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Report

Microplastics from biodegradable plastics

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Manuscripts in progress

1)“Microplastics from biodegradable plastics”, – manuscript for Water Research.

2)“Label free Metal enhanced fluorescence detection of microplastics” – Manuscript for Microchimica Acta, (results under evaluation and completion).
Abstract:

Biodegradable plastics have been regarded as a promising solution to tackle the pollution caused by the wide use of conventional plastics. However, during the biodegradation process, the fragmentation of the biodegradable polymer material into increasingly smaller pieces may pose a high risk to form a large number of microplastics. In this project, the formation of microplastics from biodegradable poly (butylene adipate-co-terephthalate) (PBAT) in four different aquatic environments was studied and compared to conventional low-density polyethylene (LDPE). The results showed that a larger quantity of plastic fragments/particles were formed in all aquatic environments from PBAT than from LDPE. The formation of microplastics was much faster in seawater than in Milli-Q water. Furthermore, an UV pretreatment of the PBAT films promotes the formation of microplastics. Interestingly, the UV treatment also changed the morphology of the formed microplastics. The size distribution of the formed particles was also systematically studied. Additionally, changes in thermal stability, crystallinity, and mechanical properties of the PBAT films during the exposure to water were investigated. This work demonstrates that the generation of microplastics from biodegradable plastics in most aquatic environments, from pure water to seawater, can be substantial and pose a potential risk for natural environments and ecosystems. The risk of microplastic formation from biodegradable plastics needs to be further evaluated with regards to longer timeframes, biological fate of intermediate products and final products in fresh water, estuarine and seawater natural habitats.
1. Introduction

The wide use of plastics has caused many concerns over the environment pollution. One of the main concerns is microplastics (particle size lower than 5 mm) originating from manufacturing (primary sources) and the degradation of plastic wastes (secondary sources) [1]. Microplastics are prone to accumulate in the environment and pose a significant risk to ecosystems [2]. To tackle the pollution, the replacement of conventional polymer materials by biodegradable polymer materials has been regarded as a promising solution. Biodegradable plastics, often converted from renewable raw materials, can break down into low molecular weight compounds such as water, methane and carbon dioxide by microorganisms such as bacteria, fungi and algae [3, 4]. Biodegradable plastics also undergo fragmentation into small particles during the biodegradation (break-down) process and tremendous amounts of small plastic particles (microplastics) are thus formed [5, 6]. Microplastics formed from biodegradable plastic products thus pose a risk to the environment before being completely degraded. In addition to biodegradation, biodegradable plastics also undergo “traditional” degradation such as hydrolysis, photodegradation, weathering ageing, etc., which accelerate the formation of microplastics [7-9].

Despite the potential for biodegradation, the microplastics formed from biodegradable plastics may have a very long lifetime. There are several reasons for this. One is that the biodegradation itself is a time-taking process. Biodegradability is affected by both biotic and abiotic factors of the environment, such as temperature, moisture, pH, bio-surfactant and enzymes [5, 10]. The ideal conditions are easy to achieve in labs and composting sites but not in nature. For instance, poly(lactic acid) (PLA), one of the most common biodegradable polymers[11], can be rapidly degraded in industrial composting conditions (three weeks for PLA thin films and six weeks for PLA rope [12]) but its biodegradation process is much slower under natural soil burial
conditions [13]. As a result, depending on the type of polymer, the microplastics formed from biodegradable plastics can thus be present for decades in natural environments [6]. When the possible migration from an optimal condition for biodegradation to sub-optimal conditions (scarce nutrients, insufficient water activity, low temperature, etc.) by the environmental forces such as rain and wind are considered, the lifetime of the formed microplastic can be even much longer. Furthermore, biodegradability is also influenced by polymer characteristics, such as crystallinity, functional groups, and molecular weight. For semi-crystalline plastics, the amorphous region is degraded more easily than the crystal region since the crystals are impenetrable for the ageing media such as water, oxygen or enzymes. After the degradation of the amorphous region, the residual particles consisting of crystallites have a much lower biodegradation rate and can exist for a long time. Nevertheless, the formation of microplastics from biodegradable plastics has not been thoroughly studied [5, 6].

In this study, the formation of microplastics from biodegradable poly (butylene adipate-co-terephthalate) (PBAT) in four different aquatic environments at room temperature was studied and compared to conventional low-density polyethylene (LDPE). PBAT, having similar mechanical properties to LDPE, has been regarded as a promising biodegradable alternative to LDPE, especially in disposable products such as mulch films and plastic shopping bags [8, 9, 14, 15]. The results show that a large number of plastic fragments were formed in all aquatic environments from PBAT but not from LDPE. Especially, an UV pretreatment resulted in larger amounts of formed microplastics. The morphology of the microplastics was also investigated. Furthermore, the deterioration in mechanical properties of the PBAT films during the exposure to water was investigated and was related to the changes in its morphology.
2. Experimental

2.1 Materials and sample preparation

PBAT, having a trademark of Ecoflex® F Blend C1200 and a density of 1260 kg/m³, was supplied by BASF. LDPE with a trademark of LUPOLEN 2420K and a density of 924 kg/m³ was purchased from ALBIS Plastic Scandinavia AB. The film with a thickness of ca. 20 μm was made by a twin-screw extruder (Brabender 20-40 LS) with an extrusion temperature region of 150-250 °C from feeding zone to film die.

The film strips (100 x 20 mm) were cut from the extruded film by using a metal template and scalpel. One-third of the prepared film strips were exposed to UV light at 50 °C for 79 h in a QUV accelerated weathering tester to mimic the ageing condition of plastic under sunshine. The irradiance of the UV light used was 0.76 W/m² at a wavenumber of 340 nm.

![Fig. 1. Schematic presentation of sample presentation and biodegradation exposure process](image)

2.2 Biodegradation exposure

Biodegradation conditions of the plastic in water were simulated in culture flasks with ventilated caps. The biodegradation tests were performed in aquatic medium, as presented in Figure 1. In particular, the film strips with or without UV ageing were exposed to four different
aquatic media: Milli-Q water (MQW), artificial sea water (ASW), artificial sea water with sediment (ASW+S) and real sea water with sediment (SW+S). Three strips and 100 ml of each aquatic medium were placed in each culture flask with a growth area (cross-section) of 75 m². Seawater with microorganisms was collected from the ocean at Näset, Gothenburg, the west coast in south Sweden. ASW was prepared according to ISO19679-2017 and by dissolving NaCl (22g), MgCl₂·6H₂O (9.7g), Na₂SO₄ (3.7g), CaCl₂ (1g), KCl (0.65g), NaHCO₃, (0.20g) in Milli-Q water up to 1000 ml yield.

The prepared flasks were placed under plant culture lamps (fluorescent light with an intensity of 190 µmol/m²/s; 16 h illuminated and 8 h dark per day) in a conditioning room (23 °C and 50%RH). The flasks were shaken twice a week to improve oxygen supply in the aquatic medium, e.g. for the growth of microorganisms. Sampling was performed after 3, 5, 8 and 10 weeks of exposure. The aged film strips were taken from the test vessels and rinsed in deionized water. After drying under room temperature, the films were collected and stored in a conditioning room (23 °C and 50%RH) before evaluation, and the remaining flasks filled with aged water were collected and stored in a refrigerator with a temperature of 4 °C before further tests.

2.3 pH measurement

The pH of the aquatic environment in the flask during the ageing was measured by a SevenCompact pH/ion Mettler pH-meter.

2.4 Morphology Characterizations (OM and SEM)

The morphology of the formed microplastics and the surface morphology of the films were investigated with an optical microscope and a scanning electron microscope.
2.5 Thermogravimetry (TG)

Specimens weighing approximately 7 mg were placed in 70 µL alumina crucibles and tested in a TG/DSC 1 analyzer (Mettler-Toledo, Switzerland). TG curves of the unexposed and exposed samples were obtained at 25-600 °C with a heating rate of 10 °C min⁻¹ and a nitrogen gas flow rate of 50 ml min⁻¹.

2.5 Differential scanning calorimetry (DSC)

The glass transition and melting behaviour of the unexposed and exposed samples were studied with a Mettler-Toledo DSC 1 calorimeter (Switzerland). Samples weighing ~ 5 mg, were placed in 40 µL aluminum cups. The samples were heated from -50 to 180 °C at a rate of 10 °C min⁻¹ with a nitrogen gas flow rate of 50 ml min⁻¹. The degree of crystallinity was calculated by dividing the melting enthalpy by the melting enthalpy of 100 % crystalline PBAT, i.e., 114 J g⁻¹.

2.6 Attenuated total reflectance infrared (ATR-IR) spectroscopy

The IR spectra of the films were recorded on a Thermo Nicolet 6700 equipped with a single ATR accessory.

2.7 Mechanical tests

Tensile tests on films strips were carried out at 23 ± 1 °C and 50 ± 2.5% RH in a Zwick, Model Z1 Tensile Testing Machine with a 50 N load cell, according to ISO 37. The specimens were strained at a crosshead speed of 50 mm min⁻¹ and a gauge length of 30 mm. Specially designed grips with a clamping surface made by soft plastic were employed to significantly reduce the break of films at the clamping area. The strain was calculated as the relative increase in the grip-to-grip distance. Young’s modulus was determined from the slope in the linear region
with the strain range of 1-3%, and the tensile strength was reported as the maximum value of the tensile stress.

3. Results and discussion

3.1 Formation of microplastic

![Fig. 2. Changes in pH of the different types of water with the immersed PBAT (a) and LDPE (b) samples during the exposure. The unfilled symbols represent the cases immersed films without UV treatment while the filled symbols represent the cases immersed films with UV treatment.](image)

Milli-Q water displayed a pH of 5.5 while the sea waters displayed a pH of around 8.0. In the vials containing non-UV pre-treated PBAT or LDPE films, the pH of the water for all four cases displayed small extent of fluctuation during the 10 weeks exposure. For all cases containing the UV pre-treated PBAT films, the pH was lower than the corresponding ones without UV pre-treatment. The decrease in pH was most distinct for the case of Milli-Q water containing the UV pre-treated PBAT films, from 5.5 (before immersion) to 4.9 after 5 weeks ageing, approaching 4.5 after 10 weeks ageing. In contrast, the water vials containing UV pre-treated LDPE films showed similar pH values as the corresponding ones without UV pre-treatment.
**Fig. 3.** Images of the flasks filled with non-UV treated and UV treated PBAT in MQW and ASW after 10 weeks.

**Fig. 4.** OM images of the flasks filled with non-UV treated and UV treated PBAT in MQW and ASW after 10 weeks.

Fig. 3 and Fig. 4 show the images of the flasks filled with non-UV treated and UV treated PBAT in MQW and ASW after 10 weeks of exposure. Very few particles were observed in the Milli-Q water with the non-UV treated PBAT, while a large number of fragments appeared in ASW. This result indicates that the formation of microplastics is faster in ASW than in MQW. As a
polyester, PBAT undergoes hydrolysis in aquatic environments, and studies have shown that the hydrolysis of polyesters is faster in a basic solution than in an acidic solution. The ASW is weakly basic and the MQW is weakly acidic. This means a faster hydrolysis process occurred in ASW than in MQW, leading to a faster formation of microplastics in ASW than in MQW. More fragments were observed in the UV-treated samples compared to non UV treated PBAT samples, indicating that UV treatment promotes the formation process of microplastics. Interestingly, the fragments formed from UV-treated samples showed a fiber-like shape. Several fiber fragments entangled together and formed a large fragment with a length as long as 20 mm. The fragments from non-UV treated samples showed a flocculent shape in water with a much smaller size. The difference in morphology can also be clearly observed in SEM images as shown in Fig. 5 below. Additionally, the SEM images clearly show that the fragments consist of both large particles with a size of several hundred micrometers and many small particles with a size of several micrometers.

![SEM images of PBAT fragments](image.png)

**Fig. 5.** SEM images of PBAT fragments without and with UV treatment and aged for 10 weeks in MilliQ water. The bottom row shows the enlarged images.
No fragments were visibly observed in the water with LDPE films (see Fig. 6). This indicates that the formation of microplastics is much faster for PBAT in water environments than LDPE.

Optical microscopy images of evaporated water samples (all water types) after 5 weeks of ageing of LDPE and PBAT plastic films are demonstrated in Fig. 7 and Fig. 8, respectively. As the water samples were evaporated, it is difficult to distinguish between plastic fragments and salt crystals and other material from the seawater/sand, and this is valid for all samples except the ones in MilliQ water. For this reason, the initial evaluation of plastic content and particle sizes and distributions were only performed on the MilliQ water samples. These images only focused on the group of fragments with a smaller size.
Fig. 7. Evaporated water droplets (25 µl) from different water types in which LDPE film strips was aged for five weeks. Some films were exposed to 80 h of UV pre-ageing. Scalebars are 10 x 1 µm in size.
Fig. 8. Evaporated water droplets (25 µl) from different water types in which PBAT film strips was aged for five weeks. Some films were exposed to 80 h of UV pre-ageing. Scalebars are 10 x 1 µm in size.
Fig. 9, 10 and 11 display MilliQ water samples from the plastic films aged for 5, 8 and 10 weeks, respectively. Also, these figures show ImageJ particle analyzed corresponding pictures with overlay masks and histograms of the particle size distributions.

Fig. 12a shows that the formed microplastics had a diameter of 1-3 μm for both LDPE and PBAT samples with and without UV pretreatment.

Fig. 12b shows that the relative particle amount was around 4.2% coverage for LDPE samples.
after 10 weeks of aging. Whereas, the corresponding coverage for PBAT was much higher, reaching 11%. The coverage area was 3.4% for UV aged PBAT sample after 10 weeks of ageing, which was the lowest among the samples studied. What needs to be pointed out here is that only the particles with small size were counted. As discussed before, the UV treated PBAT tended to form long fiber-shape fragments, while fragments with a flocculent shape with a much smaller size dominated for the non-UV treated PBAT cases. This is why a smaller coverage was observed for the UV treated PBAT sample than the non UV treated PBAT. Since there are no visible large fragments formed in LDPE samples, we can conclude that the number of microplastics formed was much larger for PBAT samples than for LDPE samples.

Fig. 9. Top row are microscope images of 5 weeks aged MilliQ water (25 µl evaporated) samples of: A) LDPE B) LDPE UV treated C) PBAT D) PBAT UV treated, scalebars are 10x1 µm. Middle row are corresponding particle analyzed (in ImageJ) images with overlay masks. Bottom row are particle Feret diameter distributions in pixels (pixel size is 0.1 µm).
Fig. 10. Top row are microscope images of 8 weeks aged MilliQ water (25 µl evaporated) samples of: A) LDPE and B) PBAT. UV treated samples were not collected at this sampling occasion. Scalebars are 10x1 µm. Middle row images are corresponding particle analyzed (in ImageJ) images with overlay masks. Bottom row are particle Feret diameter distributions in pixels (pixel size is 0.1 µm).

Fig. 11. Top row are microscope images of 10 weeks aged MilliQ water (25 µl evaporated) samples of: A) LDPE B) LDPE UV treated C) PBAT and D) PBAT UV treated, scalebars are 10x1 µm. Middle row are corresponding particle analyzed (in ImageJ) images with overlay masks. Bottom row are particle Feret diameter distributions in pixels (pixel size is 0.1 µm).
3.2 Changes in plastic films

3.2.1 Thermal stability

TGA was employed to reveal the changes in the thermal stability of PBAT films during the exposure. The unaged PBAT samples started to decompose at 384 °C upon heating. Here, the temperature at 10 % mass loss in the TGA curves was taken as the initial decomposition temperature ($T_d$) of the sample. Table 1 shows that the $T_d$ of PBAT samples were almost unchanged after the 10 weeks of exposure to four different aquatic environments. This finding suggests the uneffected thermal stability of PBAT after the exposure. The $T_d$ decreased by 9 °C from 384 to 375 °C after the UV pretreatment due to photodegradation. Upon further ageing in the aquatic environments, the $T_d$ further decreased to 364 °C in MQW and to ~ 355 °C in the three seawater environments. This finding indicates that UV treated PBAT samples underwent
a much faster degradation in aquatic environments than the non-UV treated samples, leading to a deterioration in the thermal stability of the PBAT films. Besides, the degradation of PBAT is faster in seawater environments than in MQW.

Table 1. Temperature (°C) at 10% mass loss, extracted from TGA analysis for the unaged and 10 weeks-aged (non-UV and UV treated) PBAT samples in different types of water environments.

<table>
<thead>
<tr>
<th>Samples</th>
<th>non-UV</th>
<th>UV pre-treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>unexposed</td>
<td>384</td>
<td>375</td>
</tr>
<tr>
<td>10w-MQW</td>
<td>384</td>
<td>364</td>
</tr>
<tr>
<td>10w-ASW</td>
<td>382</td>
<td>355</td>
</tr>
<tr>
<td>10w-ASW+S</td>
<td>382</td>
<td>357</td>
</tr>
<tr>
<td>10w-SW+S</td>
<td>383</td>
<td>353</td>
</tr>
</tbody>
</table>

3.2.2 Melting behaviours

![Fig. 13. First heating DSC curves of the unaged and 10 weeks-aged (non-UV and UV treated) PBAT samples under different types of water environments.](image)
Table 2. DSC results of the unaged and 10 weeks-aged (non-UV and UV treated) PBAT samples under different types of water environments.

<table>
<thead>
<tr>
<th>Samples</th>
<th>non-UV</th>
<th>UV pre-treated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_g$ (°C)</td>
<td>$T_{m1}$ (°C)</td>
</tr>
<tr>
<td>unexposed</td>
<td>-28.4</td>
<td>113.0</td>
</tr>
<tr>
<td>10w-MQW</td>
<td>-28.0</td>
<td>113.1</td>
</tr>
<tr>
<td>10w-ASW</td>
<td>-27.5</td>
<td>113.5</td>
</tr>
<tr>
<td>10w-ASW+S</td>
<td>-28.1</td>
<td>112.3</td>
</tr>
<tr>
<td>10w-SW+S</td>
<td>-28.0</td>
<td>111.8</td>
</tr>
</tbody>
</table>

Fig. 13 shows that the unaged PBAT had a glass transition temperature ($T_g$) of -28 °C and two melting peaks at 50 and 113 °C, respectively. $T_g$ and the two melting peak temperatures ($T_{m1}$) were unchanged after 10 weeks of exposure to all four types of water environments and the crystallinity also remained constant at 26 % (see Table 2). The DSC result suggests that the ageing condition, i.e. room temperature in water, barely affect the crystallization properties of PBAT.

After the UV treatment, the double melting peaks merged into one melting peak at 98 °C. This peak merging was due to the shift of the melting peak at lower temperature towards higher temperature during the UV treatment. Note that the UV treatment was performed at 50 °C which is exactly the lower melting temperature of PBAT. Consequently, the crystals were partially melted and re-arranged to form crystals with greater thickness and/or perfection. This annealing effect led to an increase in melting temperature, which accounted for the peak merging. The crystallinity slightly increased from 22.6 to 23.8 % due to the annealing effect. Furthermore, $T_g$ increased by 3 °C from -28.4 to -25 °C after the UV treatment. After 10 weeks of exposure to water, $T_m$ of the UV treated PBAT increased slightly, while the crystallinity was the same for
the samples exposed to MQW or SW+S. However, the crystallinity increased significantly from 23.8% to 30% for the samples exposed to ASW or ASW+S.

3.2.2 FTIR

FTIR spectra from films of both PBAT and LDPE (unaged and 10 weeks aged; with and without UV exposure) were obtained. Fig. 14 displays the spectra of PBAT as both a pristine material and aged in 4 different mediums for 10 weeks. When PBAT is aged with no UV pretreatment, there is no detected change in the functional groups of the material. Similarly, Fig. 15 depicts LDPE in an identical test situation, and again no change is present between unaged and aged samples. Fig. 16 shows PBAT samples that have not only been aged but also have undergone an UV treatment. The samples show negligible changes between non-aged and aged exposures, as is the case for Fig. 17 which shows LDPE in an identical test situation.

Fig. 14. FTIR spectra of pristine and 10 weeks aged non-UV exposed PBAT. Aging performed in Mili-Q water (MQW), artificial seawater (ASW) with and without beach sand, and seawater (SW) with beach sand.
**Fig. 15.** FTIR spectra of pristine and 10 weeks aged non-UV exposed LDPE. Aging performed in Mili-Q water (MQW), artificial seawater (ASW) with and without beach sand, and seawater (SW) with beach sand.

**Fig. 16.** FTIR spectra of unaged and 10 weeks aged UV exposed PBAT. Aging performed in Mili-Q water (MQW), artificial seawater (ASW), and seawater (SW) with beach sand.
Fig. 17. FTIR spectra of unaged and 10 weeks aged UV exposed LDPE. Aging performed in Mili-Q water (MQW), artificial seawater (ASW) with and without beach sand, and seawater (SW) with beach sand.

The results indicate that UV-treatment and ageing, both individually and in combination, do not affect the functional groups of PBAT or LDPE. Degradation of these materials, i.e. formation of microplastics, must therefore occur at a site not detectable with FTIR i.e. the degradation does not occur at functional group sites. Thus, the microplastics must be comprised of lower molecular weight fractions of PBAT or LDPE.

3.2.3 Morphology of the films

Fig. 18. Scanning electron microscopy images of pristine plastic film materials (LDPE, top row; PBAT, bottom row). Increasing magnification from left to right.
Fig. 19. Scanning electron microscopy images of plastic films (LDPE, top row; PBAT, bottom row), aged by UV treatment and five weeks in MilliQ water. Increasing magnification from left to right.

The plastic film strips fine structure were examined by scanning electron microscopy (SEM). In Fig. 18 SEM images of the pristine start samples are displayed, illustrating the finer structures of the produced LDPE and PBAT materials including some minor defects.

Fig. 19 demonstrates SEM images of plastic films that has been exposed to 79 h UV pre-treatment and five weeks exposure to in MilliQ water. There are indications that the PBAT film is more affected and degraded with strings shredding off the film while the LDPE film seems smooth and non-structured.

3.2.4 Mechanical properties
Tensile tests were performed to reveal the changes in the mechanical properties of PBAT and LDPE films during the exposure. Fig. 20 shows the tensile stress-strain curves of the representative samples and Fig. 21 and Fig. 22 display Young’s modulus, tensile strength, and
strain at break of the unaged and aged samples without UV treatment. As shown in Fig. 21a, Young’s modulus of PBAT films remained almost constant during the exposure to all four different water environments. The tensile strength and the strain at break also kept unchanged during the exposure except for those aged in ASW where a decrease can be discerned.

A special tensile fracture behavior was observed for most of the PBAT samples aged in ASW. As shown in Fig. 23a, three out of four specimens of PBAT films aged in ASW for 10 weeks displayed a “tearing” type of fracture. Taking specimen 3 as an example, when the film was stretched to about 170% of strain, a hole/void with a shape of parallelogram appeared in the middle part of the film (II in Fig. 23b). The appearance of the void led to the sharp decrease in the tensile stress (II in Fig. 23a). With further stretching, the size of the void grew gradually (III in Fig. 23) until its tip reached the edges of the strained film, leading to the fracture of the whole sample (IV in Fig. 23). Of importance is that the point when the void firstly appeared was reported as the breaking point of the sample. This special fracture behaviour was only observed for the PBAT samples aged in ASW. One reasonable explanation is that large pieces of fragments were detached from the film surface during exposure to ASW which created plenty of small voids on the surface. These voids, acting as defects, grew larger during stretching, leading to the occurrence of this special fracture behaviour and the reduction in the extensibility of the PBAT film. This fracture behaviour was not observed for the samples aged in other water environments.

Fig. 22 shows that the 10 weeks of ageing in different water environments barely altered the mechanical properties of LDPE, as indicated by the unchanged stiffness, strength and extensibility.
Fig. 23. (a) Tensile stress-strain curves of four specimens of PBAT film strips aged in ASW for 10 weeks and (b) schematic presentation of the corresponding fracture behaviour.

Table 3. Mechanical properties of pristine, UV-treated, PBAT and LDPE samples and the UV-treated samples aged in different types of water for 10 weeks.

<table>
<thead>
<tr>
<th>samples</th>
<th>PBAT</th>
<th>LDPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modulus (MPa)</td>
<td>Strength (MPa)</td>
</tr>
<tr>
<td>Pristine</td>
<td>113 ± 10</td>
<td>50 ± 4</td>
</tr>
<tr>
<td>UV-treated</td>
<td>79 ± 8</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>10w-MQW</td>
<td>101 ± 2</td>
<td>11 ± 1</td>
</tr>
<tr>
<td>10w-ASW</td>
<td>147 ± 17</td>
<td>15 ± 1</td>
</tr>
<tr>
<td>10w-ASW+S</td>
<td>140 ± 8</td>
<td>14 ± 1</td>
</tr>
<tr>
<td>10w-SW+S</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 20 and Table 3 show that the UV treatment deteriorated the mechanical properties of PBAT significantly, as indicated by the 30%, 70% and 60% reduction in stiffness (from 113 to 79 MPa), strength (from 50 to 15 MPa) and extensibility (from 355% to 137%), respectively, compared to the pristine films. Kijchavengkul et al. [7] reported that UV exposure reduced the molecular weight of PBAT remarkably which in turn deteriorated its mechanical properties. The “tearing” type of fracture behavior was also observed for the 10 weeks aged UV-PBAT films (see Fig. 20) and the strain at break further decreased from 137 to ~ 50 %. In contrast, Young’s modulus increased after the 10 weeks exposure. Particularly, Young’s modulus doubled for the films exposed to ASW and ASW with sand, which was probably due to the increase in crystallinity after the exposure (see Table 2).

Compared to the pristine LDPE films, the UV-treated samples showed a slight increase in stiffness but around 40 % reduction in strength and 30 % reduction in extensibility. This finding indicates that the effects of the UV exposure on mechanical properties of the films were less significant for LDPE than PBAT. Visually we can see that the LDPE films displayed higher transparency than the PBAT film which had a colour of light milky. This suggests that the absorbance of UV light was higher in PBAT films than in LDPE films, which probably lead to a more severe deterioration in PBAT than LDPE. Table 3 also shows that the stiffness, strength and extensibility of the UV-treated LDPE films remained unchanged after further ageing in all four types of water environments.

4. Conclusions

Taking PBAT as an example of a biodegradable plastic, this study demonstrated that large quantities of microplastics can be formed from biodegradable plastics in aquatic environments. UV or sunlight could further promote the formation of microplastics from these materials. The
microplastic formation is faster in a seawater environment than in Milli-Q water due to the difference in pH. The formation of microplastics is much more evident from PBAT than conventional LDPE in aquatic environments. The results suggest that biodegradable plastics probably have a higher risk to cause microplastic pollution compared to conventional plastics. Before being completely degraded, the microplastic could potentially enter the ecosystem and pose a risk to the environment.

The non-UV treated PBAT samples showed unchanged properties in terms of crystallinity, thermal stability, and mechanical properties after 10 weeks of ageing in the water environments. More significant changes occurred in the UV-treated PBAT samples during the 10 weeks of ageing. LDPE underwent less deterioration compared to PBAT after the 10 weeks exposure.

Acknowledgments

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References


