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Biodegradation of bioplastics in natural environments

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ABSTRACT

The extensive production of conventional plastics and their use in different commercial applications poses a significant threat to both the fossil fuels sources and the environment. Alternatives called bioplastics evolved during development of renewable resources. Utilizing renewable resources like agricultural wastes (instead of petroleum sources) and their biodegradability in different environments enabled these polymers to be more easily acceptable than the conventional plastics. The biodegradability of bioplastics is highly affected by their physical and chemical structure. On the other hand, the environment in which they are located, plays a crucial role in their biodegradation. This review highlights the recent findings attributed to the biodegradation of bioplastics in various environments, environmental conditions, degree of biodegradation, including the identified bioplastic-degrading microorganisms from different microbial communities.

Contents

1. Introduction

Plastics are considered to be the most widely used polymers in our daily life especially in packaging applications. The annual production of petroleum based plastics exceeded 300 million tons in 2015 (Mekonnen et al., 2013). This excessive production of petroleum-based plastics demands sustainable alternatives from renewable resources. In addition, the adverse environmental impacts including carbon dioxide (CO_2) emissions and their long-period accumulation in the environment due to their non-biodegradability are the significant drawbacks of using the non-biodegradable plastics (Tokiwa et al., 2009; Pathak et al., 2014; Jain and Tiwari, 2015). In fact, 34 million tons of plastic wastes are generated each year throughout the world and 93% of them are disposed of in landfills and oceans (Pathak et al., 2014). Although some members of the European Union (EU) have banned landfilling applications, approximately 50% of plastic wastes are still disposed of in landfills. Countries such as Germany, Netherlands, Sweden, Denmark and Austria were successful in achieving 80–100% in recovery of the plastic wastes, however, they were able to recycle only 28% on average (EU, 2013). Although, the EU attempts to encounter the disposal of plastic wastes and improve reusing and recycling applications, developing countries are still dependent on the conventional landfilling. The plastic consumption in developing countries has been reported to be more than that of the world average because of the higher rate of urbanization and economic development (Muenmee and Chiemchaisri, 2016). For instance, developing countries including China, Indonesia, Philippines, Sri Lanka and Vietnam were reported to generate more

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Table 1
Classification of the most produced bioplastics (European Bioplastic, 2015).

	Source	Name	Abbreviation
Bioplastics	Petroleum based	Polybutylene succinate	PBS
		Polylcaprolactone	PCL
		Polyethylene succinate	PES
		Polybutyrate adipate terephthalate	PBAT
		Polyamide	PA
		Polyethylene	PE
		Poly(ethylene terephtalate)	PET
		Polypropylene	PP
	Bio-based	Poly(lactic acid)	PLA
		Polyhydroxyalkanoate	PHA
		Starch plastics	–
		Cellulose esters	–
		Bio-polyethylene	Bio-PE
		Bio-poly(ethylene terephtalate)	Bio-PET
		Bio-polyamide	Bio-PA

than 50% of global plastic pollution in marine environment (Li et al., 2016). Although the technologies for recovering the plastics wastes have been improved, an increase in the world population to about 9 billion in 2050 requires a higher demand for plastic production and eventually, an increase in the amount of plastic wastes (EU, 2013). Incineration of plastic wastes were also particularly applied in European countries such as Denmark which had the highest rate of incineration (76%). Despite constructing incineration plants according the standard criteria, some environmental drawbacks can be encountered during this process. Energy recovery from plastic wastes may enhance the net CO_2 emissions. Moreover, a huge amount of ash and slag containing hazardous and toxic compounds are required to be disposed of which can cause other serious environmental problems (European Commission, 2011). Thus, in order to create a sustainable environment and prevent the possible disposal of recalcitrant plastic wastes in the environment, production of bioplastics gained a lot of attention due to their biodegradability. Actually, the word bioplastic can refer either to bio-based plastics synthesized from biomass and renewable resources such as Poly(lactic acid) (PLA) and Polyhydroxyalkanoate (PHA) or plastics produced from fossil fuel including aliphatic plastics like Polybutylene succinate (PBS), which can also be utilized as a substrate by microorganisms (Table 1) (Tokiwa et al., 2009; Mekonnen et al., 2013). For instance, utilizing starch as a renewable resource in production of packaging bioplastic resulted in a lower consumption of non-renewable

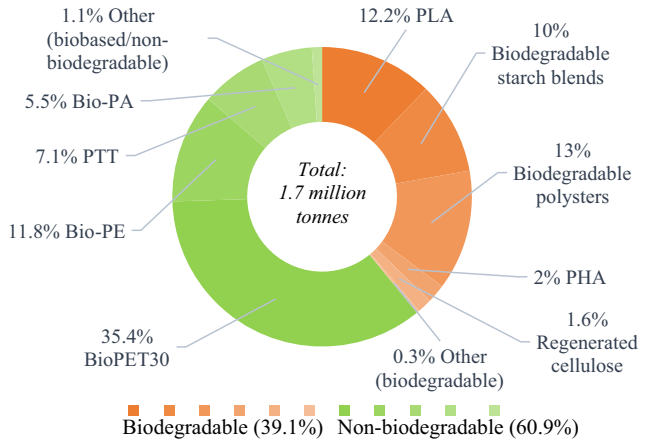

Fig. 1. Global production of bioplastics 2014 (by material type) (European Bioplastic, 2015).

energy resources (−50%) and therefore less greenhouse gas emissions (−60%) when compared to the polystyrene packaging (Razza et al., 2015).

In 2014, 1.7 million tons of bioplastics were produced throughout the world (European Bioplastic, 2015). The production of bioplastics is expected to reach 6.2 million tons in 2018 (Mostafa et al., 2015) (Fig. 1). In 2012, PLA and starch-based were the most utilized bioplastics by 47 and 41% of total consumption, respectively (Mostafa et al., 2015). Moreover, Polyhydroxybutyrate (PHB) bioplastics got the attention of the scientific community due to their low CO_2 emission (Mostafa et al., 2015).

Although bioplastics are considered to be environmental friendly materials, they also have some limitations such as high production cost and poor mechanical properties. High production cost drawback can be managed by utilizing the low cost of renewable resources such as agricultural wastes (Jain and Tiwari, 2015). Among the bio-based plastics, Poly(lactic acid) (PLA) reveals optimum properties including high tensile strength and modulus. Poly (hydroxyalkonates) (PHAs) are their commercial competitors although they lack some optical and mechanical properties when compared to PLAs (Tabasi and Ajji, 2015).

Accumulation of plastic wastes in the environment forces industry to produce a sustainable and a biodegradable type of a plastic (Pathak et al., 2014). The term biodegradation involves biological activity. The biodegradation of polymers consists of three important steps: (1) Biodeterioration, which is the modification of mechanical, chemical, and physical properties of the polymer due to the growth of microorganisms on or inside the surface of the polymers. (2) Biofragmentation, which is the conversion of polymers to oligomers and monomers by the action of microorganisms and (3) Assimilation where microorganisms are supplied by necessary carbon, energy and nutrient sources from the fragmentation of polymers and convert carbon of plastic to CO_2, water and biomass (Lucas et al., 2008). The important factors that affect the plastic's biodegradation in the environment are the chemical structure, the polymer chain, crystallinity and the complexity of polymer formula. In fact, the specific functional groups are selected by enzymes and can be processed. Generally, polymers with a shorter chain, more amorphous part, and less complex formula are more susceptible to biodegradation by microorganisms. Moreover, the environment, in which the polymers are placed or disposed of, plays as a key factor for their biodegradation. The pH, temperature, moisture and the oxygen content are among the most significant environmental factors that must be considered in biodegradation of polymers (Massardier-Nageotte et al., 2006; Kale et al., 2007b).

Previously, the non-biodegradability of synthetic plastics resulted in the accumulation of millions of tons of plastic wastes (Pathak et al., 2014). However, by developing bioplastics as a substitute material for conventional plastics, certain applications have become mandatory for the production of real biodegradable polymers (Eubeler et al., 2009). Therefore, the main objectives of this review paper are to summarize the biodegradation of bioplastics in different environments and to discuss the activity of the microorganisms that are responsible for their degradation.

2. Biodegradation of bioplastics under different environmental conditions

Many studies were conducted to investigate the biodegradability of bioplastics under different environmental conditions, such as soil, compost, marine and other aquatic environments. Among these environmental conditions, mostly soil and compost were taken into account due to their high microbial diversity (Anstey et al., 2014). Although most of the plastic wastes are disposed of in landfills, the

Table 2
Biodegradation of bioplastics in different environments.

Source of bioplastic	Name of bioplastic		Type of environment	Conditions	Bio-degrad-ability/ degradability method	Bio-degrad-ability (%)	Period of bio-degrad-ability (days)	Reference
Bio-based	PLA-based	PLA	Compost	58 °C	Produced CO_2	13	60	Ahn et al. (2011)
		PLA	Compost	58 °C, pH-8.5, 63% humidity	Produced CO_2	84	58	Kale et al. (2007a)
		PLA	Compost	70% moisture, 55 °C	Produced CO_2	~70	28	Tabasi and Ajji (2015)
		PLA	Compost	Aerobic, 58 °C, 60% humidity	Weight loss	60	30	Mihai et al. (2014)
		PLA	Synthetic material containing compost	Aerobic, 58 °C	Weight loss	63.6	90	Sarasa et al. (2009)
		PLA	Synthetic material containing compost	58 °C	Weight loss	100	28	Arrieta et al. (2014)
		PLA	Soil	30% moisture	Weight loss	10	98	Wu (2012b)
		PLA	Inoculum from a municipal wastewater treatment plant	30 °C, aerobic	Weight loss	39	28	Massardier-Nageotte et al. (2006)
		PLA (powdered)	Soil	25 °C, 60% humidity	Weight loss	13.8	28	Adhikari et al. (2016)
		PLA/PFF/starch (80/5/15%)[a]	Compost	58 °C	Produced CO_2	53	60	Ahn et al. (2011)
		PLA/NPK (63.5/37.5%)	Soil	30 °C, 80% humidity	Weight loss	37.4	56	Harmaen et al. (2015)
		PLA/NPK/EFB (25/37.5/37.5%)	Soil	30 °C, 80% humidity	Weight loss	43	56	Harmaen et al. (2015)
		PLA/Soft wood (70/30%)	Compost	Aerobic, 58 °C, 60% humidity	Weight loss	40	30	Mihai et al. (2014)
		PLA/corn (90/10%)	Synthetic material containing compost	Aerobic, 58 °C	Weight loss	79.7	90	Sarasa et al. (2009)
		PLA/sisal fiber (SF) (60/40%)	Soil	30% moisture	Weight loss	>60	98	Wu (2012b)
		PLA/PHB (75/25%)	Synthetic material containing compost	58 °C	Weight loss	100	35	Arrieta et al. (2014)
	PHA-based	PHB	Soil	–	Weight loss	64.3	180	Jain and Tiwari (2015)
		PHB	Microbial culture from soil	–	Weight loss	~18	18	Woolnough et al. (2008)
		PHB	Soil	Real conditions, temperature and humidity were measured regularly	Weight loss	98	300	Boyandin et al. (2013)
		PHA	Soil	35 °C	Weight loss	35	60	Wu (2014)
		PHA	Soil/compost (90/10%)	25 °C, 65% humidity	Produced CO_2	40–50	15	Arcos-Hernandez et al. (2012)
		PHA	Soil	60% moisture, 20 °C	Produced CO_2	48.5	280	Gómez and Michel (2013)
		PHB	Compost	58 °C	Produced CO_2	79.9	110	Weng et al. (2011)
		PHB	Compost	70% moisture, 55 °C	Produced CO_2	~80	28	Tabasi and Ajji (2015)
		PHB	Sea water	25 °C	BOD bio-degradability	80	14	Tachibana et al. (2013)
		PHB	Sea water	Static incubation, 21 °C	Weight loss	99	49	Thellen et al. (2008)
		PHB	Sea water	Dynamic incubation, 12–22 °C, pH 7.9–8.1	Weight loss	30	90	Thellen et al. (2008)
		PHBV	Sea water	Static incubation, 21 °C	Weight loss	99	49	Thellen et al. (2008)
		PHBV	Sea water	Dynamic incubation, 12–22 °C, pH 7.9–8.1	Weight loss	30	90	Thellen et al. (2008)
		PHB	River water	Real condition ~20 °C	Weight loss	43.5	42	Volova et al. (2007)
		PHB	Brackish water sediment	32 °C, pH = 7.06	Weight loss	100	56	Sridewi et al. (2006)
		PHB	Marine water	28.75 °C (average temperature, pH = 7–7.5	Weight loss	58	160	Volova et al. (2010)
		PHB/CAB (50/50%)	Soil	–	Weight loss	31.5	180	Jain and Tiwari (2015)
		Poly[(3-hydroxybutyrate)-co-(3-hydroxyvalerate)]	Microbial culture from soil	–	Weight loss	~41	18	Woolnough et al. (2008)
		PHA/Rice Husk (RH) (60/40%)	Soil	35 °C	Weight loss	>90	60	Wu (2014)

Table 2 (*continued*)

Source of bioplastic	Name of bioplastic		Type of environment	Conditions	Bio-degrad-ability/ degradability method	Bio-degrad-ability (%)	Period of bio-degrad-ability (days)	Reference
	Starch-based	Bioplastic (made from potato almidon)	Compost	Aerobic, 58 °C	Weight loss	~85	90	Javierre et al. (2015)
		Starch-based	Soil	60% moisture, 20 °C	Produced CO_2	14.2	110	Gómez and Michel (2013)
		Mater-Bi bioplastic	Marine water with sediment	Room temperature	BOD bio-degradability	68.9	236	Tosin et al. (2012)
		Mater-bi bioplastic (MB) (60% starch + 40% resin)	Compost	55% moisture, aerobic, 23 °C	Weight loss	26.9	72	Mohee et al. (2008)
	Cellulose-based	CA (Produced from fiber flax)	Municipal solid waste mixture	–	Weight loss	44	14	Mostafa et al. (2015)
		CA (Produced from cotton linters)	Municipal solid waste mixture	–	Weight loss	35	14	Mostafa et al. (2015)
		Sponge cloth (cellulose-based)	Synthetic material containing compost	Aerobic, 58 °C	Weight loss	>80	154	Vaverková and Adamcová (2015)
	PA-based	Nylon 4 (Polyamides, Bio-based)	Sea water	25 °C	BOD bio-degradability/weight loss	80/30	25/21	Tachibana et al. (2013)
		Nylon 4 (Polyamides, Bio-based)	Composted soil	25 °C, 80% humidity, ph = 7.5–7.6	Weight loss	100	120	Hashimoto et al. (2002)
Petroleum-based	PBS-based	PBS	Compost	Aerobic, pH 7–8, 58–65 °C, 50–55% moisture	Produced CO_2	90	160	Anstey et al. (2014)
		PBS (films)	Soil	25 °C, 60% humidity	Weight loss	1	28	Adhikari et al. (2016)
		PBS (powdered)	Soil	25 °C, 60% humidity	Weight loss	16.8	28	Adhikari et al. (2016)
		PBS/soy meal (75/25%)	Compost	Aerobic, pH 7–8, 58–65 °C, 50–55% moisture	Produced CO_2	90	100	Anstey et al. (2014)
		PBS/Canola meal (75/25%)	Compost	Aerobic, pH 7–8, 58–65 °C, 50–55% moisture	Produced CO_2	90	100	Anstey et al. (2014)
		PBS/Corn gluten meal (75/25%)	Compost	Aerobic, pH 7–8, 58–65 °C, 50–55% moisture	Produced CO_2	90	100	Anstey et al. (2014)
		PBS/switch grass (75/25%)	Compost	Aerobic, pH 7–8, 58–65 °C, 50–55% moisture	Produced CO_2	90	170	Anstey et al. (2014)
		PBS/Starch (films)	Soil	25 °C, 60% humidity	Weight loss	7	28	Adhikari et al. (2016)
		PBS/Starch (powdered)	Soil	25 °C, 60% humidity	Weight loss	24.4	28	Adhikari et al. (2016)
	PCL-based	PCL	Inoculum from a municipal wastewater treatment plant	30 °C, aerobic	Weight loss	7.6	28	Massardier-Nageotte et al. (2006)
		Starch/PCL	Inoculum from a municipal wastewater treatment plant	30 °C, aerobic	Weight loss	53	28	Massardier-Nageotte et al. (2006)
		PCL	Compost	55 °C	Produced CO_2	38	6	Nakasaki et al. (2006)

[a] (wt/wt%).

biodegradation of bioplastics in landfills have not been studied much yet. Therefore, the biodegradation of bioplastics in compost, soil and aquatic environments are particularly discussed here.

2.1. Compost

A huge amount of plastic wastes is disposed of in landfills which eventually leads to generation of greenhouse gases and leachate. Therefore, other solid waste management methods including composting or recycling are considered to be more preferable for the recovery of plastics. Composting is a process in which the organic matter is converted to CO_2 and a soil-like material (humus) by activity of a mixed group of microorganisms (Kale et al., 2007b). As defined by the American Society for Testing and Materials (ASTM), compostable plastic is "*a plastic that undergoes degradation by biological processes during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leaves no visually distinguishable or toxic residues*" (ASTM D6400-04, 2004). Therefore, a compostable plastic is biodegradable whereas a biodegradable plastic is not always compostable (Kale et al., 2007a,b). Using compost as a microbial community for the biodegradation of different bioplastics was extensively studied during the past decade (Table 2). Both bio-based and petroleum-based bioplastics including PLA, PHA, starch-based, PBS, PES and PCL are susceptible to biodegradation by compost under specific environmental conditions (such as temperature, pH and moisture content).

The conditions differences between home and industrial composting may lead to a significant difference in biodegradation of bioplastics. Studying the biodegradation of PLA bioplastic under home composting conditions during 11 months showed a very slow biodegradation. This could be attributed to the lower temperature than that of the industrial scale trial which could be performed at a higher temperature range (Thermophilic) (Rudnik and Briassoulis, 2011).

Some studies were conducted to improve the biodegradability of bioplastics in a compost environment. For instance, increasing the content of soluble sugar in the biocomposites through the addition of materials containing high protein content enhanced the biodegradability of bioplastics. In order to increase the biodegradability of PBS containing bioplastics, biofuel byproducts were involved in their mixture as composite bioplastics. It was seen that the presence of a meal-based filler enhances the rate of biodegradation compared to pure PBS bioplastic, which was attributed to the high concentration of soluble sugars in meal-based fillers (Anstey et al., 2014). The presence of corn in PLA/corn bioplastic seemed to enhance the biodegradation in compost since corn was a highly biodegradable material. Thus, microorganisms degraded the material and the PLA fraction more efficiently (Sarasa et al., 2009). The PLA pots in association with poultry feather fibers (PFF) showed a higher rate of deterioration than those of the pure PLA which might be related to the other components used in molding and extrusion processes of the PLA pot production that inhibited the biodegradation (Ahn et al., 2011). Biodegradation of acrylic acid-grafted Polyhydroxyalkanoate/Rice Husk (PHA-g-AA/RH) and Polyhydroxyalkanoate/Rice Husk (PHA/RH) biocomposites has a direct relationship to its RH content. In fact, the presence of these compounds in a PHA matrix increased the biocomposite properties including the tensile strength. Although the tensile strength of PHA-g-AA/RH was more than that of PHA/RH, its biodegradation was slightly lower, which was due to the resistance of the former composites to water absorption (Wu, 2014). Moreover, Sisal Fibers (SF) were dispersed in the PLA matrix which resulted in more than 50% higher weight loss after soil burial of 14 weeks (Wu, 2012b). On the other hand, the addition of Cellulose Acetate Butyrate (CAB) as a blending agent to PLA matrix worsened its biodegradation since the polymer became more hydrophobic (Jain and Tiwari, 2015).

Blending of PLA or PHB bioplastics with poly (butylene adipate-*co*-terephtalate) (PBAT) showed a lower degree of biodegradation than those of the pure PLA or PHB. Fourier Transform Infrared (FTIR) results elucidated that the changes in these blend's composition during the composting process led to the commencement of biodegradation from the PLA or PHB part of the blend. Interestingly, forming a PBAT rich 3D network led to a lower disintegration of the blend (Tabasi and Ajji, 2015). In another study, the biodegradation of PHAs films with different structures was reported. The order of biodegradation was Poly(hydroxybutyrate-*co*-40 mol% hydroxyvalerate) (PHBV-40) ≈ Poly(3-hydroxybutyrate-*co*-40 mol% 4-hydroxybutyrate) P(3HB-*co*-40 mol% 4HB) > Poly (hydroxybutyrate-*co*-20 mol%-hydroxyvalerate) (PHBV-20) > Poly (hydroxybutyrate-*co*-3 mol% hydroxyvalerate) (PHBV-3) > PHB suggesting that involvement of Hydroxyvalerate (HV) and Hydroxybutyrate (4HB) in polymer structure reduce its crystallinity and improve the bioplastic biodegradability (Weng et al., 2011).

As stated previously, renewable resources can be employed to produce bioplastics. For instance, cellulose acetate (CA) bioplastics can be produced from agricultural wastes. In a relatively recent work, it was reported that the biodegradation of CA bioplastics from low cost fiber flax and cotton linters was 44 and 35%, respectively, after 14 days of composting (Mostafa et al., 2015).

Some bioplastics in markets are labeled as 100% biodegradable. However, their potential for composting has not been verified. In a relevant study, the biodegradability of two different samples of sponge cloth bioplastics (sample A and B), which were widely used for cleaning the surfaces, were composted. The results showed that the sample B had a biodegradability of more than 80%, whereas sample A slightly biodegraded indicating that the biodegradability of bioplastics could strongly be attributed to the type of the environment and also to the chemical structure of the polymer (Vaverková and Adamcová, 2015).

2.2. Soil

Since plastic wastes are also widely disposed of in soil environments, investigating their changes and influences in this particular environment should also be discussed. Mainly, soil environments contain a vast biodiversity of microorganisms, which enable the plastic biodegradation to be more feasible with respect to other environments, such as water or air. In the literature, many studies investigated the biodegradability of PHA and PLA bioplastics and this topic seemed to be more popular than the biodegradability of other bio or petroleum based bioplastics as shown in Table 2.

In a recent work, in order to improve the biodegradability of bioplastics, the blending of other biodegradable materials was investigated. It was reported that, the biodegradation of PHB/PPW-FR (potato peel waste fermentation residue) biocomposite was more efficient than the sole PHB since PPW-FR fibers reduced the crystallinity of PHB biocomposite (Wei et al., 2015). In another study, adding the empty fruit bunch (EFB) fibers increased the rate of PLA biocomposite biodegradation (Harmaen et al., 2015). The biodegradation of PLA bioplastics in a real soil environment under Mediterranean real field conditions was studied throughout an 11 months period. The biodegradation process was very slow although the cellulose which was utilized as the positive control was completely degraded. This might be correlated to the lower temperature of the systems under real conditions and duration of the experiment. In fact, these bioplastics require higher temperature and longer time to be effectively degraded (Rudnik and Briassoulis, 2011).

Depending on the soil environment, the biodegradation of bioplastic can differ. For instance, more than 98% of PHA films were degraded in the soil environment at Hoa Lac, Vietnam whereas

the same films lost 47% of their weight in the soil environment of Dam Bai, Vietnam. This significant reduction in PHA films degradation in Dam Bai region might be related to the relatively low pH of 5.48 which probably deteriorated the microbial activity (Boyandin et al., 2013).

2.3. Aquatic systems

The plastic wastes were found to be largely accumulated evenly in deep marine environment. Due to their semi-permanent stability in a marine ecosystem, the plastic wastes potentially result in marine pollution, which can have impacts on marine animals (Volova et al., 2010; Sekiguchi et al., 2011). Therefore, bioplastics which are considered as biodegradable polymers in the environment, can also be used to develop a sustainable environment even in marine and aquatic systems. The researchers suggested that in order to understand the biodegradation of bioplastics in marine habitats, the test methodology should include six different habitats (supralittoral, eulittoral, sublittoral benthic, deep sea benthic, pelagic and buried in the sediments). It was found out that the degradation in pelagic habitat was more efficient with respect to eutrophic habitat. In addition, the authors also suggested that the highest biodegradation could be achieved at the interface of water-sediment since the environmental conditions at the interface supported the activity of plastic-degrading microorganisms (Tosin et al., 2012). In another work, in order to compare the biodegradability of bioplastics under laboratory and real conditions, the biodegradation of PHB and PHBV bioplastics in sea water under both static and dynamic conditions was studied. The laboratory (static) incubation was conducted in batch flasks containing natural seawater at 21 °C while the dynamic incubation was performed in an open system with continuous seawater flow at temperature between 12 and 22 °C and pH ranged from 7.9 to 8.1. For both bioplastics, the weight loss percent was the same under both static and dynamic conditions although the weight loss was less under dynamic conditions rather than the static one. This might be attributed to the fact that the dynamic condition was more realistic, which provided nutrient supply limitation and the temperature change of sea water. In addition, addition of sediments was studies to understand its effects on biodegradation. It was investigated that the sediments could have a favorable effect on biodegradation, however, no definite correlation could be determined (Thellen et al., 2008).

The water temperature can also have a significant influence on biodegradation of bioplastics. It was reported that the rate of PHA films biodegradation was different in various periods of the year 1999 and 2000 due to the changes in weather temperature (Volova et al., 2007). In addition, different sea waters might have played a substantial role in biodegradation, depending on the existing bioplastic-degrading microorganisms. The degradation of PCL, PBS and PHB biopolymers in three different sea water types was investigated by measuring their strength retention. The findings showed that the strength retention changed in different sea water environment, which might be attributed to the different bioplastic-degrading microorganisms available in these three particular sea waters types (Sekiguchi et al., 2011).

Another parameter, which can alter the degree of biodegradation in marine water is the shape of the polymer. It was stated that the PHA films were degraded faster than PHA pellets because of their larger surface area. Furthermore, a larger polymer/water interface also facilitated the attachment of microorganisms to the surface of the polymer (Volova et al., 2010). This pattern was also observed for PHA films in tropical soil environments in another work as well (Boyandin et al., 2013).

Recently, the entrance of microscale plastics to marine environment through wastewater discharges is a topic of broad interest for researchers. However, no information was encountered in current literature about the release and/or fate of bioplastics through the wastewater discharges.

3. Bioplastic-degrading microorganisms

More than 90 types of microorganisms including: aerobes, anaerobes, photosynthetic bacteria, archaebacterial and lower eukaryotic are responsible for the biodegradation and catabolism of bioplastics. These microorganisms can be found extensively in soil or compost materials (Lee et al., 2005; Kumaravel et al., 2010; Accinelli et al., 2012). The degradation of bioplastics by bacteria or fungal species is recognized through the appearance of a clear zone surrounding the growth in a plate containing the bioplastic as the only carbon source, followed by the consideration of the diameter for the biodegradation extension (Tezuka et al., 2004; Lee et al., 2005; Ishii et al., 2008; Kumaravel et al., 2010). Scanning electron microscopic (SEM) observations were widely used by researches in order to determine the change of polymer structure due to the biological activity. For example, instability of PHA bioplastic was observed by utilizing the SEM method verifying the PHA biodegradation (Tezuka et al., 2004; Wu, 2009, 2011; Phukon et al., 2012; Tachibana et al., 2013). Moreover, Fourier Transform Infrared (FTIR) spectroscopy was also employed to detect the change in bond intensity, which was caused by microbial degradation (Wu, 2009, 2011, 2014; Phukon et al., 2012.

Enzymes which can be either intracellular or extracellular, are responsible for enzymatic degradation of bioplastics. Depolymerases which can be obtained from bioplastic-degrading microorganisms were investigated as enzymes play a significant rule in bioplastics biodegradation. (Tokiwa and Calabia, 2004; Chua et al., 2013). Many studies have been conducted on depolymerase purification from bioplastic-degrading microorganisms. Intercellular depolymerase from *Rhodospirillum rubrum* were investigated as PHB-degrading enzymes (Tokiwa and Calabia, 2004). The depolymerase enzyme responsible for PCL degradation was isolated from *Streptomyces thermoviolaceus* subsp. *Thermoviolaceus* 76T-2 (Chua et al., 2013). Other enzymes such as lipase from *Alcaligenes faecalis*, estrase from *Comomonas acidivorans* and serine from *Pestalotiopsis microspora* were also produced that involved in bioplastic biodegradation (Trivedi et al., 2016).

According to the literature, the biodiversity of bioplastic-degrading microorganisms was not the same under different environmental conditions. Although bio-based plastics such as PLA produced from renewable resources can be degraded in different microbial environments, the biodegradation of petroleum-based bioplastics such as PES depends on the resource (source of water) on which it is located (Tezuka et al., 2004). Also, the distribution of PBS bioplastic-degrading microorganisms in soil environments is not comparable to other bioplastics including PCL (Abe et al., 2010). In another study, 31 isolates capable of degrading PES, PHB and PCL were obtained from different environments. In fact, this study showed that a larger number of isolates, able to degrading these three bioplastics, were obtained from the soil rather than compost and sediment (Tseng et al., 2007).

Soil and compost environments were intensively investigated and it was observed that they both contained a high numbers of bioplastic-degrading microorganisms because of the higher microbial biodiversity than that of found in other environments such as marine waters. It was reported that the fungal species in soil or compost had a more tendency to degrade Mater-Bi (MB) starch based bioplastics (Accinelli et al., 2012). In a relatively previous study, the PHB-degrading fungal strains were isolated from soil compost, garden soil, hay compost, farm hay, cotton boll fallen leaf, living leaf, plant root, ceiling pipe, pond, shower stall and air.

Table 3
Isolated bioplastics-degrading microorganisms from different environments.

Source of bioplastic	Name of bioplastic		Type of microorganism	Microorganism	Source	Reference
Bio-based	PLA-based	PLA	Bacteria	*Amycolatopsis* sp., *Amycolatopsis thailandensis*, *Thermomactinomyces* sp., *Laceyella* sp., *Nonomuraea* sp, *Bacillus licheniformis*, *Actinomadura keratinilytica*, *Micromonospora* sp., *Streptomyces* sp., *Bortetella petrii*, *Paenibacillus amylolyticus*, *Paenibacillus* sp.	Soil	Teeraphatpornchai et al. (2003), Sukkhum et al. (2009), Kim and Park (2010), Chomchoei et al. (2011), Penkhrue et al. (2015)
		PLA	Bacteria	*Amycolatopsis* sp.	–	Jarerat et al. (2002)
		PLA	Bacteria	*Saccharaothrix* sp.	–	Jarerat et al. (2002)
		PLA	Bacteria	*Lentzea* sp.	–	Jarerat et al. (2002)
		PLA	Bacteria	*Kibdelosporangium* sp.	–	Jarerat et al. (2002)
		PLA	Bacteria	*Streptoalloteichus* sp.	–	Jarerat et al. (2002)
		PLA	Bacteria	*Burkholderia capacia*	–	Wu (2009)
		PLA	Fungi	*Thermomyces lanuginosus*, *Aspergillus fumigatus*, *Mortierella* sp., *Doratomyces microsporus*	Soil/ Compost	Karamanlioglu et al. (2014)
		PLA	Fungi	*Fennellomyces linderi*, *Fusarium solani*, *Purpureocillium* sp., *Cladosporium* sp.	Soil	Karamanlioglu et al. (2014), Penkhrue et al. (2015)
		PLA	Fungi	*Verticillium* sp., *Lecanicillium saksenae*, *Cladosporium* sp.	Compost	Karamanlioglu et al. (2014)
		PLA	Fungi	*Aspergillus ustus*, *Penicillium verrucosum*, *Aspergillus fumigatus*, *Aspergillus Sydowii*, *Paecilomyces lilacinus*	Composted soil	Szumigaj et al. (2008)
		PLLA + Starch-based	Bacteria	*Laceyella sacchari*	Soil	Lomthong et al. (2015)
		PDLA	Bacteria	*Bacillus stearthermophilus*	Soil	Tomita et al. (2003)
		PLA/NPK biocomposite	Fungi	*Trametes versicolor*	–	Harmaen et al. (2015)
		PLA/(green coconut fiber (GFC)) (90/10%)[a]	Bacteria	*Burkholderia capacia*	–	Wu (2009)
	PHA-based	PHB	Bacteria	*Streptomyces* sp., *Burkholderia capacia*, *Bacillus* sp., *Cupriavidus* sp. *Mycobacterium* sp., *Nocardiopsis* sp.	River sediment	Hoang et al. (2006), Boyandin et al. (2013)
		PHB	Bacteria	*Streptomyces bangladeshensis*	Soil	Hsu et al. (2012)
		PHA	Bacteria	*Pseudomonas aerogusina*, *Bacillus subtilis*	Soil	Phukon et al. (2012)
		PHA	Bacteria	*Pseudomonas putida*, *Leptothrix* sp., *Variovorax* sp.	River water	Volova et al. (2007)
		PHA	Bacteria	*Pseudomonas fluorescens*, *Pseudomonas putida*, *Pseudomonas aeruginosa*, *Pseudomonas* sp.	Soil	Colak and Güner (2004), Bhatt et al. (2008)
		PHA	Fungi	*Candida albicans*, *Fusarium oxysporum*	Soil	Phukon et al. (2012)
		PHB	Bacteria	*Pseudomonas lemoignei*	Soil	Kumaravel et al. (2010)
		PHB	Fungi	*Aspergillus niger*	Soil	Kumaravel et al. (2010)
		PHB	Fungi	*Penicillium* sp., *Aspergillus* sp.	Compost/soil	Lee et al. (2005)
		PHB	Bacteria	*Entrobacter* sp., *Bacillus* sp., *Gracilibacillus* sp.	Marine water	Volova et al. (2010)
		PHB	Fungi	*Penicillium* sp., *Trichoderma pseudokoningii*, *Paecilomyces lilacinus*, *Cogronella* sp., *Acremonium recifei*	Soil	Boyandin et al. (2013)
		PHBV	Bacteria	*Actinomadura* sp.	Soil	Shah et al. (2010)
		PHBV	Bacteria	*Micrococcus* sp., *Bacillus* sp.	Active sludge	Shah et al. (2007)
	Starch-based	Starch-based	Fungi	*Aspergillus* sp.	Compost/soil	Accinelli et al. (2012)
		Starch-based	Fungi	*Aspergillus niger*	–	Li et al. (2015)
		Starch-based	Bacteria	*Clostridium acetobutylicum*	Soil	Yoshida et al. (2013)
		PLLA + Starch-based	Bacteria	*Laceyella sacchari*	Soil	Lomthong et al. (2015)
	PA-based	Nylon 4 (PA)	Bacteria	*Stenotrophomonas*	Composted soil	Tachibana et al. (2010)
		Nylon 4 (PA)	Fungi	*Fusarium* sp., *Fusarium solani*, *Fusarium oxysporum*, *Clonostachys rosea*	Composted soil	Hashimoto et al. (2002), Tachibana et al. (2010)

Table 3 (*continued*)

Source of bioplastic	Name of bioplastic		Type of microorganism	Microorganism	Source	Reference
Petroleum-based	PCL-based	PCL	Bacteria	*Amycolatopsis* sp., *Streptomyces* sp., *Streptomyces thermovioaceus*, *Paenibacillus* sp.	Soil	Chua et al. (2013), Penkhrue et al. (2015)
		PCL	Bacteria	*Streptomyces thermonitrificans*	Compost	Nakasaki et al. (2006)
		PCL	Bacteria	*Streptomyces* sp.	River sediment	Hoang et al. (2006)
		PCL	Bacteria	*Bacillus pumilus*	Fresh water	Tezuka et al. (2004)
		PCL	Bacteria	*Leptothrix* sp.	Soil/fresh water	Nakajima-Kambe et al. (2009)
		PCL	Bacteria	*Pseudomonas* sp., *Tenacibaculum* sp., *Alcanivorax* sp.	Sea water	Sekiguchi et al. (2011)
		PCL	Bacteria	*Psychrobacter* sp., *Pseudomonas* sp., *Moritella* sp., *Shewanella* sp.	Sea sediment	Sekiguchi et al. (2010)
		PCL	Bacteria	*Paenibacillus amylolyticus*	Soil	Teeraphatpornchai et al. (2003)
		PCL	Fungi	*Purpureocillium* sp., *Cladosporium* sp.	Soil	Penkhrue et al. (2015)
	PBS-based	PBS	Bacteria	*Amycolatopsis* sp., *Streptomyces* sp, *Paenibacillus* sp., *Paenibacillus amylolyticus*	Soil	Teeraphatpornchai et al. (2003), Penkhrue et al. (2015)
		PBS	Fungi	*Purpureocillium* sp., *Cladosporium* sp., *Aspergillus fumigatus*, *Aspergillus niger*, *Fusarium solani*	Soil	Ishii et al. (2008), Abe et al. (2010), Li et al. (2011), Penkhrue et al. (2015)
		PBS	Fungi	*Aspergillus oryzae*	–	Maeda et al. (2005)
		PBSA	Bacteria	*Azospirillum brasilense*	–	Wu (2012a)
		PBSA	Bacteria	*Paenibacillus amylolyticus*, *Pseudomonas aeruginosa*, *Burkholderia capacia*, *Bacillus pumilus*	Soil	Teeraphatpornchai et al. (2003), Hayase et al. (2004), Tezuka et al. (2004), Lee and Kim (2010)
		PBSA	Bacteria	*Leptothrix* sp.	Soil/fresh water	Nakajima-Kambe et al. (2009)
		PBSA	Bacteria	*Pseudomonas aeruginosa*	Activated sludge soil	Lee and Kim (2010)
		PBSA	Fungi	*Rhizopus Oryzae*	–	Wu (2011)
		PBSA	Fungi	*Aspergillus oryzae*	–	Maeda et al. (2005)
		PBSA/SCB (60/40%)	Fungi	*Rhizopus Oryzae*	–	Wu (2011)
		PBSA/Rice Husk (RH) (60/40%)	Bacteria	*Azospirillum brasilense*	–	Wu (2012a)
	PES-based	PES	Bacteria	*Streptomyces* sp.	River sediment	Hoang et al. (2006)
		PES	Bacteria	*Bacillus pumilus*	Fresh water	Tezuka et al. (2004)
		PES	Bacteria	*Paenibacillus amylolyticus*	Soil	Teeraphatpornchai et al. (2003), Tezuka et al. (2004)
		PES	Bacteria	*Leptothrix* sp.	Soil/fresh water	Nakajima-Kambe et al. (2009)
		PES	Fungi	*Aspergillus clavatus*	Soil	Ishii et al. (2007)

[a] (wt/wt%).

However, the largest number of PHB-degraders were isolated from the soil compost, soils and farm hay among the total 26 PHB-degraders (Lee et al., 2005).

Bacteria species able to biodegrade different biopolymers such as, Stenotrophomonas, fungi species like Penicillium, Aspergillus, Thermomyces, Fusarium, Clonostachys, Verticillium, Lecanicillium, cladosporium, Mortierella and Doratomyces and actinobacteria species including Streptomyces were all isolated from compost environments as summarized in Table 3.

Various microorganisms isolated from soil environments utilized bioplastics as the carbon source. Actinobacteria species such as *Amycolatopsis, Thermomactimyces, Actinomadura, Nonomuraea, Laceyella* and *Streptomyces* species were obtained from soil among which *Amycolatopsis* and *Streptomyces* were the most common species. *Paenibacillus, Pseudomonas, Bacillus* and *Bulkholderia* species were mainly isolated from different soil environments and they were capable of degrading the bioplastics. Among the soil-isolated fungi species responsible for bioplastics biodegradation, *Aspergillus, Fusarium* and *Penicillium* were mainly encountered (Table 3).

Agricultural soils were investigated as a suitable source for PLA-degrading microorganisms because of their high organic content. 16 out of 79 soil isolated microorganisms were capable of degrading all PLA, PCL and PBS bioplastics according to clear zone method and among them Actinomyces accounted for the highest number. *Amycolatopsis* sp. Strain SCM_MK2_4 represented the highest enzyme activity toward the PLA and PCL bioplastics (Penkhrue et al., 2015). In another study, 20 filamentous fungal strains isolated from different soil and fresh water samples capable of producing clear zones on minimal agar plates containing PES. These fungal strains were also able to generate clear zones on plates containing Poly(3-hydroxybutyrate) (P3HB) (Ishii et al., 2007).

Bacteria species were the main microorganisms obtained from aquatic systems including marine and river water that were able to degrade bioplastics. Bioplastic-degrading bacteria such as *Pseudomonas, Bacillus, Alvanivorax, Tenacibaculum, Lepthotrix, Entrobacter, Variovorax* and *Gracilibacillus* species were isolated from these environments as reported in several studies. Actinomyces species including *Streptomyces* able to utilize the bioplastics were also isolated from the sea and river sediments (Table 3).

The PCL-degrading bacteria were isolated from deep sea sediments. These strains did not degrade the other bioplastics including PLA, PHB, PBS and PBSA. Therefore, studying the aforementioned bioplastics-degrading microorganisms is necessary since the conditions in deep sea environments are different than the land environments due to the low temperature and high pressure (Sekiguchi et al., 2010).

Co-culture of different microorganisms may enhance the biodegradation of bioplastics. In fact, the other microorganism may help the biodegradation by utilizing the intermediates of bioplastic biodegradation by the main microorganism. It was reported that the mixture of *Fusarium solani* WF-6 with *Stenotrophomonas maltophilia* YB-6 increased the biodegradation of PBS bioplastic although strain YB-6 was unable to solely degrade the PBS (Abe et al., 2010). It was also stated that the co-culturing of *Sphinogomonas paucimobilis* sp. with hydrolyzates degrading strains strongly improved the biodegradation of poly(p-dioxanone) (Nishida et al., 2000). In another study, higher PCL biodegradation by *Streptomyces thermonitrificans* PDS-1 was detected when co-cultured with *Bacillus licheniformis* HA1 (Nakasaki et al., 2006).

Biocomposite which contains some other chemicals or materials in bioplastics matrix can have an impact on its biodegradability by microorganisms. The addition of soft wood fibers to PLA enhanced its tensile and elastic modulus whereas the biodegradation of the biocomposite was less than the virgin PLA since the wood fibers were biodegraded at a slower rate (Mihai et al., 2014). In another study, increasing the Green Coconut Fibers (GFCs) content in PLA/GFC biocomposite significantly enhanced its biodegradation by *Burkholderia capacia* BCRC 14253 (Wu, 2009). Wu (2011) also reported that the Sugarcane Baggasse (SCB) in Polybutylene Succinate-co-Adipate (PBSA) matrix decreased its intrinsic viscosity and this led to a higher biodegradation of PBSA/SCB biocomposite (Wu, 2011). The same trend also took place for biodegradation of PBSA biocomposite with and without agricultural residues Rice Husk (RH) by *Azospirillum brasilense* BCRC 12270 (Wu, 2012a).

4. Conclusions

The depletion of fossil fuel sources and the adverse environmental impacts resulting from the poor degradability of conventional plastics led the researchers to search for and to develop new and alternative materials to substitute plastics. In addition to consumption of our limited resources, global disposal of plastic wastes in an uncontrolled manner significantly contributes to generation of gaseous and liquid pollutants in the environment posing threat to public health and nature. Since the new generation bio-based plastics are produced from renewable resources such as crops and agricultural wastes, their utilization is considered to be beneficial but there is a need to address any potential negative environmental impacts. In the last two decades, many studies were conducted in order to determine and discuss the biodegradation of bioplastics in different environments. The biodegradation of PLA and PHA bioplastics was studied more than the other biopolymers such as PCL and PES due to their bio-based and specific mechanical properties.

Environmental conditions such as medium pH, moisture and oxygen contents, and temperature play a significant role in the degree of the biodegradation of bioplastics. Moreover, the structure and the composition of biopolymer or biocomposite extremely affect the biodegradation process which can be considered during their production stages. Modifying the composition of biopolymer, including the addition of material with a high soluble sugar content, may enhance the bioplastic biodegradability. Although biocomposite production from bioplastics may have some improved mechanical properties such as high tensile strength, still the biodegradation process may not be favorable under certain circumstances or become interrupted at same stage. Therefore, the optimization of the biocomposite mixture can lead to a more applicable and biodegradable product.

As explained previously, microorganisms are responsible for the biodegradation of bioplastics in different ecosystems. In fact, microorganisms catalyze the biodegradation of biopolymers through responsible enzymes. Fungal and bacterial species were isolated from soil, compost, marine water, river water and other environments, which were capable of utilizing the bioplastics to end products. Among the actinomyces or actinobacteria, *Amycolatopsis* and *Streptomyces* species, bacterial species such as *Paenibacillus, Pseudomonas, Bacillus* and *Bulkholderia* species and *Aspergillus, Fusarium* and *Penicillium* species as fungal species were the most commonly isolated microorganisms from different environments.

As discussed in this paper, the biodegradation of bioplastics was extensively investigated in soil and compost environments. Bioplastics mainly showed high degradability in these environments. However, a large amount of these plastics do find their ways to the water bodies and to marine systems. Subsequently, they may eventually cause unavoidable impacts on fresh water and marine ecosystems, affecting different species of plant and animals adversely. It is well known that a huge amount of plastic waste is available in the marine environment either by direct disposing of solid wastes into oceans or by wastewater discharge. Therefore,

the biodegradability of bioplastics in aquatic systems must be further studied in detail. In addition, the release of bioplastics through wastewater discharges from wastewater treatment plants to aquatic environments has to be investigated as well in order to understand their behavior after reaching the fresh water and marine ecosystems. Moreover, instead of disposing bio-based bioplastics into the landfills, alternative management techniques such as composting should be considered as an important recovery option within the integrated waste management approach due to their acceptable degradation properties. Disposal of bioplastics in landfills, contributes to more management problems in landfills rather than offering a sustainable solution. Management of bioplastics in developing regions, along with conventional plastic wastes, is another challenging area, where further study seems to be required.

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