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Review Article

From microbes to ecosystems: a review of the ecological effects of biodegradable plastics

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Biodegradable plastics have been proposed as a potential solution to plastic pollution, as they can be biodegraded into their elemental components by microbial action. However, the degradation rate of biodegradable plastics is highly variable across environments, leading to the potential for accumulation of plastic particles, chemical co-contaminants and/or degradation products. This paper reviews the toxicological effects of biodegradable plastics on species and ecosystems, and contextualises these impacts with those previously reported for conventional polymers. While the impacts of biodegradable plastics and their co-contaminants across levels of biological organisation are poorly researched compared with conventional plastics, evidence suggests that individual-level effects could be broadly similar. Where differences in the associated toxicity may arise is due to the chemical structure of biodegradable polymers which should facilitate enzymatic depolymerisation and the utilisation of the polymer carbon by the microbial community. The input of carbon can alter microbial composition, causing an enrichment of carbon-degrading bacteria and fungi, which can have wider implications for carbon and nitrogen dynamics. Furthermore, there is the potential for toxic degradation products to form during biodegradation, however understanding the environmental concentration and effects of degradation products are lacking. As global production of biodegradable polymers continues to increase, further evaluation of their ecotoxicological effects on organisms and ecosystem function are required.

Introduction

Over recent years, the widespread prevalence of plastics in the environment along with their associated ecological impacts, have become a major focus of research and media coverage has raised public awareness of these issues. Biodegradable plastics (Figure 1) have been proposed as one of the solutions to the accumulation of plastics, as in theory these polymers can be converted by microbial action into their elemental components (carbon dioxide, methane and microbial biomass) [1–3]. The global production of biodegradable polymers has increased over the last two decades to reach ∼1550 thousand tonnes produced in 2021, and continued annual increases (by up to a 2.5-fold increase by 2026) are projected [4]. Biodegradable polymers are used in a diverse range of applications from textiles, packaging and consumer goods to agricultural and fisheries products [4–6], which can lead to their leakage into the environment.

Currently data establishing the fate of biodegradable plastics in the environment and their associated ecological impacts are sparse. In this mini-review recent literature is evaluated to consider the toxicological impacts of biodegradable plastics on aquatic and terrestrial species and ecosystems, and are set within what has previously been published about the effects of conventional plastics. Based on available data, the potential hazard presented to organisms and ecosystems from biodegradable plastics, their associated chemicals and degradation products are critically evaluated, and the need for future research into these areas are highlighted.

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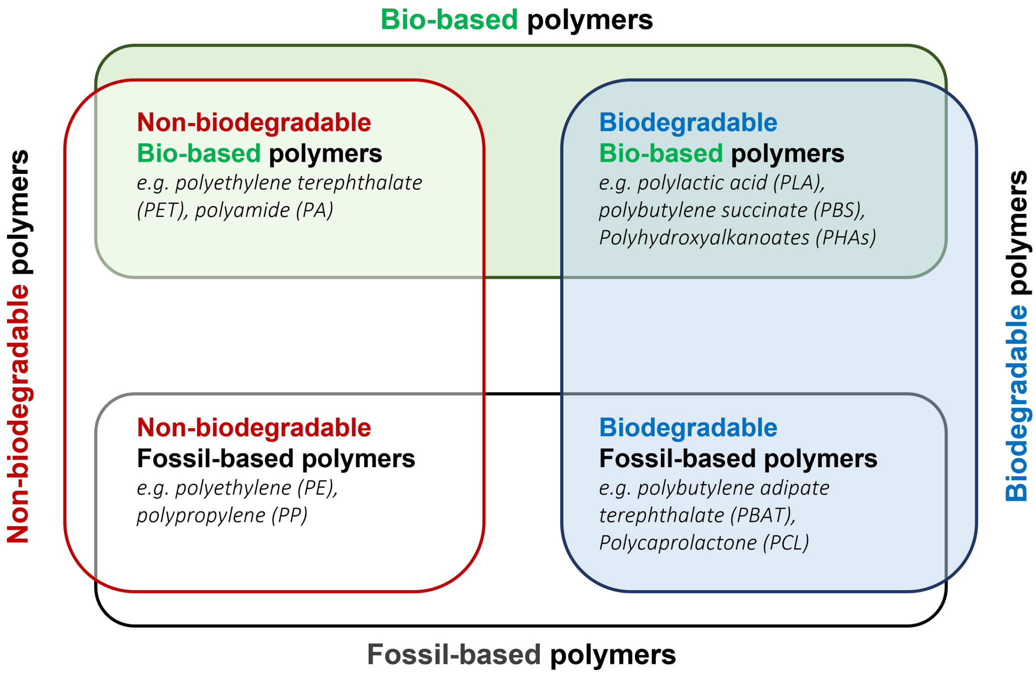

Figure 1. Schematic to illustrate the different categories of biodegradable and non-biodegradable, bio-based and fossil-based polymers.

Adapted from European Bioplastics (2021).

Biodegradability as a systems property

The term ‘biodegradable plastic’ may give rise to misinterpretation, implying that all polymers contained within this broad definition (e.g. polylactic acid (PLA), polybutylene adipate terephthalate (PBAT) or polybutylene succinate (PBS)) are universally biodegradable across different ecosystems. Whether or not a plastic product labelled as ‘biodegradable’ actually undergoes biodegradation will vary according to properties of the plastic, and the specific abiotic and biotic conditions in the environment in which the plastic resides (Figure 2) [2,7,8]. As such, biodegradability must be considered as a systems property, which is influenced by the interplay between the specific material and the environmental conditions. PLA, for example, degrades in industrial facilities (62 ± 4°C with >60% relative humidity) within weeks, yet lacks degradability in natural environments where these conditions are not present [9,10]. Currently, standardised testing on which the biodegradability of a product is demonstrated is undertaken in the laboratory where conditions do not replicate the wide diversity of scenarios present in natural environments [3,11,12]. Research studies report highly variable deterioration rates for biodegradable polymers across aquatic and terrestrial environments [13–16]. Consequently this can lead to localised accumulation of plastic particles [17,18], as well as chemical additives or degradation products (section 2.3), and the potential for interaction with organisms. If biodegradable plastics persist in the environment for a substantial time before biodegrading completely, it is likely that some of the risks of biodegradable plastics will be similar to conventional plastics.

Ecological interaction and impacts of biodegradable plastics

Microbial interactions

Conventional plastics have high stability and their chemical structures lack bonds that can be readily cleaved through abiotic or enzymatic processes. By comparison, the carbon backbone of biodegradable polymers contain functional groups that are enzymatically hydrolysable, which should facilitate enzymatic depolymerisation and utilisation of the polymer carbon by the microbial community. Microorganisms can rapidly colonise man-made surfaces, such as plastic, in aquatic [19–22] and terrestrial ecosystems [23,24], with community

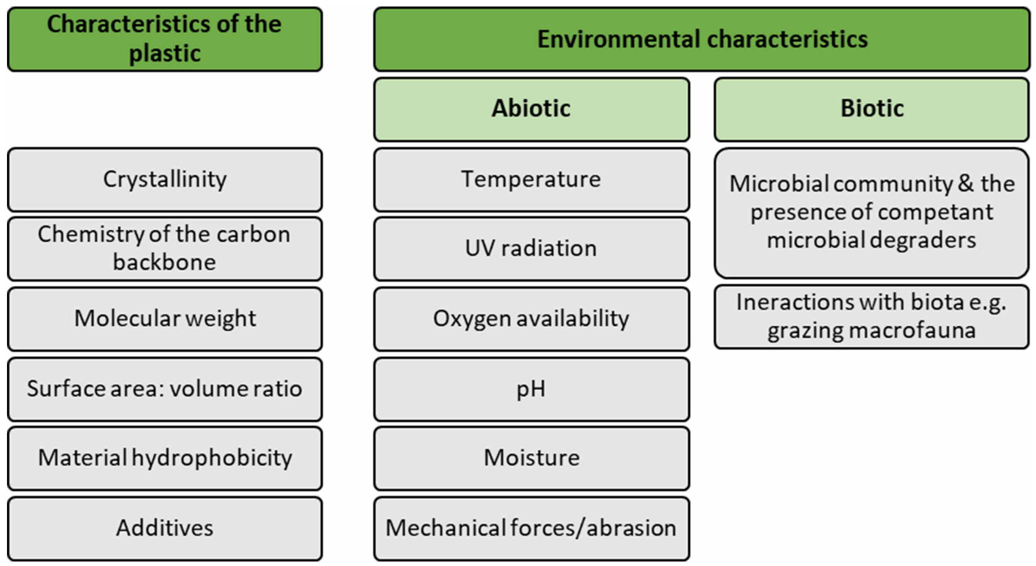

Figure 2. Summary of the characteristics of the plastic and environmental which influence deterioration rate and biodegradation.

The biodegradability of a plastic is a systems property, which is influenced by the interplay between the composition of the material and the abiotic and biotic environmental conditions in which it resides.

composition differing from the ambient environment [21,22,25]. Within marine environments the plastic biofilm can become enriched with hydrocarbonoclastic bacteria i.e. those capable of degrading hydrocarbons [26]. The abundance of carbon-degrading, and in some cases sulfur-degrading, microorganisms present on biodegradable polymers, such as Polyhydroxyalkanoates (PHAs) and cellulose acetate, far exceed those on conventional polymers [27–29]. Similar results were found in soil incubations, where communities on biodegradable polymers were enriched in carbon-degrading bacteria and specific fungal groups, for example the phylum *Ascomycota* which are important for the decomposition of organic matter and have been shown to degrade PBAT [30].

The action of biodegradation and the mineralisation of plastics into their constituent molecules may lead to a localised inputs and increases of organic carbon in the environmental compartment of concern. For example, biodegradable agricultural mulch films have become widely used as an alternative to polyethylene (PE) films as they offer the possibility of being ploughed into the soil after use where they are microbially degraded [4,6]. Although the carbon input is small compared with the volume of soil into which they are incorporated, agricultural soils are usually carbon limited [18]. Studies demonstrate that microbial biomass and enzyme activity can increase [31,32] and soil microbial community structure can alter [13,30,33] in response to the carbon input from biodegradable mulch film use, for example through an enrichment of fungal groups [13,30,34]. Moreno and Moreno [33] found that the microbial biomass carbon increased in biodegradable mulch treatments compared with PE, which suggests that biodegradable plastics may influence soil carbon dynamics. It is not clear what effects modifications of the microbiome by biodegradable plastics may have on the soil ecosystem and its functioning, or how long these effects may persist.

In addition, there may be indirect effects associated with the use of biodegradable plastics in the environment. Using the example of agricultural mulches, the film acts as a barrier which alters the soil microclimate by reducing evaporation, gas exchange and light transmission and increasing temperature [18,35]. The modified conditions can result in greater nutrient availability for rhizosphere microorganisms [18,36,37]. While these studies have focused on PE mulch films, it can be inferred that biodegradable films will have similar indirect effects on microbial community structure and diversity. Within the marine environment, biodegradable plastics bags were found to reduce the oxygen availability and increase the pH of the underlying sediment [38]. The authors did not analyse microbial communities, however it can be suggested that there would be modification in the assemblage in favour of facultative anaerobes.

Individual and population-level effects

Exposure to micro- or nano- plastics can lead to effects at different levels of biological functioning [39,40] (Figure 3). From an ecological risk assessment perspective, endpoints relating to population dynamics such as adverse effects on survival, growth and reproduction are of most concern. Numerous laboratory studies have documented individual and population-level effects such as altered feeding rates and reduced fecundity following exposure to conventional plastics [41–43]. In addition, impacts on specific cells and organs such as oxidative stress and modified metabolic demands [44–46] have also been reported. The disposition to toxicity will depend on the exposure concentration (particle size distribution, particle number concentration, etc.) as well as the ecological niche and chemical matrix (i.e. type of sediment, soil or water) where the organism lives. While the thresholds for biological effects of plastics in the environment remain to be agreed, there is a concern for the effects on biodiversity and community-level functions [47].

Nearly 14% of all biodegradable plastics produced in 2021 were used in agricultural applications (not including associated packaging) [4]. These items, such as mulch films (primarily composed of PLA or PBAT), are directly applied to the land and not recovered at the end of their life, as such there is high likelihood for interaction with terrestrial species. Toxicity with respect to earthworm reproduction were reported for fragments of the two biodegradable polymers: PLA and polypropylene carbonate, and the non-biodegradable polymer PE [48], whereby all polymers caused a similar decrease in the number of cocoons produced with increasing plastic exposure. Exposure to PLA fragments has also been shown to reduce the biomass of earthworms [49], and alter the burrowing behaviour of earthworms [50]. Similar effects have been documented for conventional plastics whereby the survival, growth rate, metabolic processes and burrowing behaviour of worms have been negatively affected [51–53]. It is hard to draw conclusions about the comparative effects of biodegradable and conventional plastics on earthworms due to the differing concentrations, particles sizes and exposure times used between the aforementioned studies. Earthworms are key ecosystem engineers with an important role in maintaining soil health and the breakdown and recycling of organic matter [54,55], and provide a food source to many higher trophic level species. Consequently, a reduction in earthworm population or their function may have ramifications on the soil ecosystem as a whole [49,56].

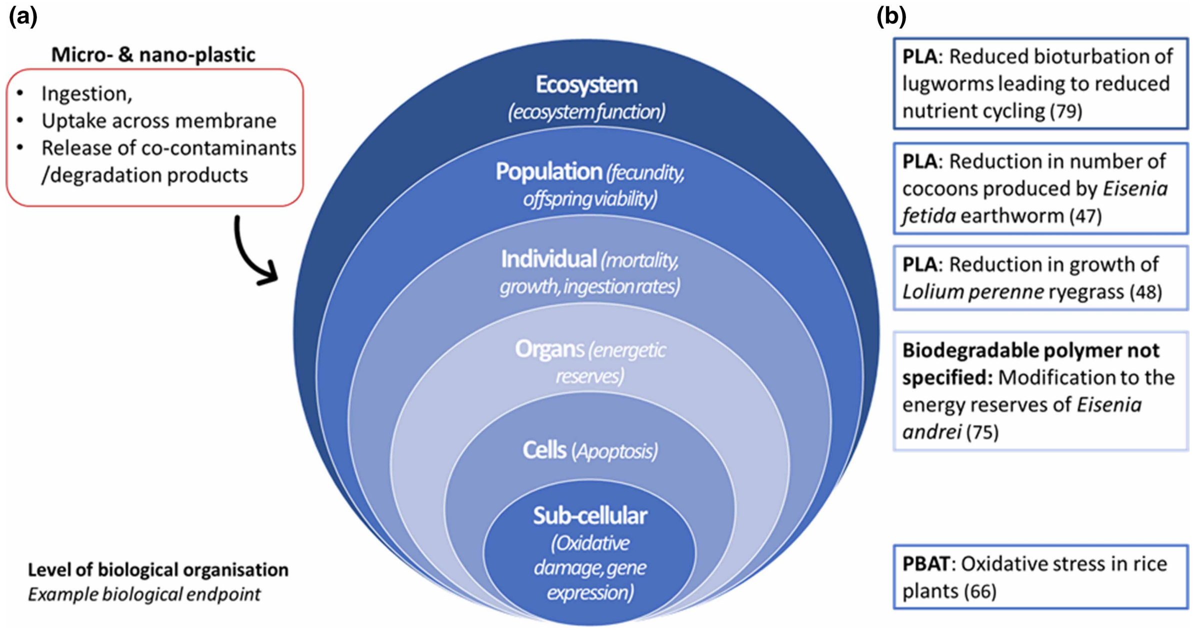

Figure 3. Simplified schematic illustrating potential impacts of exposure to biodegradable polymers across successive levels of biological organisation (a). Effects induced by exposure to biodegradable polymers are presented in the boxes (b) at the corresponding levels of biological organisation (where data are available), with citations in parentheses.

Nanoplastics have been shown to enter plants primarily via the root tips [57–61], and can be transported to the ariel parts of the plant [62,63]. The factors influencing uptake and the subsequent transport mechanisms are not fully assessed and quantitative data are limited, which are required to evaluate wider environmental impacts and potential risk to human health from crops. These studies have mainly used polystyrene (PS) nanoplastics and evidence a range of effects; for example, significant reductions in growth (roots and stems) and development (germination success) of mung beans [63], wheat [64], corn [65] and cress [66] following acute exposure to nano-PS. Conversely, other studies report no observed effect of PS exposure on the germination success for wheat [59], or on the growth or development of radish [65], which may be explained by methodological differences (exposure concentrations and duration) between studies.

Exposure to PLA microplastics (0.1% w/w) caused significant effects on the development and growth of perennial ryegrass, where fewer seeds geminated and root length was supressed compared with control groups [49]. A similar result was demonstrated for rice plants exposed to PBAT-based film fragments, where growth of the roots and shoots were significantly impaired leading to reduced nitrogen metabolism and photosynthesis [67]. The root system is essential for plant growth and development due to its role in the uptake of water and nutrients; roots are sensitive to perturbations [68] which in turn can affect crop productivity. Numerous studies have evidenced that microplastics (both conventional and biodegradable) have significant impacts on plant growth, development and reproduction, and suggest that the effects may be more pronounced for biodegradable polymers compared with PE [49,69,70], however further work is required to more comprehensively evaluate this.

As with conventional plastic products, those made from biodegradable plastics also contain a range of chemical additives such as flame retardants, stabilisers, and colourants, used to enhance their functionality or confer desirable properties. Non-targeted chemical screening of biodegradable plastics (including PLA, PHA, PBAT and starch and cellulose based materials) indicated that the materials broadly contained a similar number of chemicals as conventional polymers [71–73] and induced similar toxicity in *Allivibrio fischeri* [71]. Other studies have also attributed the toxicity of biodegradable and conventional polymers on the development of cress seedlings [74] and on the suppression of reproduction in the solitary ascidian *Microcosmus exasperates* [75], to the chemicals present within them. Both of the aforementioned studies found no significant differences between materials (i.e. conventional or biodegradable) indicating that biodegradable plastics present a similar hazard as conventional plastics to these organisms. However, a wider view is needed to evaluate the ecotoxicological implications of biodegradable plastics on a range of species.

Impacts on ecosystem functioning

The individual and population effects of plastic pollution can cause implications on community structure and ecosystem processes such as bioturbation, decomposition, primary production and carbon and nitrogen cycling [50,77–81], which could ultimately induce a reduction of ecosystem functions and services. Despite the number of studies assessing the impact of biodegradable plastics on ecosystems being low compared with conventional plastics, there is increasing evidence of the potential effects that biodegradable plastics have at ecosystem scale.

Microparticles of biodegradable (PLA) and conventional plastics (PE and acrylic and polyamide clothing fibres) caused reduced growth rates and bioturbation activity of earthworms (*Aporrectodea rosea*) independent of the polymer type [49]. Marine worms, such as lugworms (*Arenicola marina*), have also been shown to have reduced feeding activity and hence, a decrease in the volume of sediment overturned when exposed to different concentrations or types of microplastics (i.e. biodegradable (PLA) or conventional (PE and PVC)) [80]. Similar trends were reported for conventional plastics for both marine [44,82,83] and terrestrial species [51–53]. The oxygenation of the sediment/soil and recycling of organic matter exert control over ecosystem services such as nutrient cycling and primary productivity [84]. Thus, alterations to the behaviour of these invertebrates due to exposure to microplastic implies reductions in nutrient availability and sediment/soil quality and stability, which have consequences on primary producers and microbial communities.

Microplastic pollution can indirectly influence the performance of primary producers via the control of limiting inorganic nutrient from sediments [79]. Green et al. [80] suggested that limited inorganic nutrient availability triggered a reduction in biomass of microalgae within the surface of marine sediments, which was caused by the suppression of lugworm burrowing activity as a result of exposure to biodegradable and conventional microplastics. Laboratory mesocosms illustrated reduced cyanobacteria biomass as a consequence of the reduction in ammonium in sediment pore water, which was indirectly induced through the exposure of oysters and mussels to PLA and HDPE microplastics [79]. Photosynthetic primary producers can be directly impacted by biodegradable and conventional polymers, causing a reduction in chlorophyll content and photosynthetic inhibition in terrestrial [49], marine [79,80] and freshwater [85–87] species. A decrease in chlorophyll contents in primary producers could suggest reduced photosynthetic efficiency [88], hence reduced primary production of the system; with consequences for grazing invertebrate species.

Decreases in the biomass of primary producers may have cascading effects, where fewer resources are available for higher trophic levels [78]. Several studies document reduced rates of leaf litter decomposition by macroinvertebrates in streams due to altered aquatic fungal and microbial communities after being exposed to conventional nanoplastics [81,89,90]. While there are no records on how biodegradable plastics may affect leaf litter decomposition, we could expect similar effects to conventional plastics due to the similarity of the eco-toxicological effect that both types of plastics have at the individual level. However, it is important to note that while biodegradable plastics are not persistent by design, they require specific conditions for biodegradation to occur (e.g. PLA requires industrial composting conditions (62 ± 4°C, >60% relative humidity) [9]. Whether ecosystem-level effects will have time to manifest at environmentally realistic (transient) concentrations is less clear, and uncertain for the degradation products of those plastics (see section 2.4).

Impacts of exposure to chemical degradation products

From the viewpoint of the ecotoxicology, there is clear relationship between the bioenergetics of organisms and population level events [91]. Thus, also their ability to deliver ecosystem services and functions (see sections 2.1–2.3). In essence, an organism spends its daily energy on physiological maintenance (i.e. keeping tissues healthy), growth, reproduction, and/or locomotion. To survive in the long term, energy intake usually from food (assimilation after the cost of digestion/absorption) should slightly exceed energy expenditure. Ideally, wild animals will have a good metabolic reserve (aerobic metabolic scope) to deal with stressful situations, such as having the necessary energy and locomotor ability for evading predators [92]. During chemical exposures, the energy budget can be compromised and there may be a trade-off to meet the cost of toxicity and tissue repair to enable survival. For sessile organisms, such as marine mussels, there may be a reduction in growth to meet the cost of chemical exposure [93]. For active animals, such as a predatory rainbow trout, some two-thirds of its daily energy budget may be spent on locomotion (i.e. foraging and other behaviours), and swimming speed distributions are shifted to low speeds in order to meet the energetic cost of tissue repair (e.g. copper, [94]). The consequences of bioenergetics events for ecosystem functions could be substantial. For example, the disruption of prey-predator interactions in food webs or the social hierarchy of the animals [95], and even the loss of an ecosystem service. For instance, damage to the skeletal muscle of earthworms to prevent locomotion (e.g. carbon nanoparticles, [96]), would ultimately impact the ecosystem service of soil turnover. However, it is not yet clear if the organic chemicals that are the degradation products of biodegradable plastics will affect the bioenergetics of organisms and subsequently the ecosystem functions they provide.

For biodegradable polymers such as PBAT and PLA, the organic chemicals released during either their chemical hydrolysis in the environment or microbial degradation are now being reported [97,98]. For PLA, the main degradation product is lactic acid. According to the European Chemicals Agency (ECHA) database [99] lactic acid is also identified as a 'biocidal active substance.' Lactic acid is a substrate for fermentation in microbes. However, ATP production by fermentation is well-known to be much less efficient than aerobic metabolism, and bioenergetic consequences of excess lactic acid in the environment could include impaired efficiency of energy production in some microbes, with consequent changes in microbial biodiversity in the biofilms in the ecosystem. However, there are also specialist microbes that can routinely use lactic acid as a substrate. Lactic acid bacteria (order: *Lactobacillales*) are widely founds in ecosystems with important roles in soil-plant interactions, etc., [100] and lactic acid will promote their growth. These organisms subsequently produce a range of organic acids that are biocides especially to fungi and other microbes [101]. Thus, the potential for PLA to alter the biodiversity and functions of microbial biofilms is a concern. Ingestion of PLA also effects the avoidance behaviour of earthworms [102], but effects on gut microbiomes are not yet reported.

Crucially, some biodegradable plastics will result in degradation products that have some toxicity. For example, the biodegradation of PBAT results in the release of terephthalic acid (TPA) [98], which has an acute oral toxicity to rodents (LD50) of ∼5000 mg/kg [103]. Terephthalic acid may impair the germination of plant seedling [104] and for esters of TPA the lethal toxicity for *Daphnia magna* is ∼0.4 mg/l [105], and so there are ecological concerns regarding this metabolite of PBAT. However, the research on the degradation products released from biodegradable plastics in ecological scenarios is still in early days, and in order to address the environmental risks, a wider view is needed. This includes the types of degradation products, measured environmental concentrations of those organic chemicals, as well as a range of toxicity data from different organisms to create species sensitivity distributions that may inform on biodiversity concerns. If the concentrations and identity of the degradation products can be established, then it may be possible to use existing toxicology databases to obtain information on hazards to organisms and bioaccumulation potential. However, mesocosm experiments will be needed for more complex aspects of fate and effects in food webs, and ultimately field studies with ecological surveys to identify ecosystem-level effects.

Conclusion

While biodegradable plastics are sometimes perceived as an 'environmentally-friendly' alternative to conventional plastics [106,107], evidence shows that they have the capacity to exert similar toxic effects on animals and plants as conventional plastics [48,73,80]. Individual-level effects may become amplified with levels of biological organisation, i.e. a reduction in an individual's reproductive rate [48] or particular behaviours such as bioturbation [80] can have ramifications on the population and on ecosystem functioning. Microbial biodegradation may limit the long-term environmental persistence of biodegradable plastics and consequently the hazard posed to other organisms; however the rate of degradation is highly variable under natural conditions [8,16,108]. Microbial biodegradation can make small contributions to changes in nutrient cycling in ecosystems, however it is not clear how long these changes may persist or the scale of these effects on biogeochemical cycles. Chemical degradation products may also present hazards, e.g. terephthalic acid as a metabolite of polybutylene adipate terephthalate (PBAT), but these have not been evaluated in terms of their environmental concentrations or toxicity to a range of organisms. Currently, there is insufficient data to evaluate the hazard posed by biodegradable plastics, and thus uncertainty would remain high in any risk analysis.

Summary

- Biodegradable plastics induce effects at a range of ecological scales: from individual to ecosystem-wide impacts.
- Toxic degradation products can arise during biodegradation; however, the effects of these are not fully evaluated.
- Biodegradable plastics can alter carbon and nitrogen dynamic in soils and sediments, leading to alterations in microbial community structure and diversity.
- Akin to conventional plastics, biodegradable plastics contain additives which can induce toxicity.
- Currently, data on the exposure and effects of biodegradable plastics, including degradation products and co-contaminants, is too sparse to conduct a reliable ecological risk assessment.

Competing Interests

The authors declare that there are no competing interests associated with the manuscript.

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Author Contribution

All authors contributed to all aspects of this publication.

Abbreviations

PBAT, polybutylene adipate terephthalate; PE, polyethylene; PLA, polylactic acid; PS, polystyrene; TPA, terephthalic acid.

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