm, and < 1 mm) for the three samples are shown in Fig. 5. PHBV had the highest degradation, at approximately 71% of the residual fragments for the fraction greater than 6.73 mm. At 45 days under test conditions, PBS and PBAT showed a similar profile of fragmentation and deterioration. During the degradation test, the sieved fraction of pieces greater than 6.73 mm was the primary fraction in both PBS and PBAT. However, the other smaller fractions were increased with the increasing degradation times. At the

Fig. 5. Particle size fractions for residual samples of (a) PHBV, (b) PBS, and (c) PBAT at different degradation times. The size ranges are > 6.73 mm, 6.73–2 mm, 2–1 mm, and < 1 mm.



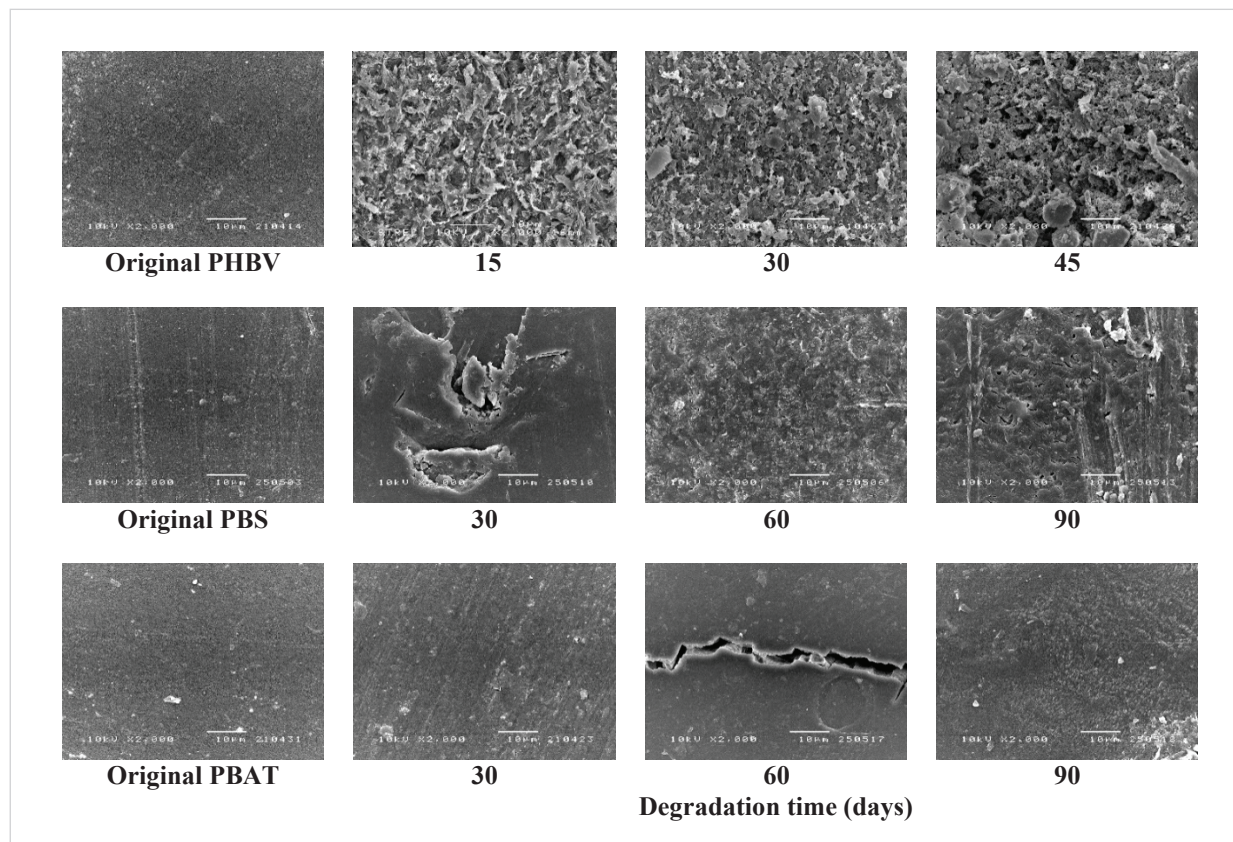
end of the testing, PBS and PBAT consisted of $33.05\% \pm 0.14\%$ and $27.23\% \pm 11.30\%$ of 6.73–2 mm fraction, $19.65\% \pm 2.13\%$ and $11.64\% \pm 4.34\%$ of 2–1 mm fraction, and $4.90\% \pm 0.33\%$ and $1.75\% \pm 0.75\%$ of < 1 mm fraction, respectively.

Surface morphology

Fig. 6 reveals the SEM micrographs of the three samples at various testing times. The plastic surface was normally smooth. After the degradation test, PHBV changed the most. Many holes and cavities were observed on the PHBV surface at 15 days. More irregular, rough, and porous surfaces were found with the increasing testing times. This finding is consistent with several studies (Weng et al., 2011; Iggui et al., 2015; González-Ausejo et al., 2017; Muniyasamy et al., 2019). In the case of PBS, the samples showed a rougher surface than the original samples after 60 days of incubation. At 90 days, holes and cracks were present on the PBS surface. For PBAT, in the SEM images taken at 60 days, cracks were found on the surface. However, most of the surfaces were still smooth even after 90 days of the test.

Similar behavior in the PHBV surface change has also been reported. The eroded pattern and irregular pits on the surface are due to microorganisms such as *Streptomyces* sp. SNG9 (Mabrouk & Sabry, 2001), *Actinomyces* sp. AF-555 (Shah et al., 2010) and *Enterobacter* sp., *Bacillus* sp., and *Gracilibacillus* sp. (Volova et al., 2010). The microorganisms that colonized the surface would release depolymerase onto the surface. This process caused irregular roughness, pores, cracks, and hole formation. The enzymes were also gradually accelerating the formation of holes inside the film matrix, inducing hydrolysis in the amorphous phase of the polymer (Weng et al., 2010; Tao et al., 2009). For PBS, after being buried under composting conditions, it displayed many holes and more erosion on the surface, while a slight change in the surface was found after the soil burial test (Kim et al., 2006; Phua et al., 2012; Huang et al., 2018). The surface morphology of PBAT seems unchanged. A similar phenomenon was also reported by Kijchavengkul et al. (2010) and Wang et al. (2015). However, Muroi et al. (2017) reported small cracks and slightly rough

Fig. 6. SEM micrographs of residual samples: (a) PHBV, (b) PBS, and (c) PBAT at different degradation times



on the surface of PBAT film after buried at 30°C for 3 months in soil conditions and the large cracks were found after 6 months. Kasuya et al. (2009) revealed many cracks on the PBAT surface after incubation under aerobic conditions.

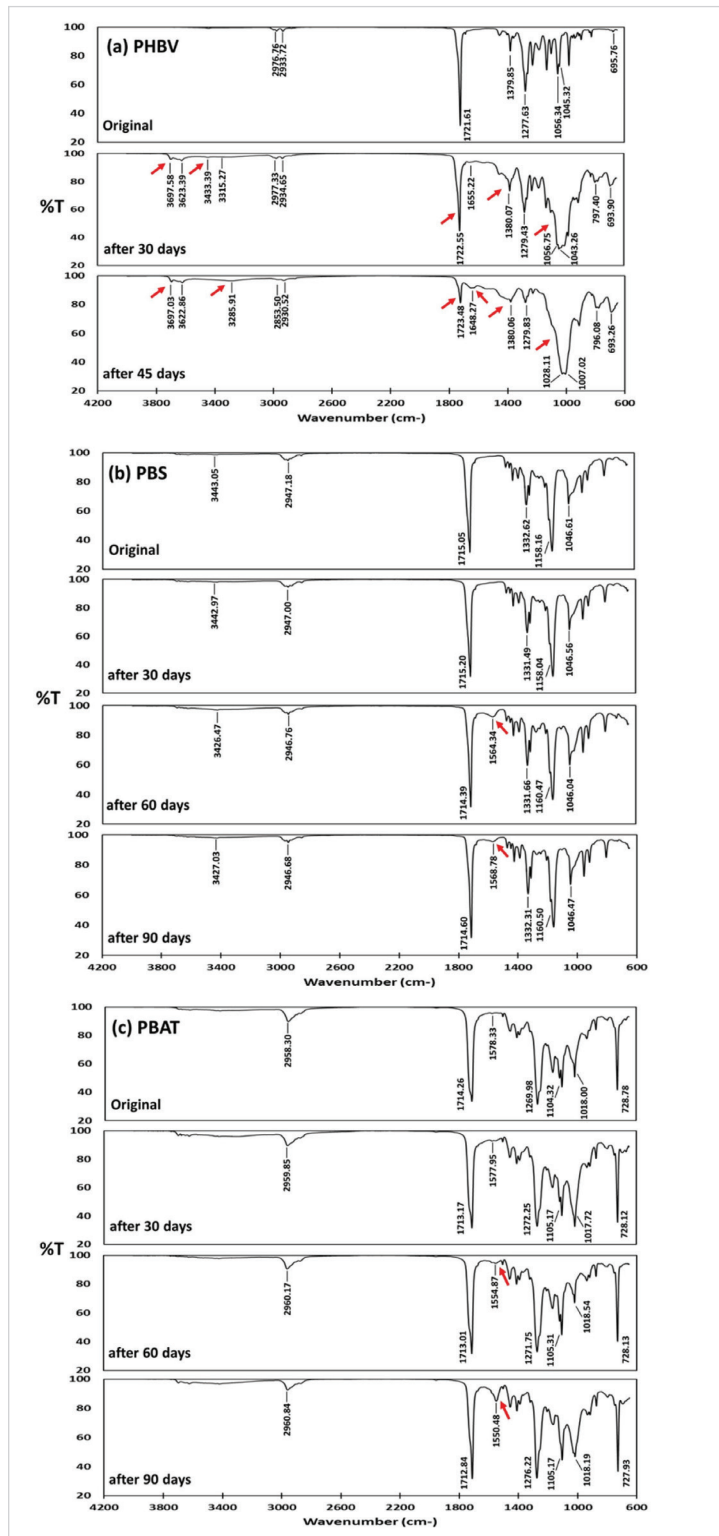
Fourier transform infrared (FTIR) examination

FTIR spectra of the original and treated samples are shown in Fig. 7. The FTIR spectra of the treated PHBV samples showed some differences in the shape and intensities of IR peaks from the original PHBV (Fig. 7(a)). The absorption peak of the C=O stretching vibration at 1721.61 cm^{-1} shifted to 1722.55 cm^{-1} and 1723.48 cm^{-1} after 30 and 45 days of testing, respectively. The intensities of the C=O ester peaks were found to decrease after the degradation. These findings were consistent with the study by Kuntanoo and Promkotra (2013). Moreover, the IR results showed that the broader OH

stretching (4000–3000 cm^{-1}) and the C–H stretching vibrations (3300–2700 cm^{-1}) occurred after degradation. Similar results were reported by Weng et al. (2011). It is suggested that the hydrolysis of the C=O ester bond occurred, resulting in the formation of hydroxyl and carboxylic groups. In addition, the shape of peaks associated with $-\text{CH}_3$ out-of-plane bending vibrations (1500–1300 cm^{-1}) and C–O and C–C skeletal vibrations (1300–1000 cm^{-1}) was changed. This may be because these regions were the degradation sites of PHBV.

The FTIR spectra of PBS and PBAT at different degradation times are shown in Fig. 7(b) and 7(c), respectively. Similar spectral patterns for the original and treated sample were found even after 90 days of degradation. These results indicated that the primary chemical structures of residual samples were not significantly changed. According to Bonilla et al., (2020), no significant changes of FTIR spectra can be

Fig. 7. FTIR spectra of (a) PHBV, (b) PBS, and (c) PBAT at different degradation time



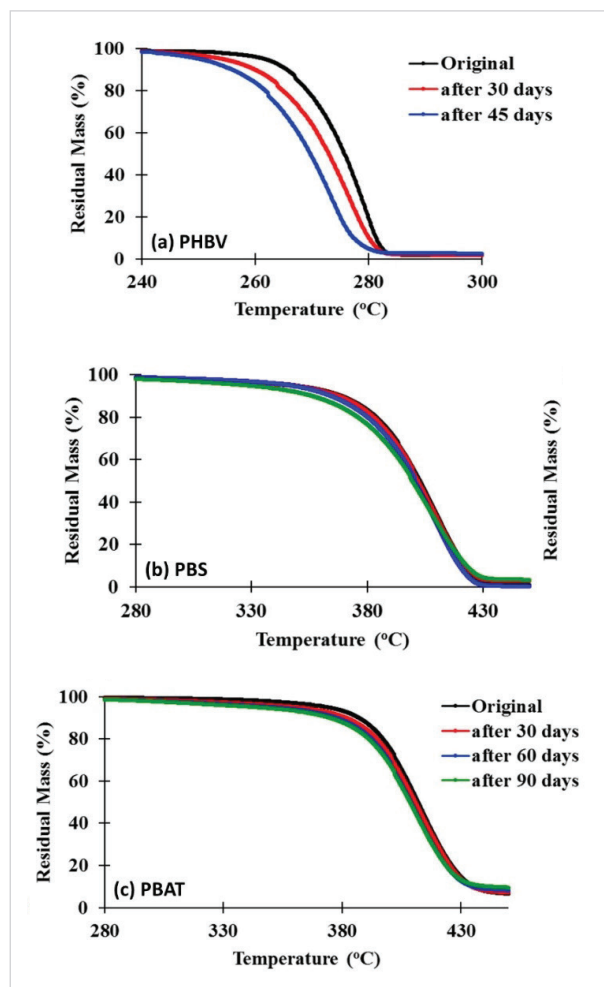
identified during 28 days of PBAT degradation in an aquatic system. However, in this study, the peak associated with the formation of carboxylate ions (located at approximately 1600 cm^{-1}) was found after the incubation of all the samples. The occurrence of the peak was also reported for PLA degradation by Arrieta et al. (2014) and Boonmee et al. (2016a). The presence of this peak suggested that the microorganisms degraded the polymeric chains and left the carboxylate ions at the end of the product chains.

Thermal stability analysis

The thermal stability of the samples before and after the degradation test is illustrated by the thermogravimetric (TG) curves shown in Fig. 8. The TG curves show the relationship between the percentage mass loss and the temperature. In Fig. 8, all the tested samples exhibit a single-stage decomposition temperature pattern. The original pattern for PHBV indicated a cumulative mass loss at 265.9°C (T_i = the initial temperature) and showed the maximum cumulative mass loss when the temperature reached 283°C (T_f = the final temperature). After 45 days of degradation testing, the T_i and T_f of the residual PHBV decreased to 256.7°C and 278.4°C , respectively. The original PBS had a reaction interval of mass loss between 376.8°C and 425.2°C (T_i and T_f). The temperature of the residual PBS decreased slightly after 90 days of degradation testing (366.4°C of T_i and 424.8°C of T_f). Among the samples, PBAT had the highest thermal stability. The original PBAT showed the reaction interval of mass loss between 388.6°C and 432.1°C . However, the temperature interval decreased to 383.8°C of T_i and 427.9°C of T_f after 90 days of degradation testing. According to these results, all the plastics lost their thermal stability after the degradation process. These changes in thermal stability probably occurred because the long

chains of polymer were hydrolyzed into shorter polymer chains. Thus, low molecular mass polymer chains formed by chain scission, leading to reduced thermal stability.

Fig. 8. TG curves of (a) PHBV, (b) PBS, and (c) PBAT at different degradation time



Elemental content analysis

The C, H, and O contents of the PHBV, PBS, and PBAT sheets before and after the degradation test were analyzed, and the results are shown in Table 2. The carbon content of all the samples decreased, whereas the oxygen content increased. A similar phenomenon was also found in our previous study on the PLA degradation test (Boonmee et al., 2016a). A similar trend was also presented by Weng et al. (2013). The authors suggested

Table 2. Elemental content of %C, %H and %O in PHBV, PBS, and PBAT before and after degradation

Degradation time (days)	%C	%H	%O
Original PHBV	55.31	7.06	37.10
15	54.62	6.94	37.91
30	54.28	6.91	38.35
45	54.03	6.88	38.55
Original PBS	54.92	6.93	38.14
30	54.33	6.95	38.71
60	54.21	6.98	38.80
90	53.93	6.92	39.15
Original PBAT	61.91	6.75	31.17
30	60.74	6.66	32.44
60	60.99	6.65	32.20
90	60.83	6.56	32.40

that the increased content of oxygen atoms was due to an increase in the carboxyl groups in the residuals. Some carbon atoms could be released as CO_2 or CH_4 , while some were turned into microbial biomass.

Conclusions

PHBV, PBS, and PBAT were previously known as compostable materials. However, studies on these materials under anaerobic and oxygen-limited conditions have been limited. In this study, we focused on the degradability behavior of PHBV, PBS, and PBAT under thermophilic oxygen-limited conditions, in a real landfill environment, by using a mixture of landfill soil and anaerobic sludge as the sources of microorganisms. Under the testing conditions, PHBV experienced complete degradation in 60 days, while PBS and PBAT showed moderate degradation and the slowest degradation, respectively. The degradation of PHBV began on the surface and edges, resulting in a thinner sheet, which became more eroded and rougher, while the degradation of PBS and PBAT occurred randomly on the surfaces, causing disintegration into smaller pieces. The FTIR spectra of PHBV indicated changes in

both shape and intensity, while there were no obvious changes in the IR spectra of PBS and PBAT after degradation at times. During the degradation test, all the materials showed a decrease in the thermal stability and a reduction of the carbon content in the molecular structures. At the end of the degradation test, all the materials displayed a peak of carboxylate ions due to the degradation of polymeric chains. As shown in this study, landfill conditions were reasonable for reducing biodegradable plastics, especially PHBV, which showed rapid degradation. PBS was suitable for disposal in a landfill environment. However, thermophilic conditions were required to accelerate the degradation and disintegration rate. PBAT shows disintegrability, but

slow degradability was found under test conditions. In considering the capabilities of the waste management process, PBAT should be considered under other conditions such as composting or aerobic conditions. This study could be used to develop further knowledge to reduce the environmental impact of plastic materials.

Acknowledgments

The Scholarship from the Graduate School, Chulalongkorn University to commemorate the 72nd anniversary of his Majesty King Bhumibol Adulyadej is gratefully acknowledged along with the 90th Anniversary Chulalongkorn University Fund (Ratchadaphiseksomphot Endowment Fund).

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