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Review

Anaerobic degradation of bioplastics: A review

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ABSTRACT

Anaerobic digestion (AD) of the organic fraction of municipal solid waste (OFMSW), leading to renewable energy production in the form of methane, is a preferable method for dealing with the increasing amount of waste. Food waste is separated at the source in many countries for anaerobic digestion. However, the presence of plastic bags is a major challenge for such processes. This study investigated the anaerobic degradability of different bioplastics, aiming at potential use as collecting bags for the OFMSW. The chemical composition of the bioplastics and the microbial community structure in the AD process affected the biodegradation of the bioplastics. Some biopolymers can be degraded at hydraulic retention times usually applied at the biogas plants, such as poly(hydroxyalkanoate)s, starch, cellulose and pectin, so no possible contamination would occur. In the future, updated standardization of collecting bags for the OFMSW will be required to meet the requirements of effective operation of a biogas plant.

1. Introduction

Anaerobic digestion is a method for the treatment of the organic fraction of municipal solid waste (OFMSW) supported by legislation and principally used worldwide for its ability to produce renewable energy in the form of methane. Moreover, the nutrient-rich digestate residue can be utilized as a bio-fertilizer (Albanna, 2013). However, plastic bags, such as those used for OFMSW collection, are not separated properly and are a serious challenge for digesters, even in regions where advanced waste management technologies are used.

The OFMSW is mostly composed of food waste, accounting for up to approximately 45% of municipal solid waste (MSW) in Europe (Cerda et al., 2018) and 46% globally (Hoornweg and Bhada-Tata, 2012). Because of its high moisture content (approximately 80% or some reports as high as 85–90% (Albanna, 2013)) and organic matter content, the OFMSW is commonly treated via composting or anaerobic digestion in many countries, such as Sweden, Germany, and the Netherlands. While composting produces good quality soil fertilizer and heat that are difficult to collect (Smith et al., 2017), anaerobic digestion results in the production of biogas containing mostly methane and carbon dioxide that is easy to collect and use for renewable energy production. Therefore, from an energy perspective, anaerobic digestion is a preferable method for treating the OFMSW. If the OFMSW is separated with source sorted collection, a practice already applied in several countries, such as the Nordic countries, Germany and Austria, it is then usually collected in plastic or paper bags. However, the use of plastic bags can lead to plastic contamination in the biogas plants. A pretreatment method that is often applied in Sweden is pressing the OFMSW together with the collection bags through a star press, by which an easily degradable fraction, called a slurry, is formed, which is sent to the anaerobic digestion plant. The remaining part that does not go through the press is called "reject" and contains, among other components, most of the plastics, but it also contains a large amount of remaining organic matter that otherwise could be utilized for the production of methane. An alternative collection method for the OFMSW, which is applied in certain regions of Sweden, is the use of paper bags. However, some problems still can occur because paper bags can easily be damaged, and acidic leakage that causes corrosion problems in the collection trucks is common. Hence, biodegradable carrier bags, namely, bioplastic bags, could solve the problems mentioned above.

The use of bioplastics has been increasing worldwide for numerous applications, but since various bioplastics are relatively new products on the market, the disposal of bioplastics has been intensively investigated for the most appropriate implementation in existing disposal systems. Studies have thoroughly evaluated the different end-of-life options (Endres and Siebert-Raths, 2011) and the biodegradation and composting processes (Ahmed et al., 2018; Kale et al., 2007; Shah et al., 2008; Song et al., 2009) for bioplastics. A recent review (Ahmed et al., 2018) also highlighted the microbial strains involved in the degradation processes and the

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application of certain types of non-biodegradable and biodegradable polymers. However, to the best of our knowledge, there is a lack of comprehensive reviews on the anaerobic digestion of bioplastics. Therefore, this review focuses on the degradation of bioplastics in anaerobic conditions while also considering the requirements for smooth operation at biogas plants.

2. What are bioplastics?

Within the term bioplastics, we distinguish (a) bio-based and (b) biodegradable plastics, but a bioplastic can also fulfil both of these criteria. Bio-based plastics are typically made from renewable sources by the action of living organisms. They can be polysaccharides (e.g., starches, such as thermoplastic starch (TPS); cellulose, such as regenerated cellulose; pectin, and chitin), proteins (e.g., wheat gluten, wool, silk, casein and gelatine), lipids (e.g., animal fats, plant oils), or products of microorganisms (e.g., poly(hydroxyalkanoate)s (PHAs) such as poly(hydroxybutyrate) (PHB)). Furthermore, bio-based plastics can also be chemically synthesized from bio-derived products (e.g., poly(lactic acid) (PLA), poly(butylene succinate) (PBS), and poly(trimethylene terephthalate) (PTT)) (IfBB, 2017; Song et al., 2009). Moreover, there is another fraction of plastics that is bio-based but not biodegradable that is called “drop-ins” (e.g., bio-PET, bio-PE, bio-PP) with identical features as their petrochemical ancestors. Moreover, biodegradable plastics, with a certain degree of biodegradability, can also be synthesized from petrochemical origins, such as poly(glycolic acid) (PGA), poly(caprolactone) (PCL), poly(butylene succinate-*co*-terephthalate) (PBST), poly(butylene adipate-*co*-terephthalate) (PBAT) and poly(vinyl alcohol) (PVA). Some of these biodegradable bioplastics are already on the market and produced by different companies under different trade names. One example for PBAT is Ecoflex®, Wango, Ecoworld™, etc. The classification of different bioplastics is illustrated in Fig. 1.

3. Degradation of bioplastics

3.1. Biodegradable plastics

Different polymer degradation pathways, such as photodegradation, thermo-oxidative degradation and biodegradation, are well discussed in the literature (Amass et al., 1998; Hawkins, 1984; Shah et al., 2008). During biodegradation, the organic substances are broken down by means of microorganisms. Several biodegradability tests exist. The so called “screening tests” are performed in enzymatic or aquatic conditions, and the latter can be anaerobic or aerobic. The “real-life tests” distinguish composting, soil burial and field testing (Itävaara and Vikman, 1996; Lucas et al., 2008). However, in many cases, the biodegradability of a bioplastic is highly dependent on the properties of the plastic (Tokiwa et al., 2009) because both the chemical and physical properties of plastics affect biodegradation. These properties are the surface characteristics (hydrophobic or hydrophilic, surface area), the first-order structures (molecular weight, molecular weight distribution, chemical structure) and the higher order structures (crystallinity, crystal structure, modulus of elasticity, glass transition temperature, melting temperature) of polymers. (Tokiwa et al., 2009).

Biopolymers are long-chain molecules, and in order to mineralize the biopolymers (converting organic matter to minerals or plant available compounds), an important, often abiotic chain scission has to occur prior to biodegradation (Fig. 2). During that process, the long polymeric chains are broken down due to the effects of temperature, water and sunlight (i.e., photodegradation) to shorter oligomers, dimers or monomers. These shorter units are small enough to pass through the cell walls of microorganisms and be used as substrates for their biochemical processes and thus can be degraded (Shah et al., 2008) by microbial enzymes (Fig. 2). Two main types of enzymes are involved in microbial depolymerization processes: extracellular and intracellular depolymerases (Shah et al., 2008). As the term suggests, extracellular enzymes act outside the cells in order to break the longer units down into shorter molecules, preparing them for further degradation by intracellular enzymes. As biodegradation can occur in two ways, aerobically and anaerobically, it offers two types of biological waste treatment. While the aerobic degradation of biopolymers has been studied in detail with extended reviews written (Briassoulis et al., 2010; Calmon-Decriaud et al., 1998; Grima et al., 2000; Kale et al., 2007; Meeks et al., 2015), the research on anaerobic degradation of biopolymers is still in its infancy. This review, therefore, aims to survey the anaerobic digestion of bioplastics. According to the ISO 17088:2012 standards, a plastic can be considered biodegradable if a significant change in the chemical structure, i.e., degradation, occurs in the exposed material resulting in carbon dioxide, water, inorganic compounds, and biomass (new microbial cell constituents) but no visible or toxic residues (Standardization, 2012) under composting conditions. The CEN standard, EN 13432:2000 (Standardization, 2000), for biodegradable polymeric materials also requires that a substance is 90% converted to carbon dioxide within six months as a condition for composting in the presence of oxygen. For anaerobic degradation, it specifies a minimum of 50% conversion of the substance to biogas based on the theoretical value in a maximum of two months' time (Standardization, 2000).

3.2. Aerobic and anaerobic degradation

Aerobic biodegradation usually means composting within industrial composting conditions. In a high-oxygen environment (not less than 6%) (Kale et al., 2007), microorganisms utilize the polymer as a carbon and energy source and produce carbon dioxide and water as the main degradation by-products in addition to the remaining part, which is called compost (Eq. (1)). Industrially composting is performed in a warm (approximately 60–70 °C) and moist (approximately 60%) environment under controlled conditions (~ pH 8.5) (Mohee et al., 2008):

$$\text{Organic matter} + S + O_2 \rightarrow CO_2 + H_2O + NO_2 + SO_2 + \text{Heat} + \text{Compost} \tag{1}$$

Anaerobic biodegradation usually means anaerobic digestion in oxygen-free conditions in mesophilic (37 °C) or thermophilic (55 °C) biogas plants. In the absence of oxygen, the organic matter is converted to methane gas, carbon dioxide, water, hydrogen sulphide, ammonia and hydrogen, which results in a sequence of metabolic interactions by different groups of microorganisms (Mohee et al., 2008). The remaining part is called the digestate residue (Eq. (2)):

$$\begin{aligned}&\text{Organic matter} + H_2O + \text{Nutrients} \rightarrow \\ &\text{Digestateresidue} + CO_2 + CH_4 + NH_3 + H_2S + \text{Lessheat}\end{aligned} \tag{2}$$

The energy stored in organic matter is released in the form of heat during aerobic degradation, and it requires continuous turning of the biomass to release some of this heat for a healthy microbial community. This heat is lost and cannot be captured. On the contrary, in anaerobic degradation, the energy stored in organic matter is mainly released as methane, and due to the lack of oxygen in the process, less heat and less microbial biomass are produced (Fig. 2).

4. Biodegradation of bioplastics under anaerobic conditions

Extensive reviews of the various microbial communities are mostly focused on aerobic degradation of plastics and are available