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The lesser of two evils: Enhancing biodegradable bioplastics use to fight plastic pollution requires policy makers interventions in Europe

Mirko Cucina

National Research Council of Italy, Institute for Agriculture and Forestry Systems in the Mediterranean (ISAFOM-CNR), Via della Madonna Alta 128, 06128 Perugia, Italy

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A B S T R A C T

Plastic pollution is a ubiquitous and universally recognized environmental threat, and bioplastics have emerged as a potential solution to this issue in the last years. Being biobased and biodegradable, bioplastics have a reduced carbon footprint with respect to plastics, and they are not expected to accumulate and fragmentate in the environments as plastics do. Nevertheless, some bioplastics drawbacks such as their slow biodegradation in engineered (i.e., anaerobic digestion and composting) and natural (i.e., soil and water) environments have been used by sceptics to discredit bioplastics, and this have induced policy makers to use a precautionary approach to the topic (i.e., including bioplastics in the ban of single use products and in the count of inert materials in organic fertilizers).

Using a simplified ecologic risk assessment analysis, this Opinion paper aimed to show that bioplastics that are proven to be intrinsically biodegradable are always a better choice than plastics. Having a residence time in natural environments of about 1–10 years, the likelihood of bioplastics causing harmful effects on living organisms is about 100–1000 times lower than plastics that resides thousands of years in the environments. Taking this into consideration, policy makers are asked to revise recent regulations and directives to enhance bioplastics diffusion and fight plastic pollution. In this sense, Single Use Plastic Directive 2019/904 may exclude biodegradable bioplastic items from the ban, and European Regulation on Fertilizers 2019/1009 may exclude biodegradable bioplastics residues from the count of inert materials in organic fertilizers. Bioplastics collection within biowastes and subsequent anaerobic digestion should be also favoured, in order to force controlled bioplastics biodegradation into biogas and reduce their leakage into the environment, resulting in the enhanced circularity of bioplastics products.

1. Introduction and aim of the paper

Plastics pollution is a widespread threat to the environment, and there are several reports describing the ubiquitous nature of this phenomenon, from the Arctic to the deserts, from the mountaintops to the oceans. Plastics enter natural environments as a result of incorrect management, and due to their resistance to degradation, they can remain for hundreds of years and thus accumulate (Bergmann et al., 2022). There, plastics undergo fragmentation processes, originating microplastics and nanoplastics, which have been proven to be harmful for living organisms both due to their bioaccumulation and to the possible absorption of hazardous pollutants (i.e., heavy metals, hormone-like molecules, hydrocarbons, and dioxins) (Fred-Ahmadu et al., 2020). Furthermore, plastics are mainly produced from fossil raw materials, whose non-renewability and heavy environmental footprints represent serious threats to global sustainability. To contrast plastics pollution, the Directive EU 2019/904 on the reduction of the impact of certain plastic products on the environment, better known as the Single-Use Plastics Directive, or SUPD, was passed in June 2019 and came into force on July 3, 2021 (European Parliament and the Council, 2019a).

Although recycling of plastics wastes and their recovery is a developing approach to reducing plastics leakage into the environment, this strategy does not address the issue at the source (Li et al., 2021). In this context, biobased biodegradable bioplastics (i.e., starch-based bioplastics - SBB, polylactic acid-based bioplastics - PLA, polybutylene succinate - PBS, polyhydroxyalkanoates - PHAs) have emerged as viable plastic alternatives in the last decade (Rosenboom et al., 2022). Biodegradable bioplastics are considered environmentally friendly since they are made from renewable materials and are biodegradable, limiting their GHG emissions and accumulation in natural environments in the

E-mail address: mirko.cucina@cnr.it.

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event of leakage. Bioplastics production from renewable agricultural materials is a promising strategy that has many advantages, such as (i) being less energy-intensive, (ii) improving agricultural-based economies, and (iii) allowing for desired product characteristics by material modification (Nanda et al., 2022). Furthermore, some kinds of bioplastics (i.e., PLA) are potentially recyclable by hydrolysis to obtain the initial monomers, which may be reutilized in bioplastics production or other green chemistry applications (Yang et al., 2022).

Non-biodegradable bioplastics (i.e., biobased polyethylene, biobased polypropylene, and biobased polyethylene-terephthalate) are produced from renewable materials but are not biodegradable, thus presenting the same environmental issues as plastics (e.g., accumulation in natural environments because of incorrect disposal). Therefore, non-biodegradable bioplastics were not considered in this work, and the term bioplastics was used to refer to biobased biodegradable bioplastics.

Bioplastics are used for an increasing variety of applications, ranging from packaging to consumer products (i.e., electronics, automotive, and textiles), with packaging being the largest market segment for bioplastics (48% of the total bioplastics market in 2022) (European Bioplastics, 2022). Due to increased consumer consciousness, the bioplastics market is expected to increase sharply, i.e., approximately 2.23 million tonnes of bioplastics were produced globally in 2022, and 6.3 million tonnes will be produced in 2027 (+182%) (European Bioplastics, 2022). Indeed, evidence gathered from Filho et al. (2021) suggests that most consumers showed awareness of the plastic pollution problem and an interest in being engaged in reducing the use of plastics by adopting sustainable alternatives (i.e., bioplastics).

Recently, bioplastics end-of-life has emerged as a key driver of bioplastics' circularity (Rosenboom et al., 2022). In many countries (e.g., Italy), biodegradable bioplastics certified as compostable according to standard EN 13432:2000 are collected within the organic fraction of municipal wastes. Therefore, they are treated with the biowastes in anaerobic digestion (AD) and composting plants, which are the most widespread treatment technologies for the valorisation and disposal of biowastes. The circularity of bioplastics is particularly enhanced in the case of AD systems, where they may be converted to biogas, producing a relevant amount of renewable energy, reducing their leakage into the environment, and thus increasing the overall sustainability of bioplastics (Cucina et al., 2022).

Despite all the potential benefits of bioplastics introduction and diffusion, *all that glitter is not gold*. Indeed, some drawbacks and limits of bioplastics have emerged in the scientific literature in the last years, and this has led to doubts about their effectiveness in fighting plastic pollution (Nandakumar et al., 2021). In this context, the present Opinion paper aimed to summarise all the current limits of bioplastics and described for the first time how they have impacted policy makers' decisions in Europe in the last few years. Thereafter, this work aimed to propose for the first time an approach to defining whether or not bioplastics are *the lesser of two evils* when compared to plastics. Using a simplified ecologic risk assessment analysis, bioplastics and plastics were compared, and based on the results obtained, some possible ways to enhance bioplastics usage and fight plastics pollution were highlighted (both from a policy and investigation point of view).

2. Bioplastics: Analysis of the main current issues

Generally, bioplastics have been negatively addressed because the raw materials they are made of are often also used for food, there is not enough production, and their costs are higher than those of conventional plastics (Ortiz, 2023). Reviewing the literature, many authors have pointed out that biodegradable bioplastics do not effectively degrade during real AD and composting processes, even when bioplastics are certified as compostable (Cazaudehore et al., 2022; Cucina et al., 2021a). This may be due to several factors, such as the fact that real operating conditions in plants treating biowastes are far from those established by standard tests aiming to evaluate the biodegradability and compostability of bioplastics (i.e., shorter retention times, lower temperatures). Furthermore, biodegradability of bioplastics depends on their chemical composition while biodegradation rate on external factors, being temperature recognized as the key driver. Specifically, temperatures higher than 58–60 °C are usually required to switch the crystalline structures of some bioplastics into more biodegradable amorphous ones (Papa et al., 2023). The incomplete degradation of bioplastics during AD and composting processes often results in the presence of high amounts of bioplastics' residues in the digestate and compost, which are materials intended to be applied to soil as bio-based organic fertilizers due to their chemical characteristics (i.e., high concentrations of organic matter and nutrients) (Bandini et al., 2022; Cucina et al., 2022, 2021b; Gadaleta et al., 2022). This latter issue has serious implications for agricultural reclamation of digestate and compost because of (i) the normative requirements established for organic fertilizers by the new European Regulation on Fertilizers (European Parliament and the Council, 2019b) and (ii) the debated fate of bioplastics in soil. The new European Regulation on Fertilizers that entered in force in 2021 has established a limit of 0.3% weight bases for plastics impurities larger than 2 mm in digestate and compost (limit to be strengthened to 0.25% weight bases from 2026), without distinction between fossil-based plastics and bioplastics. In the near future, it may be likely that increasing amounts of digestate and compost will not comply with the Fertilizers regulation due to bioplastics' residues contamination, limiting the reclamation of nutrients and organic matter into the soils, which is clearly in contrast with the Circular Economy Strategy objectives. The absence of distinction between plastics and bioplastics in the European Regulation on Fertilizers might be seen as a precautionary point of view due to the scientific evidence that shows that the biodegradation of bioplastics in the soil takes place over a long period of time (Chah et al., 2022; Papa et al., 2023). Bioplastics biodegrade slowly in soils as a consequence of different factors, including the low concentration of microorganisms, the low water availability, and the low temperature. Nevertheless, it should be noted that each soil provides a different environment and microbial diversity, resulting in different biodegradation rates (Chah et al., 2022). Despite some authors have shown that bioplastics can effectively biodegrade in a few months/years in soil and that biodegradation of bioplastics' residues from biological treatments is enhanced (Cucina et al., 2021a; Papa et al., 2023), there is an increasing warning about bioplastics and bioplastics' fragments accumulation in soil. Since bioplastics biodegrade in soil in months/years, for some authors, it is likely that bioplastics can accumulate in soil, as well as undergo fragmentation processes resulting in micro-bioplastics and nano-bioplastics, similarly to plastics (Fojt et al., 2020; Okoffo et al., 2022). Furthermore, the potential bioaccumulation and biomagnification of micro-bioplastics, as well as the potential adsorption of hazardous contaminants on bioplastics fragments have recently been pointed out, with some authors suggesting that micro-bioplastics may be as harmful as microplastics (Ali et al., 2023). As if that were not enough, the reputation of bioplastics has taken a serious hit due to their inclusion in the SUPD. The SUPD makes no distinction between conventional and bio-based plastics, as well as biodegradable and compostable bioplastics. The EU Commission states that biodegradable/compostable plastics, as well as bio-based plastics, are deemed plastic and hence subject to the SUPD (European Parliament and the Council, 2019a). Due to the inclusion of biodegradable and compostable bioplastics in the directive's purview, the SUPD has had an impact on the bioplastics industry in a similar way to how it has on the entire plastics industry.

Assuming that all the described concerns about bioplastics might be scientifically funded, is it reasonable to consider bioplastics as hazardous as plastics?

3. The role of bioplastics intrinsic biodegradability in reducing their ecological risk

This Section aimed to provide reliable answers to the question raised in the previous paragraph. To do that, a simplified ecological risk assessment (ERA) analysis was carried out to clarify if bioplastics have to be considered as hazardous as plastics or not.

ERA is described as a process that evaluates the likelihood that adverse ecological effects on ecosystems exposed to one or more stressors may occur or are already happening (Chen et al., 2013). *Probability* and *severity* are the elements contributing to the definition of risk, and they serve as generic concerns in the process of risk formulation (Chen et al., 2013). Severity is an intrinsic property of the stressor, whereas the probability that a living organism meets the stressor depends on the exposure, which in turn depends on the *environmental concentration* and on the *residence time* (Degli Innocenti and Breton, 2020). Therefore, a simplified ERA may be defined using the following Equations:

$$Risk = S \times P \quad (1)$$

$$P = C \times Rt \quad (2)$$

$$Risk = S \times C \times Rt \quad (3)$$

Where S is the severity, P is the probability, C is the concentration and Rt is the residence time.

In a worst-case scenario, it might be assumed that the stressors analysed in this paper (plastics and bioplastics) have the same harmful effects on living organisms and, thus, the same severity. In other words, it can be assumed that the risk only depends on the likelihood that adverse ecological effects may occur as a result of exposure to the stressors (probability), according to the following Equations:

$$Risk = P \quad (4)$$

$$Risk = C \times Rt \quad (5)$$

If the same concentration of plastic and bioplastics is considered (i.e., one bag per square metre of soil), the risk may finally depend only on the residence time:

$$Risk = Rt \quad (6)$$

Since Rt represents the time in which the stressor will remain in the environment and in which it can carry out its harmful effect, it is evident that bioplastics represent a significantly lower risk than plastics. Indeed, bioplastics are expected to degrade in natural environments like soil and water in a range of 1 to 10 years, depending on bioplastics characteristics and environmental conditions (Cucina et al., 2021a). Assuming a Rt of 1000 years for plastics (Chamas et al., 2020), it is possible to estimate that bioplastics have a reduced risk with respect to traditional plastics by a 1/100–1/1000 factor. For example, if a plastic bag and a bioplastic one are leaked into the sea, a fish will be 100 times more likely to swallow the plastic bag than the bioplastic one (Fig. 1). If bioplastics are intercepted, collected, and processed alongside other biowaste in AD and composting plants, they can also significantly lower the concentration factor in the risk definition. Summarising, the intrinsic biodegradability of bioplastics decreases residence time and concentration factors in risk definition. Despite their limits, it is therefore unquestionable that bioplastics represent *the lesser of two evils* with respect to plastics.

4. Implications of bioplastics intrinsic biodegradability on policy makers decisions and future research

Having provided simple and reliable proofs that bioplastics are less hazardous than plastics, the next steps to favour bioplastics' spread and fight plastics pollution are to increase their diffusion, favour their correct disposal and end-of-life management, and encourage scientific

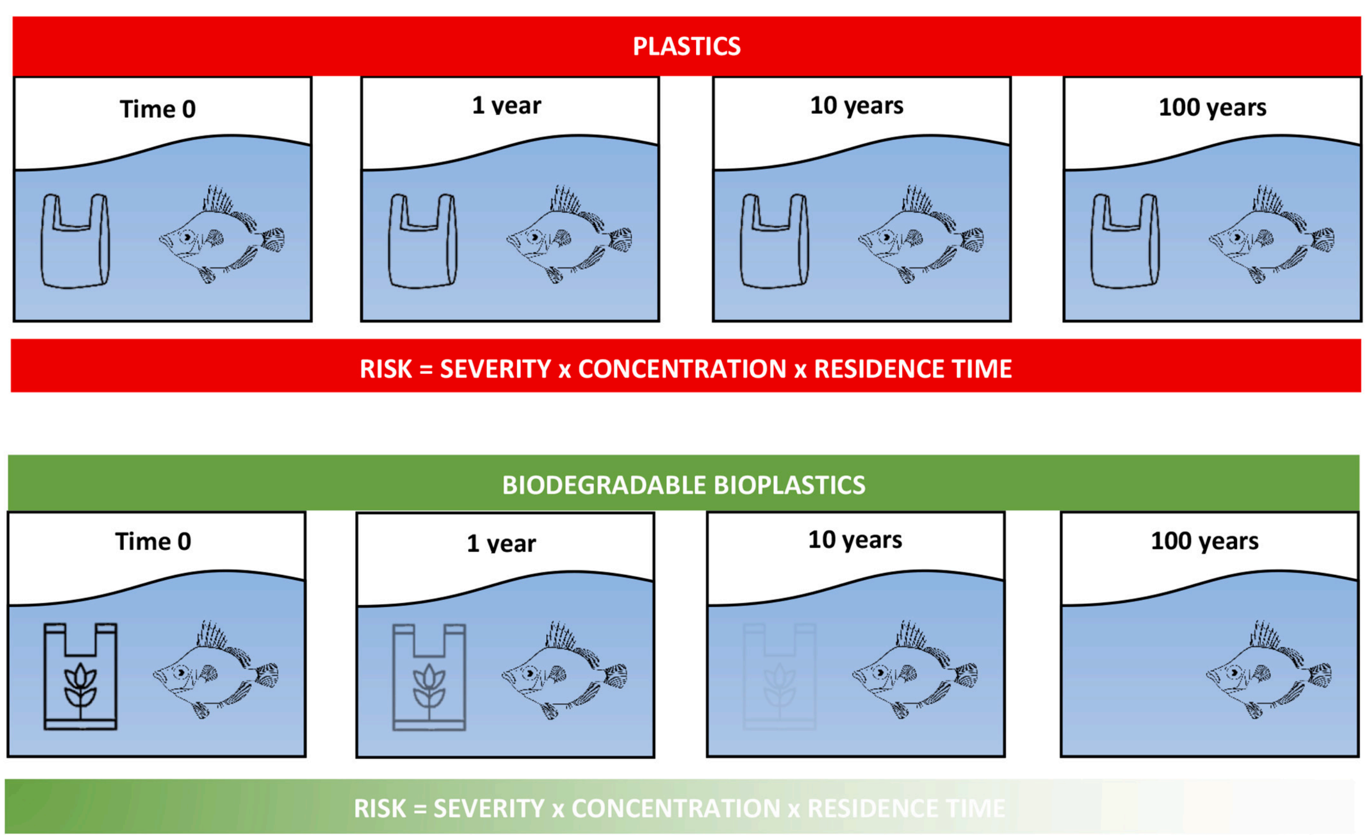

Fig. 1. Intrinsic biodegradability of biodegradable bioplastics and its effect on ecological risk of bioplastics leakage into the environment.

research to introduce easy biodegradable bioplastics. To reach these goals, European policy makers are required to take a step forward and move from the precautionary principle used in SUPD and fertilizers Regulation 2019/1009 to a scientific principle, assuming that bioplastics are intrinsically biodegradable and thus the ecological risk associated with their leakage into the environment is always lower than plastics.

First, SUPD should be revised to exclude biodegradable compostable bioplastics from the banned items. In this sense, the Directive revision foreseen for 2027 needs to include an assessment of the scientific and technical progress concerning standards for biodegradability in the environment applicable to single-use plastic products and confirm the ban only for plastic and non-biodegradable items. In this sense, some countries (i.e., Italy and Slovakia) have already transposed SUPD into National Regulations, with some modifications excluding compostable plastics from the ban. For instance, in Italy, compostable bioplastics with a defined bio-based content may be marketed, and in Slovakia, biodegradable alternatives may be offered for food containers and cups for beverages, besides opting for a fee or a reusable solution (Decreto Legislativo n. 196, 2021; National Council of the Slovak Republic, 2019).

The expected increase in bioplastics spread will result in an increased amount of bioplastics' waste to be correctly collected and managed. As already mentioned, bioplastics' circularity is sustained by the separate collection of bioplastics within biowastes and the subsequent treatment in AD plants producing biogas. Finally, composting of digestate will allow organic matter and nutrients to be recovered from the biowaste streams, including bioplastics. To increase bioplastics' circularity, policy makers are therefore required to favour bioplastics' collection within biowaste and the recovery of biogas through biowastes' AD. This will also help reaching the objectives of the Circular Economy Strategy, i.e., recycling of biowastes will be key to meeting the EU target to recycle 65% of municipal waste by 2035. To provide plastic-free biowastes for the AD and composting processes, precise guidelines on the labelling of compostable and biodegradable bioplastics are required. This will assist customers in performing a properly sorted collection. This is indeed of crucial importance to avoid technical issues during the processes (i.e., clogging of pumps in wet AD processes) and to produce high-quality digestate and compost. With regard to this latter point, European policy makers are asked to revise the new fertilizers Regulation 2019/1009 and exclude biodegradable bioplastics from the count of inert materials in digestate and compost (i.e., plastic, glass, and metals). In the light of the scientific evidence, bioplastics' residues leaking into the soil after digestate or compost application are likely to behave as natural biopolymers that constitute soil organic matter. To make this possible, the development of simple analytical methods to separate bioplastics from plastics after the recovery of inert materials from digestate and compost by oxidation of organic matter with hydrogen peroxide is mandatory. Methods based on spectroscopic recognition of residues (i.e., FT-IR) or based on physico-chemical properties of residues (i.e., solubility, density) appear promising to quickly define a reliable method to be included in the fertilizers Regulation 2019/1009 and allow excluding bioplastics residues from the 0.3% weight bases limits foreseen for plastics in organic fertilizers.

Overall, the effort of the policy maker must be accompanied by an effort of scientific research to enhance biodegradation of bioplastics to minimise the environmental risk, both in natural (i.e., soil, freshwater, and seawater) and engineered (i.e., AD and composting) environments, as also suggested by Ingrao et al. (2022) in the conclusions of a Life Cycle Assessment study on new bioplastics made from spent-coffee grounds. To increase the circularity of bioplastics, favour their conversion into biogas under controlled conditions, and decrease their leakage into the environment, it is necessary to introduce novel bioplastics that are highly biodegradable under AD conditions or new pretreatments to enhance anaerobic biodegradation of bioplastics. This should be accompanied by research aimed at replacing raw materials for the production of bioplastics with those that do not conflict with the production of food and feed and guarantee a lower cost of the finished product.

Furthermore, taking into consideration that social impact is crucial to spreading good practises of wastes reduction, reuse, and recycling in the context of a circular bioeconomy (Ferreira et al., 2022), the concept of intrinsic biodegradability of bioplastics should be highlighted and communicated to final consumers, who could be more conscious of the advantages of bioplastics with respect to plastics. To do this, researchers are required to carry out social impact studies of consumer awareness on the topic of bioplastics biodegradability that would be helpful in addressing an efficient strategy to communicate the importance of transitions from plastics to bioplastics.

5. Conclusions

Bioplastics have emerged in the last few years as promising substitutes for plastics due to their lower carbon footprint and biodegradability. Nevertheless, some limitations of these materials have emerged and have been used to discredit bioplastics, leading, among other things, to the fact that policy makers have hindered their diffusion to maintain a precautionary principle. Using a simplified ecologic risk assessment analysis, this paper showed that bioplastics that are proven to be intrinsically biodegradable always pose a lower risk to the environment than plastics and that *throwing the baby* (bioplastics) *with the bathwater* (bioplastics' issues that need to be further addressed) is not the best option to achieve the Circular Economy Strategy objectives. Policy makers in Europe are asked to step forward and use scientific principles to revise the Single Use Plastic Directive 2019/904, sorted collection and recycling targets, and European Regulation on Fertilizers 2019/1009 to enhance bioplastics spread and effectively fight plastic pollution.

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Mirko Cucina: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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