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Investigation of the Effects of Biodegradable and Compostable Polymers as Sources of Microplastics on the Water-Soil Continuum: A Review

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The amount of research and publications related to microplastic pollution has been steadily increasing in recent years, but at the same time, our current knowledge on the topic is still based on occasional point measurements. As a result of these point measurements, it becomes obvious that new research areas and disciplines are also connected to the topic of microplastics. Various biotic and abiotic processes can cause microplastics to enter the environment and spread within it. All of these mechanisms can arise from the moisture conditions of the tested medium, temperature differences, or even from the decomposing and transforming activities of microorganisms. The rise of biodegradable and compostable plastic bags can also be considered a source of this kind since polymer products labelled as environmentally friendly can be identified as secondary sources during their decomposition processes. Therefore, both industrial and household compost can contain microscopic polymer residues, the application of which involves a potential risk of environmental pollution. In recent years, several international studies have dealt with various aspects of the degradation of these products, including the use of problems caused by residual microplastics and their environmental effects. The focus of our paper is not on the development of a new scientific methodology but a summary of the current situation formed through research results dealing with the current environmental safety and environmental health risks of microplastic pollution caused by biodegradable polymers.

1. Introduction

The use of plastic has grown exponentially since synthetic organic polymers were developed in the mid-20th century (Boucher and Friot, 2017). Although synthetic polymers have greatly contributed to the quality of human life in the past period, they have recently become a challenge for us due to their long service life and inadequate disposal. Many forms of plastics have been accumulating in the environment for decades (Carson et al., 2011). Annual global plastic production increased from 1.5 to 390.7 million tons from 1950 to 2021 (Pourebrahimi and Pirooz, 2023). In addition to larger plastic debris, plastic particles smaller than 5 mm are produced – microplastic sample preparation (Mári et al., 2021), identification in rivers (Martínez Rodas et al., 2023), and reviewed by Akdogan and Guven (2019). Microplastics (MP) have been analysed worldwide in air, soil, food and drinking water (both bottled and tap water), and even in the Arctic, Antarctica and polar ice. Due to the increased presence of microplastics in the environment, the exposure and risk to humans and other species are increasing rapidly (Zhang et al., 2022). Biodegradable plastics and plastic products receive a lot of attention as a substitute for traditional plastics, but they are not always transformed into environmentally friendly materials in a natural environment under the influence of microorganisms. Instead, they can break down into microplastics faster than conventional plastics, which poses an additional threat to the environment (Fan et al., 2022). Despite their small size, microplastics can adsorb heavy metals, antibiotics, as well as organic and other pollutants, so their toxic effect is significant (Qiu et al., 2022). Overall, microplastics in the environment and living organisms will increase over time. Contamination has reached the point where it is necessary to eliminate microplastics from the media, and there are several methods to do this, such as unique filtering systems, and chemical or biological methods. Although these technologies are either too costly or ineffective and may even cause more pollution, making them unsuitable for widespread use (Padervand et al., 2020).

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2. Microplastics and their environmental safety risks

Microplastics can be divided into primary and secondary categories. The primary microplastics in the industry are products or cosmetics manufactured to the appropriate shape and size. However, these materials can also be raw materials are used to produce other plastic products (Zhang et al., 2022). Secondary microplastics come from waste released into the environment and broken down there. The fragmentation of plastics is the result of mechanical, chemical, physical, and biological processes. Among these, ultraviolet radiation, mechanical wear, and weather effects are very significant factors (Uwamungu et al., 2022). The synthetic polymers are produced from non-renewable resources such as petroleum or polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL), polybutylene succinate (PBS) and so on (Fan et al., 2022). In the case of traditional petroleum-based plastics, the fragmentation of the polymer chains takes place, but this is not followed by biological degradation at the same rate because the molecular weight of the resulting fragments may be higher than microbial accessibility. This factor may be one of the main reasons for the appearance and accumulation of microplastics in the environment (Bordós, 2021). Currently, most of the research on microplastics deals only with non-biodegradable plastics, while less attention is paid to biodegradable ones (Uwamungu et al., 2022). In Hungarian surface waters, including fishponds, polypropylene and polyethylene are the most abundant and frequently occurring substances (Bordós, 2021). Examining the water and sediment samples of Hungary, it can be established that the concentration of microplastics was always lower at the outlet of the lake than at the inlet. It is likely that the lake stores microplastics (Bordós et al., 2019). Even though microplastic pollution is becoming increasingly large and affects every single environmental sphere, there is no standardised methodology for environmental analytical tests, no monitoring system, and no internationally accepted quality and quantity limits. Legislation on the production and use of plastic products has been developed in many countries, but at the same time, their primary goal is only to reduce plastic use to reduce future microplastic emissions (Conti et al., 2021). In 2019, the European Union approved Directive 2019/904, which restricts the use of certain plastic items from 2021. The regulation supports the production of polymer products that are reusable, degradable, and compostable (E.U. Law, 2019). As legislation on microplastics has only recently been implemented, there is a lack of environmental data or adequate quantitative information to establish outcomes (Lam et al., 2018).

3. Biodegradable and compostable polymer products as sources of microplastic pollution

Biodegradable and compostable plastic products appeared as a sustainable alternative to traditional plastic products and are present in the global plastic market, which segment is constantly and rapidly growing (Meeks et al., 2015). Biodegradable polymers are defined as materials whose chemical and physical characteristics undergo deterioration and completely degrade when exposed to microorganisms, aerobic and anaerobic processes (Abhilash and Thomas, 2017). Biodegradable plastic may decompose into carbon dioxide (CO_2) and water (H_2O) in 20-45 days if there is enough humidity, oxygen, and an appropriate number of microorganisms, which can be found in natural landfills or manure compared to conventional plastics that their life expectancy is about hundred to thousand years (Moshood et al., 2022). However, few people understand the consequences if new, biodegradable materials are placed on the market without proper preparation and education of consumers (Kuciel et al., 2018). Therefore, the range of biodegradable and compostable products entering the waste stream cannot be directly separated. The main difference is that compostable products have undergone testing to ensure that they decompose within a specific time frame and do not emit impact harmful to the environment. In contrast, biodegradable products have no such test requirements. In terms of biodegradability, several regulatory bodies have formulated standards that bio-based polymers can meet, but it is a problem that they do not or only partially degrade under the current environmental conditions (George et al., 2020). Biodegradable plastic products are made from starch, cellulose, protein, or biosynthetically produced materials, where the primary source of natural biopolymer materials is agriculture, animal husbandry, waste management and forestry. These materials degrade faster, although not completely, in the environment than conventional microplastics. Because of this, a larger amount of biodegradable microplastics can enter the soil in the same amount of time than traditional non-degradable plastics (Qin et al., 2021).

3.1 Waste stream of biodegradable and compostable polymer products

The management of plastic waste is gaining more attention as a result of changes in population attitudes and conscious consumer behaviour, leading to an increased demand for biodegradable plastics. Replacing petroleum-based plastics with biodegradable plastics alone would not solve the problem of plastic waste. To enhance the sustainability of compostable polymers throughout their life cycle, it is crucial to implement effective end-of-life strategies along with increasing production (Fredi and Dorigato, 2021). In particular, when biodegradable waste is disposed of in landfills, it produces harmful gases such as methane that harm the environment and climate (Sikorska et al., 2021). While commercially available biodegradable bioplastics are intended to degrade under certain conditions, such as high temperatures, they usually degrade slowly in environmental conditions, even with microorganisms present, according to Fredi and Dorigato (2021). In real life, issues such as industrial infrastructure, capabilities of composting plants, waste sorting systems, consumer knowledge, and current legislation must be considered (Kuciel et al., 2018). It is important to note that this market is young and dynamic. Biodegradable materials are becoming increasingly popular, leading to the development of biopolymers for newer applications with growing demand (Stachowiak and Łukasik, 2021). Compostable polymer products should be collected separately and then composted. These products are usually treated as classic plastic waste, and as a result, the degradable polymer waste may be accidentally recycled together with polymers from the general waste stream for mechanical or energetic recycling (Kuciel et al., 2018). Ideal recycling options include mechanical (primary or secondary) and chemical (tertiary) recycling. For example, if the material quality is high, biodegradable plastics can also be recycled mechanically through primary recycling, in which the recycled plastic has the same purpose as the primary plastic (Fredi and Dorigato, 2021). This type of recycling involves several steps that do not change the quality of the material and are endlessly performed, such as collecting, separating, sorting, cleaning, and grinding the waste (Sikorska et al., 2021). If material quality falls below a certain threshold, bioplastics could be chemically recycled to recover valuable monomers that could be used as building blocks for new polymers or valuable chemicals (Fredi and Dorigato, 2021). Through chemical recycling, polymers are broken down into monomers and then used to create new polymers, resulting in a high-quality product. One of the many advantages of this method is that it has lower greenhouse gas emissions and is a great example of the circular economy (Sikorska et al., 2021). For very low material quality, bioplastic waste could be recycled by incineration (Fredi and Dorigato, 2021).

3.2 Environmental stability of biodegradable and compostable polymer products

Two types of approaches are mainly used to determine the lifetime of plastic products: the useful lifetime and the final lifetime. The useful life of plastics can be defined as the period and condition until which the mechanical properties of the product allow the use of the given consumer item. On the other hand, the criterion of the final lifespan is that the entire mass of the product is transformed into a final product (Colwell et al., 2023) that participates in biogeochemical cycles in such a way that it does not endanger the world around us and human health (Haider et al., 2019). From the point of view of environmental protection and human health, it is the most favourable case if the disposal of biodegradable or compostable plastic waste takes place under controlled conditions of composting at the end of the life cycle (Fan et al., 2022) since the conditions necessary for decomposition are not met in the natural environment (Shen et al., 2020). When we talk about the biological degradation of polyesters, we have to mention a multi-step process. The main stages of this process are the following: 1) settlement of microorganisms, during which a biofilm layer forms on the surface, as a result of which enzymes are released; 2) after that, depolymerisation takes place with hydrolytic enzymes, resulting in the formation of monomers and oligomers (Laycock et al., 2017); 3) finally, mineralisation takes place, during which the decomposing activity of microorganisms prevails and small molecules are transformed into methane and carbon dioxide (Wei et al., 2022). If the decomposition process of biodegradable and compostable polymer products does not take place under the appropriate conditions and parameters like traditional plastics, they become pollutants with a long residence time when they get into the soil and water.

4. Overview of effects on the water-soil continuum

According to their degradation properties, microplastics are part of the cycle of the atmosphere, the earth system (lithosphere) and the water system (hydrosphere), and these systems are interconnected (Huerta Lwanga et al., 2016). According to Rodrigues et al. (2018), plastic debris polluting the environment is not static but flows from one ecosystem to another through various transport processes (Figure 1).

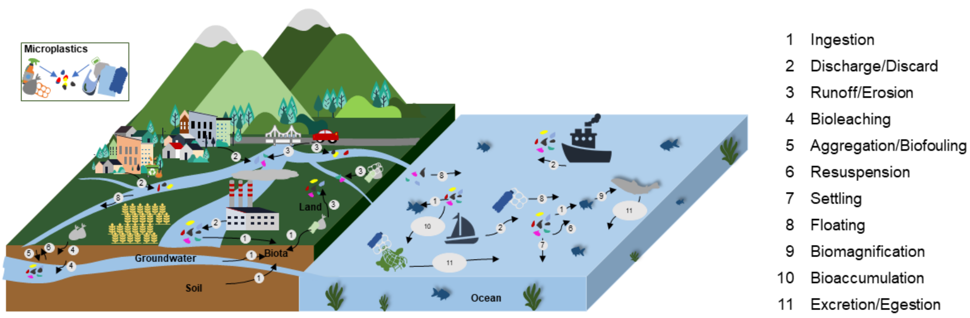

Figure 1: Typical mobilization pathways of microplastics in the water-soil continuum. Original figure.

4.1 Water pollution caused by microplastics and its risks

Matjašič et al., (2023) noted an increase in research on microplastics and their impact on the environment, with a particular focus on the ocean. Wang et al. (2021) state that research on the samples, types, distribution, and transport processes of microplastics occurring in freshwater environments is unexplored. According to preliminary research and modelling of plastic pollution in aquatic ecosystems, rivers transport about 1.2–2.4 tons of suspended plastic pollution from land to the oceans annually (Lebreton et al., 2017). Nowadays, the human and animal consumption of microplastics is a well-known fact. Microplastics can act as vectors in the transport of pollutants, microbes and viruses, thus causing a kind of combined, synergistic stress on individual direct and indirect target organisms (Wang et al., 2018). Contrary to our previous knowledge, plastics not only float in water but also flow, are transported, sink, and accumulate (Waldschläger and Schüttrumpf, 2019).

4.2 Soil pollution caused by microplastics and its risks

Through the slow decomposition processes of microplastics, the soil is part of the pollution chain as an absorber and a carrier of individual microscopic debris. The primary source of microplastics in the soil is the remains of various agricultural mulches, applied sewage sludge and compost (He et al., 2018; Huerta Lwanga et al., 2016), improper disposal of various wastes and littering (Akdogan and Guven, 2019), irrigation (Bläsing and Amelung, 2018). Since sewage sludge is rich in organic and inorganic nutrients, it is also known for its soil conditioning effect and its economic benefits, which is why it is widely used as a fertiliser (Nizzetto et al., 2016). However, Souza Machado et al. (2018) emphasise that the residence time of micropolymers from sewage sludge in the soil is much longer than that of nutrients applied in parallel, and they pose a significant environmental safety risk to soil life and potentially to soil ecosystems as well. Secondary pollution is the precipitation and deposition of pollutants from the aquatic and atmospheric ecosystems. Weber and Opp (2020) estimate that 14 % of all plastic entering the environment ends up in agricultural soil. The potential toxicological risk of microplastics lies in the fact that various pollutants and heavy metals can adsorb on their surface. According to Zhou et al. (2019), test results showed that microplastic particles in the soil environment contain various amounts of heavy metals, including Cd, Cr, Pb, Ag, Cu, Sb, Hg, Fe and Mn. Its main environmental safety risk is that it is minimally absorbed by the plants, so together with the aquatic environment, it can enter the food chain processes in two mobility ways (Guo et al., 2020). By sticking to the body surface of some saprophytic organisms (earthworms), they can hinder their movement and decomposing activity (Kim and An, 2019). Pollution has a significant effect on the nutrient uptake of living organisms, including mechanical damage to the individual digestive system, biochemical reactions (Guo et al., 2020), as well as influencing biomass intake. Microplastic contamination of the soil continuum also affects the growth of vegetation. Yan et al. (2006) showed that the accumulation of microplastics in the soil reduced crop yield and inhibited root growth, as well as reduced the efficiency of fertiliser use.

5. Conclusions

Due to the excellent functional properties of plastics, it seems that their use will increase in the future, especially in lower-income regions. Biodegradable and compostable polymers may be a long-term alternative to synthetic plastics, but this requires further research. In recent years, more and more publications have appeared which are aimed at exploring the previously unknown transport processes of microplastics and understanding their mechanisms of action. The old assumption that microplastics only cause environmental risks in the aquatic ecosystem can be refuted. Many studies examine the combination of effects on the soil-water continuum and toxic effects on plant vegetation. It is also a fact that the directive and legislation on microplastics are not available at the state or EU level as of today. In general, the post-use management of degradable plastic products is not yet solved, and no general techniques or procedures have been developed today. The perception that biodegradable polymers are environmentally safe is unfortunate, as their release into the environment poses significant risks. Additionally, their natural breakdown is complex and may lead to severe consequences due to potential microplastic pollution.

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