Plant Soil (2024) 494:85–94
https://doi.org/10.1007/s11104-023-06287-x

OPINION PAPER

Are biodegradable plastic mulch films an effective way to solve residual mulch film pollution in farmland?

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Received: 18 June 2023 / Accepted: 8 September 2023 / Published online: 19 September 2023

Abstract
Aim The pollution caused by agricultural plastic mulch film and the resulting microplastics has garnered significant attention. The partial application of biodegradable plastic mulch film (BPM) appears to be a promising method for reducing plastic pollution in agricultural soil.
Methods However, there is currently limited information available on the impact of BPM and the resulting microplastics on agricultural ecosystems. Many mechanisms and conclusions regarding this issue remain uncertain. Accordingly, a comprehensive understanding of the limitations of BPM applications is crucial for assessing the potential ecological risks and guiding future research.
Results Problematically, the actual environmental conditions of agricultural soil, climatic conditions, degradability, market price, and acceptance by farmers all significantly limit the implementation of BPM. Due to the faster and easier degradation of BPM compared to conventional plastic mulch film (CPM), a larger amount of microplastics may be generated within the same time frame. In addition, the implementation of BPM can result in significant alterations in soil microbial diversity, thereby affecting the emissions of CO2, N2O, and CH4. These changes can ultimately have unpredictable consequences on the carbon and nitrogen cycles.
Conclusion The price, uncertainty of degradation in soil, and potential negative impact on the soil environment also restrict the wide application of BPM. Overall, considering the existing knowledge gap and potential issues, further research is needed to determine whether BPM can effectively address the problem of residual mulch film and microplastic pollution in farmland. There is still a long way to go before BPM can completely replace CPM in agricultural production.

Keywords Residual mulch film · Biodegradable plastic mulch film · Plastic pollution · Microplastics · Management countermeasures

Responsible Editor: Jeff R. Powell.

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Current pollution status and harm of residual mulch film in farmland

Plastic mulch film is an important agronomic measure for improving grain and vegetable productivity. It has become an equally significant resource in agricultural production, alongside seeds, fertilizers, and pesticides (Li et al. 2023; Liu et al. 2022; Sintim and Flury 2017). The increase in soil temperature and moisture may enhance the activity of microorganisms, thereby promoting the decomposition of soil organic matter and

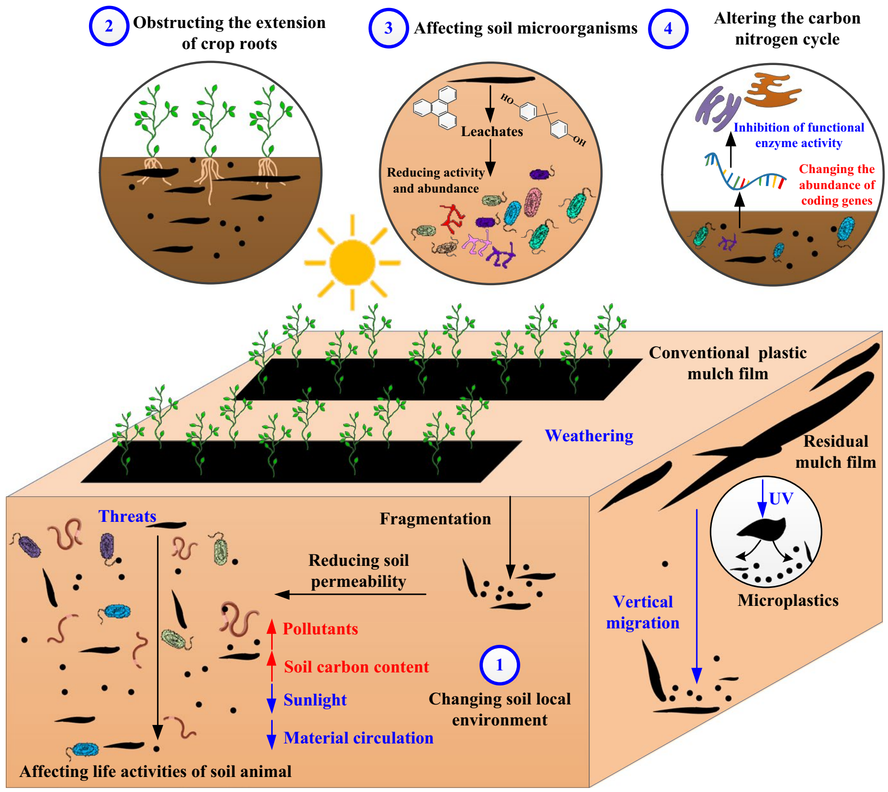

Fig. 1 Impact of traditional plastic film residues on soil environment in agricultural production

minerals. However, the benefits and drawbacks of this phenomenon still need to be assessed based on the specific conditions of the local area. The agricultural film used today is mainly made of polyolefin plastic film, which has particularly outstanding advantages. It not only has good transparency and insulation, but also has a lightweight texture that is easy to use. The use of plastic mulch is enormous globally and has been steadily increasing every year for the past 30 years (Brodhagen et al. 2017; Flury and Narayan 2021). The current value of the global plastic mulch film market is approximately US$ 5 billion, with an expected compound annual growth rate of 5.9% over the next 5 years (Zhou et al. 2023). Liu et al. (2021) showed that the consumption of polyethylene plastic film reached 1.4 million tons in 2018, covering an area of over 17.8 million hectares. At present, it is estimated that approximately 2.5 million tons of plastic mulch film are used for greenhouse planting, which accounts for about 0.5% of the global plastic production capacity. This plastic mulch film covers an area of 25 million hectares (Qadeer et al. 2021). With the pursuit of land use and food quality, the area covered by plastic mulch film will continue to increase.

Unfortunately, however, in recent years, the environmental issues and ecological risks caused by residual mulch film have gradually emerged. It is urgent to address the problem of white pollution (Qi et al. 2020; Shen et al. 2023). Residual mulch film can cause a serious "white pollution" problem in the farmland ecological environment (Ding et al. 2021). The distribution of residual mulch film in the soil exhibits various shapes and sizes of fragmented film. There is a correlation between the quality of farmland and the distribution and quantity characteristics of residual film on farmland (Shi et al. 2022). Residual mulch film can alter soil characteristics, impede soil water infiltration, impact soil moisture absorption, and lead to secondary soil salinization (Fig. 1). Wang et al. (2016) revealed that as the amount of plastic film residue increases, soil enzyme activity and microbial diversity gradually decrease, especially when the residual films exceed 450 kg/hm^2. The leaching of plastic additives can also cause soil pollution. Bisphenol A and phthalates are common plastic additives, and these two chemicals can leach into the soil, causing toxicity to soil organisms (Kim et al. 2019).

In addition, residual mulch films not only impact the soil microbial community, soil structure, water and nutrient transport, but also have a significant effect on crop production (Liu et al. 2022; Qian et al. 2018). In farmland soil without residual film, crop roots will extend vertically and horizontally underground to absorb nutrients and water from the soil. Residual film, however, hinders the normal extension of crop roots, affecting their ability to absorb water and nutrients. As a result, it limits root development and the growth of aboveground crops.

Recently, the partial application of BPM appears to be a promising solution for addressing the issues of residual film pollution and the resulting microplastics in agricultural soil environments. Common BPM include polylactic acid, polyhydroxy fatty acids (Anunciado et al. 2021), and adipic acid butyl phthalate (Bandopadhyay et al. 2020). These BPMs can theoretically be converted into H_2O, CO_2, and CH_4 through degradation. However, problematically, there are several problematic factors that greatly restrict the application of BPMs in agricultural soil. These include the real environmental conditions, mechanical strength and degradation performance, market price, and the acceptance of farmers. From the current knowledge gap and challenges, BPM cannot currently replace conventional plastic mulch. How to improve the degradation status has become a key issue faced by BPMs in addressing the global plastic pollution problem caused by agricultural residue films. This paper provides a systematic discussion on the controversy surrounding BPM, and explores its current situation, potential challenges, obstacles, and prospects. A comprehensive understanding of the limitations of BPM applications is essential for evaluating the potential ecological risks.

Treatment and disposal methods for agricultural residue film

Although the application of plastic mulch has increased crop yields, it has also posed certain challenges to sustainable agricultural development. Currently, agricultural production generally uses thin films, which lead to a high rate of film damage and makes cleaning and disposal challenging. Especially the use of "ultra-thin films" (4 μm thick) has resulted in an increasing amount of residual film in farmland. At present, the primary treatment methods for agricultural residual film include recycling, landfill, incineration, and reuse of residual film (Dong et al. 2022; Shen et al. 2022). Table 1 shows the advantages and limitations of CPM residue treatment techniques. The recycling and reuse of residual film can not only eliminate the crisis of farmland residual film but also achieve resource regeneration (Shen et al. 2020a). Kunwar et al. (2016) pointed out that the technologies for converting waste plastics into fuel oil through pyrolysis can not only solve environmental pollution problems but also alleviate energy shortages. These technologies can fundamentally address the recycling and utilization challenges associated with difficult-to-recycle low-density plastics and mixed waste plastics. Kaimal and Vijayabalan (2016) demonstrated that agricultural waste films containing long-chain hydrocarbon compounds can undergo thermal decomposition, resulting in the formation of smaller compounds. The pyrolysis products of plastics can be used as fuel, and their combustion performance is equivalent to that of diesel fuel (Kaimal and Vijayabalan 2015; Murugan et al. 2008). Unfortunately, the quality of the recycled residual film determines the quality of the oil product. The soil and crop debris present in the film residue have a significant impact on the end product (Zhang et al. 2019a). The cleaning steps required to remove soil, plants, and agricultural chemicals adsorbed by the film increase complexity (Serrano-Ruiz et al. 2021). In addition, recycling plastic mulch from soil is also a challenge (Somanathan et al. 2022). Mari et al. (2019) revealed that the cost of recovering residual film from soil is the highest compared to removal (176.5 pounds per hectare) and landfill (186 pounds per hectare), at 192 pounds per hectare.

Advantages and application status of BPMs

Most of the BPMs are blends of biobased polymers. BPMs are regarded as one of the important substitutes for commonly used agricultural plastic film (Serrano-Ruiz et al. 2021). A study performed by Griffin-LaHue et al. (2022) has shown that BPMs can be completely degraded under the action of soil microorganisms, ultimately producing only CO_2 and H_2O, and the degradation products do not pose any harm to soil or crops. Zumstein et al. (2018) found

Table 1 Advantages and limitations of CPMF residue treatment methods

Method/technology	Advantages	Limitations	Reference
Waste plastic conversion	It can solve environmental white pollution problems and alleviate energy shortages, fundamentally solving the problem of recycling mixed waste plastics.	The quality of recycled agricultural mulch determines the quality of oil products. The soil and crop debris contained in the film residue have a significant impact on the final oil product.	Kaimal and Vijayabalan (2016)
Plastic product reprocessing	Reducing oil consumption and saving resources.	The cleaning steps required to remove soil, plants, and agricultural chemicals adsorbed by the film increase complexity.	Zhang et al. (2019a)
Waste to energy	Waste resource utilization and reduction treatment.	A large amount of carbon dioxide is released, which may affect the global carbon cycle and climate change.	Shen et al. (2020a)
Open burning	Rapid treatment and reduction of farmland residual film.	After incomplete combustion, heavy metals, particulate matter, hydrocarbons, and derived pollutants will be generated.	Lin et al. (2018)
Buried or landfill	Effective, simple, and low cost	Additives and heavy metals will leach out with rainwater, polluting soil and groundwater.	Shen et al. (2022)

that carbon in poly (butyleneadipate-co-terephthalate) mulch can be metabolized by soil microorganisms, ultimately promoting microbial biomass. Sintim et al. (2020) reported that the degradation performance of BPMs depends on the nature of biodegradable materials, soil type and climate.

BPMs can not only replace traditional plastic film, but also increase crop yield and reduce the need for fertilization. Cowan et al. (2014) found that the performance of BPMs in weed control, tomato yield, and fruit quality is comparable to that of PE film. This finding suggests that BPMs have the potential to improve the sustainability of greenhouse vegetable production. Wortman et al. (2016) found that BPMs can maintain water and control weed growth during cucumber cultivation. Recently, Zhang et al. (2023) investigated the influence of BPMs and CPMs on soil properties, enzyme activities, and crop growth. The findings showed that BPMs were equivalent to CPMs, but more environmentally friendly. Somanathan et al. (2022) showed that BPMs can protect soil at depths of 20–30 centimeters from temperature fluctuations, thereby promoting root growth. Huang et al. (2022) compared the influence of PE film, BPM, and traditional flat planting on soil temperature, grain yield, and crop water productivity. The findings demonstrated that compared with traditional flat planting, both BPM and PE film increased grain yield by 2.1–93.3% and 7.6–34.6%, respectively. These differences were mainly significantly influenced by the annual precipitation in the rainfall area. The authors further pointed out that when the precipitation is greater than 600 millimeters and less than 800 millimeters, BPMs can achieve higher crop yield than CPMs.

Problems and limitations in the application of BPFMs

The cost of BPMs is a key factor hindering their application

Numerous studies have shown that BPMs can replace CPMs and have significant promotional value, as well as improving the current situation of agricultural microplastic pollution (Ding et al. 2022; Huang et al. 2022; Zhang et al. 2017). However, currently, the study and application of BPM is still in its initial stage. The cost of BPMs is higher than that of CPMs, which increases the difficulty of promoting and applying them. Recently, a study carried out by Huang et al. (2022) has revealed that the cost of BPM materials is $325.8 per hectare, which is 73.8% higher than that of PE film. Due to the limited ability of farmers to bear economic risks, the adoption of agricultural management measures often depends on the economic benefits (Zhang et al. 2015). This factor also affects the enthusiasm of farmers for participation (Li et al. 2015; Yang et al. 2023). In addition, most biodegradable plastics are made from renewable plant resources, such as corn and cassava. Problematically, corn belongs to the national strategic resource, which to some extent limits the research and application of BPs. As such, the application and promotion of BPMs still face significant limitations. Relevant technical personnel will still need to conduct research and make improvements, while also receiving government support and promotion in the future.

Uncertainty of degradation performance of BPMs in farmland soil is another key factor limiting their application

The degradation of BPMs is influenced by various environmental conditions, including temperature, pH, water content, etc. (Fig. 2). However, it is often challenging to meet all these conditions simultaneously in the field (Shen et al. 2020b). Borrowman et al. (2020) reported that biodegradation of BPs can occur in all soil types, with water content being the most significant environmental factor influencing the rate of polymer degradation. The authors further pointed out that the content of soil organic matter, pH, and polymer morphology may all be important in controlling the biodegradation process. Ghimire et al. (2020) found that BPMs can degrade over time in the field, but it takes more than one year for complete degradation. Microplastics and nanoplastics gradually form during the degradation process of BPMs. The generation of biodegradable microplastics and nanoplastics does not necessarily imply the complete degradation of BPMs, and their ecological impact on the soil environment should be promptly monitored. Sintim et al. (2020) conducted a study on the degradation performance of BPMs in compost and soil, specifically in warm and cool climates. The findings of the study revealed that BPMs are capable of degrading in soil. However, the rate of degradation is influenced by the local climate conditions and BPMs may persist in the soil for several years. The degradation rate of BPMs is faster during composting, making it more challenging to recover fragmented BPMs in soil. In addition, there are limited field research reports on the accumulation of BPMs derived microplastics and nanoplastics in agricultural soils. The persistence of BPM fragments and additives in soils requires to be addressed, taking into account soil characteristics and climatic conditions in agricultural ecosystems across different regions.

Impact of BPMs and derived microplastics on crops

Crops are the most crucial element of agricultural ecosystems, making it necessary to conduct a comprehensive evaluation of the impact of BPMs on crops. The toxicity analysis of BPMs on crops is mainly conducted by monitoring plant growth in soil containing film fragments. Figure 2 illustrates the potential effects of BPMs and derived microplastics on crops. Qi et al. (2018) studied the impacts of low-density polyethylene (LDPE) film and a starch-based BPM on wheat growth, and the results showed that residual film had a significant impact on wheat growth. Furthermore, when compared to LDPE, BPM demonstrated more pronounced negative effects. Boots et al. (2019) found that residual PLA (polylactic acid) microplastics in soil can affect the growth and development of *Lolium perenne* (perennial ryegrass), the health of *Aporrectodea rosea*, and potentially impact the functionality of soil ecosystems. Wang et al. (2020) evaluated the interaction between PE, PLA, and Cd^{2+} on maize and arbuscular mycorrhizal fungal communities. The findings suggested that a 10% concentration of PLA resulted in a reduction in maize biomass and chlorophyll content in the leaves. Furthermore, higher doses of PLA exhibited increased plant toxicity. Yang and Gao (2022) evaluated the influences of polyadipate/butylene terephthalate (PBAT) and PE mulch film-derived microplastics on the growth, physiological and chemical processes, and gene expression of rice plants. The results indicated that both microplastics interfere with photosynthesis and nitrogen metabolism in paddy. The negative impacts of microplastics on paddy can be mitigated through plant growth, and the adverse impacts of PE were relatively stronger than those of PBAT.

In addition, BPMs can affect crop growth and production by influencing soil properties and nutrient levels. Wang et al. (2022b) reported that the use of

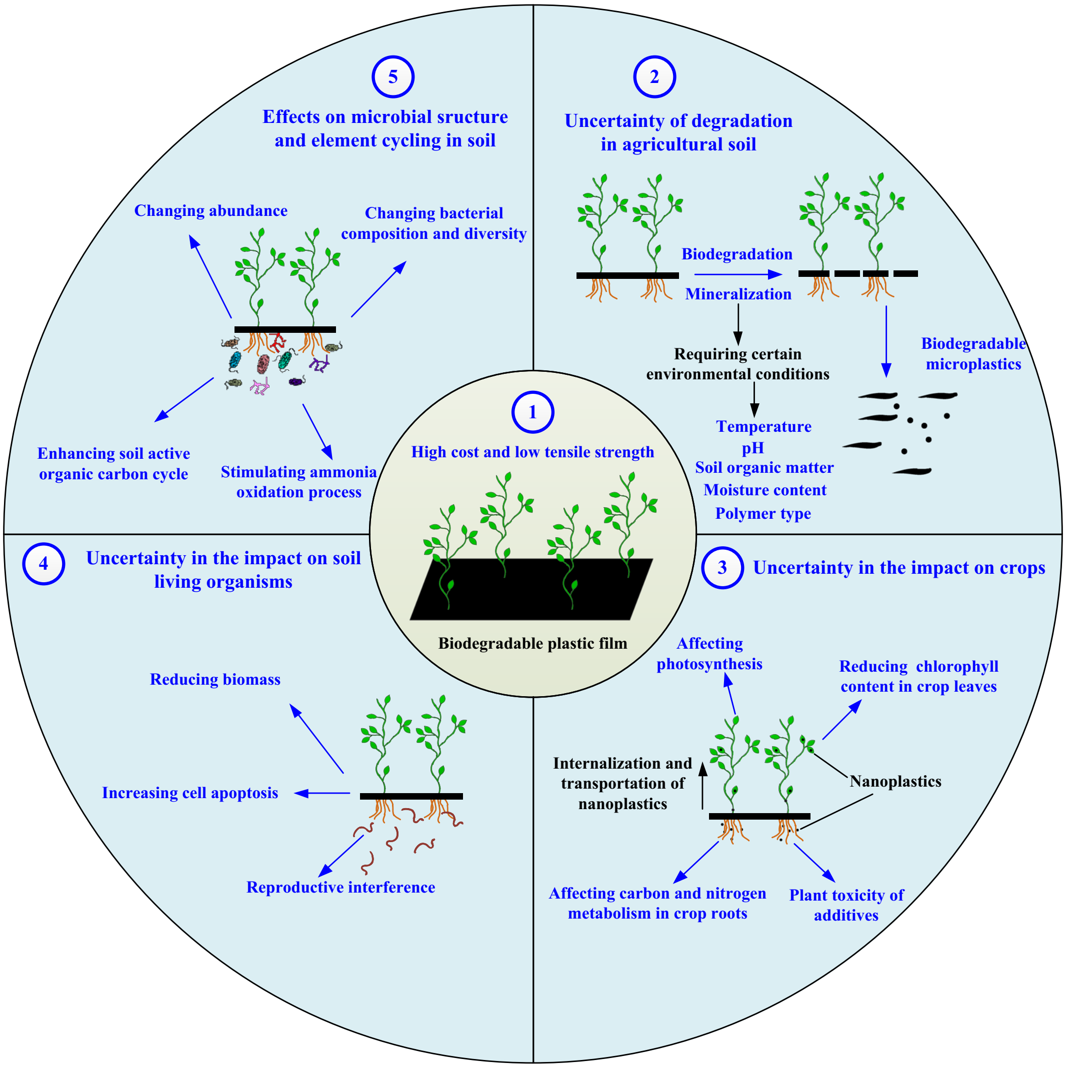

Fig. 2 Potential impacts of biodegradable plastic film and derived microplastics on agricultural ecosystems

biodegradable film mulching reduced nitrate accumulation in the 0–20 cm soil layer and also decreased nitrate accumulation in the 100–180 cm soil layer. Xue et al. (2023) also indicated that promoting the use of biodegradable plastic film on a large scale may reduce soil carbon sequestration by decreasing fungal necromass C. Chen et al. (2021) have revealed that soil temperature decreases with increasing degradation of biodegradable film mulching. Zhang et al. (2019b) showed that biodegradable film mulching reduced both soil temperature and moisture, but could enhance plant growth and increase tomato fruit quality and yield. Although limited information is available on the effects of nanoplastics derived from BPM on crops, evidence has shown that these nanoplastics may be internalized by plant roots and transported to branches, exerting pressure on plants and altering their growth (Gao et al. 2023; Sun et al. 2021; Wang et al. 2022d).

Impact of BPMs and derived microplastics on soil living organisms

Earthworms are key species in soil, whose main function is to improve soil structure and nutrient cycling (Bertrand et al. 2015). The activity of earthworms is an important indicator for assessing ecological toxicity.

Zhang et al. (2018) studied the interaction between *Lumbricus terrestris* and PE and PLA /PHA (polyhydroxyalkanoates). The findings revealed that earthworms consumed PLA/PHA, but it did not have a significant impact on their mortality rate. Boots et al. (2019) reported that the presence of PLA microplastics reduced the biomass of earthworms but did not cause death. In addition, the nematode *Caenorhabditis elegans* is widely used as a model organism for ecotoxicological research on contaminated soil. A study conducted Schoepfer et al. (2020) has revealed that the presence of PLA and PBAT microplastics in the soil environment can have an impact on the reproduction of the nematode *Caenorhabditis elegans*, potentially leading to negative effects on the regulation of the biogeochemical cycle. Additionally, Yin et al. (2018) suggested that exposure to plasticizers also decreased the number of oocytes and increased cell apoptosis in soil nematodes. Therefore, further investigation and testing are still needed to assess the potential ecological effects of BPMs.

Impact of BPMs and derived microplastics on soil microbes and carbon nitrogen cycle

BPMs are complex substrates that can be utilized by soil microorganisms, potentially altering the microbial structure and community (Accinelli et al. 2020; Feng et al. 2022; Liu et al. 2023; Wang et al. 2022c). A key issue is whether this change has any significant impact on microbial biodiversity and function (Fig. 2). Firstly, the introduction of a significant amount of organic carbon can result in the rapid proliferation of soil microbial communities (Wang et al. 2022a). Zhou et al. (2021) studied the effects of incorporating biodegradable plastics on the structure, growth, and dynamics of exoenzymes in soil microbial communities. The addition of PHBV changed the soil bacterial communities and increased alpha diversity, as well as the abundance of the *Acidobacteria* and *Verrucomicrobia* phyla. Yang et al. (2021) reported that PLA microplastics could significantly disrupt the diversity and composition of the arbuscular mycorrhizal fungal community, particularly the dominant genera. This disruption may have uncertain consequences for agricultural ecosystems. Koitabashi et al. (2012) showed that the degradation of poly(butylene succinate-co-butylene adipate) (PBSA) and polybutylene succinate (PBS) mulch film resulted in notable changes in the quantity of soil fungi. Qi et al. (2020) investigated the influences of macro and micro residues of PE and BPMs on rhizosphere microbial communities and soil properties. The results showed that BPM residues had a significant impact on rhizosphere bacterial communities and the emission of volatile compounds. Several bacterial genera have been enhanced, including *Bacillus*, *Variovorax*, and *Clostridium*, while others have been diminished. Muroi et al. (2016) studied the changes in soil microbiota caused by PBAT degradation under 30 °C conditions. Significant changes were observed in the fungal flora near the film surface, particularly in the abundance of the fungal plant pathogen *Setophoma terestris*. However, the growth of Chinese cabbage was not negatively affected after 7 months compared to the control soil, indicating that the changes in soil microbiota, after adding PBAT, had little impact on the growth of Chinese cabbage (*Brassica rapa var. chinensis*).

Additionally, the presence of BPMs can affect the conversion and cycling of carbon and nitrogen in agricultural soil (Salam et al. 2023). Gao et al. (2021) reported that microplastics have a significant impact on soil porosity, leading to an increase in the ammonia oxidation process and subsequent NH_4^+ production. Meng et al. (2022) evaluated the effect of microplastics on the dynamics of carbon and nitrogen in agricultural soil and found that BPMs had a stronger influence on dissolved organic carbon and nitrogen. They also observed an improvement in the active organic carbon cycle. In addition, biodegradable microplastics can also reduce the availability of phosphorus in soil (Wang et al. 2023). Nayab et al. (2022) reported that PHA provides a rich carbon source to microbes, enhancing nutrient cycling (C, N, P) and ecosystem multifunctionality. The increase in soluble carbon also triggers the immobilization of microbial nitrogen, resulting in increased competition between plants and microorganisms for essential nutrients such as nitrogen and phosphorus. This competition has negative effects on plant health.

Conclusions and perspectives

BPMs have emerged as a significant area of research in addressing the issues of soil residual mulch film and microplastic pollution, owing to their exceptional performance. Problematically, the environmental conditions of various agricultural soils, climatic conditions, degradability, market prices, and acceptance all greatly restrict the application of BPMs. In order to ensure the sustainable development of agricultural ecology, there are several key challenges that need to be effectively addressed. These include the high cost and degradability of agricultural practices, as well as the impact of microplastics and nanoplastics derived from these practices on the agricultural ecological environment. As of now, the effects of BPMs and derived microplastics on soil-dwelling organisms and crops are not yet clear. Efforts should be made to study the migration of compounds and chemicals released from mulch film to areas outside the agricultural system, as well as the potential hazards they may pose. A comprehensive understanding of the limitations of BPM applications is essential for evaluating the potential ecological risks. The pollution of residual film in farmland is a long-term accumulation result. The treatment of residual film not only requires government policy support and farmer efforts but also necessitates the collaborative participation of various research institutions. It should develop various agricultural tools for residual film recovery in different regions in order to enhance regional adaptability and increase the rate of residual film recovery. Measures should also be taken to reduce the production cost of BPM processes and address the problem of residual film pollution from multiple approaches. As such, there is still a lot of work to be done to solve the problem of agricultural residual film and microplastic pollution by relying on BPMs. This work will continue until (a) BPMs can completely replace CPMs; (b) BPMs can be degraded within a limited time frame without significant impact on agricultural ecosystems, (c) farmers can accept the widespread application of BPMs, and (d) cheap raw materials, instead of strategic supplies, can be continuously obtained from the environment for manufacturing BPMs.

Acknowledgements The study is financially supported by the Program for Shanghai Tongji Gaotingyao Environmental Science & Technology Development Foundation.

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Funding The study is financially supported by the Program for Shanghai Tongji Gaotingyao Environmental Science & Technology Development Foundation.

Data availability All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors have no conflict of interest to declare regarding this article.

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