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Effects of Biodegradable Mulch on Soil Microorganisms

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Abstract Revised sentence: Plastic mulching film plays a significant role in modern agricultural production. However, traditional plastic mulching film can result in residual film pollution and associated hazards. In contrast, degradable mulching film offers a fundamental solution to the problem of residual film pollution. This paper describes the classification of degradable plastic films and their effects on soil microorganisms, including four known types of biodegradable plastic films. Furthermore, it clarifies the impact of degradable plastic films on soil microbial biomass, soil respiration intensity, and microbial community structure. To compare the efficiency of agricultural production between degradable and traditional plastic films more intuitively, this study aims to identify both advantages and disadvantages of using degradable plastics for future production.
Keywords Degradable mulch; Soil microorganisms; Biodegradation

1 Introduction

As a large agricultural country, China pays great attention to crop yield and quality. Early studies have demonstrated that soil cover promotes the production and yield of annual and perennial crops (Ding et al., 2019), and mulch can cover the soil to form a physical barrier that limits soil moisture evaporation, controls weeds, maintains good soil structure, and protects crops from soil pollution. According to chemical properties mulch can be categorized into organic and inorganic mulch; according to the formation of mulch can be categorized into natural mulch and man-made mulch. Natural mulches help maintain soil organic matter and tillage (Tindall et al., 1991) and provide food and habitat for earthworms and other beneficial soil biota (Doran, 1980), but they are not available in sufficient quantities or of uniform quality, are more time-consuming and labor-intensive, and have the disadvantage that they may carry their own weed seeds, which can slow down the warming of the soil in the spring, thus causing vegetables to grow and mature more slowly. This results in longer time for vegetables to grow and mature (Hill et al., 1982), and breeds pests such as termites, slugs, snails, etc. In the case of frangipani mulch, it is often used as a protective cover for the soil. In the case of frangipani mulching, weed growth often occurs resulting in unwanted N depletion, while organic materials with a high carbon-to-nitrogen ratio, such as cereal straw, temporarily fix soil N as they decompose (Mooers et al., 1948), but prolonged mulching results in cumulative decay of the straw leading to a net mineralization of N (Ferguson and Ferguson, 1957; Steinmetz et al., 2016).

Research results have shown that natural mulching can maintain soil temperature and reduce soil evaporation, but does not always improve crop yields, so synthetic mulches are becoming increasingly popular as technology develops (Zhou and Zhu, 2002). Plastic mulch was first applied in Japan, and was introduced in China in the 1870s (Dong and Xu, 1992). With the increasing use of plastic mulch and the expanding use of plastic mulch, it has caused some pollution to the soil, and film fragments produced by mulch cover will be retained in the air, soil, and water bodies on the one hand (Steinmetz et al., 2016); on the other hand, as some of the film fragments accumulate with the food chain, they eventually become hazardous to human life safety (Steinmetz et al., 2016). At the same time, because of the non-renewable nature of petroleum, which is the main source of material for plastic mulch films, the search for new biodegradable mulch films that are not harmful to humans is particularly urgent nowadays, when petroleum resources are becoming increasingly depleted.

In this case, biodegradable mulch has emerged, which is mainly divided into non-biodegradable mulch (e.g. photodegradation, oxidative degradation, erosion, etc.) and biodegradable mulch (Kasirajan and Ngouajio, 2012). Photodegradable mulches are mainly plastics degraded by light-induced chemical reactions, and the photodegradation pathway has been shown to be effective in past studies, but it is more expensive to use (Greer and Dole, 2003). Meanwhile, photodegradable materials are usually composed of polyethylene and associated additives that accelerate the rate of degradation of mulch in sunlight, but also at a slower rate in areas with less solar radiation (Greer and Dole, 2003). The same principle is true for oxidative degradation materials. Therefore, more and more researchers are focusing on biodegradable mulch.

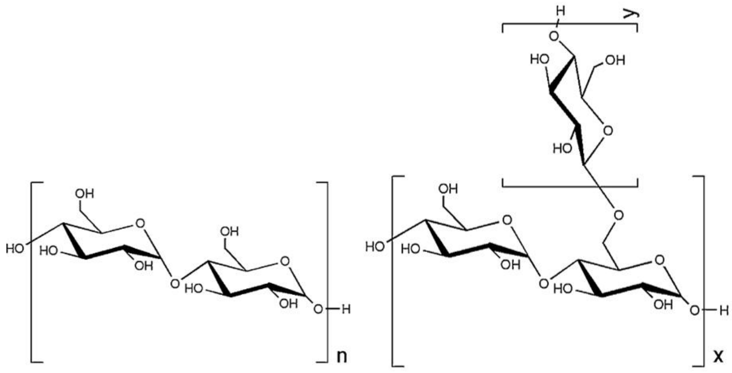
Biodegradable mulch is a more suitable alternative to plastic films. At the end of its useful life, biodegradable mulch can be integrated directly into the soil, where microbial communities convert it into carbon dioxide, methane, water, and other substances (Kyrikou and Briassoulis, 2007; Brodhagen et al., 2015). It has been concluded that this mulch has the same thermal insulation and yield-enhancing effect as plastic mulch (DeVetter et al., 2017). It can also effectively solve the problem of subsequent waste that is difficult to dispose of the mulch film (Kunioka et al., 2009). Therefore, biodegradable mulch is expected to replace the use of plastic mulch and be widely used. In this paper, we focus on the new biodegradable mulch films in recent years and describe the effects on soil microorganisms during the degradation process, as well as the future of biodegradable mulch films.

2 Types of Biodegradable Films and Their Introduction

The principle of biodegradable mulch is to mix biodegradable biomass into plastic components, so that large pieces of plastic can be easily degraded into small pieces of plastic. However, this kind of degradation is not a real and complete degradation, the plastic that has been degraded into small particles still remains in the soil (Wong et al., 2020), and this kind of material is not able to do anything about the subsequent degradation of small pieces of plastic. With the deepening of human society's understanding of environmental issues, solving the "white pollution" caused by waste mulch has become a priority. The organic macromolecule of degradable mulch has a carbon base as its backbone. Therefore, there are two main research directions for biodegradable films (1) using natural materials, such as starch, cellulose, etc.; (2) synthetic materials, such as polylactic acid (PLA), polybutylene terephthalate-ethylene glycol-ethylene terephthalate co-polyester (PBAT), etc., and this section summarizes the above four types of biodegradable films.

2.1 Starch

Starch is one of the first biopolymers used for the development of sustainable materials to replace petroleum-based synthetic plastic production. Due to their low cost, renewability, and inherent biodegradability, starch-based polymers are high-potential feedstocks for the large-scale production of bio-plastic films (Bartolucci et al., 2023). It is a mixture of straight chain starch (Figure 1a) and branched chain starch (Figure 1b) (Vamadevan and Bertoft, 2015). Starch (the structure is shown in Figure 1) is a plant reserve carbohydrate synthesized from glucose, which in turn is produced by photosynthesis of carbon dioxide and water. On the one hand, starch has poor physical properties because it is a hydrophilic substance that is soluble in water and becomes brittle upon drying (Kaur et al., 2012); On the other hand, starch polymers have strong hydrogen bonds and are difficult to melt (Zhu et al., 2020), therefore, starch polymers need to be reprocessed in order to satisfy the requirements for mulching membranes (Bastioli, 1998). Taking thermoplastic starch (TPS) as an example, after adding some plasticizers to it, these additives include alcohols, polyolefins, and surfactants (Wong et al., 2020), thermoplastic starch can be prepared under the action of heat and shear, thus improving the processing and use properties of the starch (Zhang et al., 2017), and thus producing membranes without using properties. In short, starch cannot be used as a biodegradable mulch due to its poor water resistance and high melting point, but different types of biodegradable mulch can be produced by combining it with other plasticizers (Zhao et al., 2021), but this type of mulch is not fully biodegradable, and the residual non-biodegradable components, such as PE, can pollute the soil (Rudnik and Briassoulis, 2011).



a b

Figure 1 Starch structural formula (Adopted from Vamadevan and Bertoft, 2015)
Image caption: (a) straight chain starch; (b) branched chain starch (Adopted from Vamadevan and Bertoft, 2015)

2.2 Cellulose

Cellulose is one of the most abundant naturally occurring organic polymers and is a naturally occurring polysaccharide of D-glucose linked by β-1,4-glycosidic bonds (Praveen et al., 2019). Like starch, cellulose molecules have strong hydrogen bonding between them, are highly crystalline (Xue et al., 2022), and are insoluble in common solvents (Solberg et al., 2023), which makes it difficult to be plasticized and film-forming (Figure 2). Therefore, it is necessary to modify or blend cellulosic mulch materials in the preparation of cellulosic mulch materials (Liu et al., 2008). Early on, fully degradable agricultural films were produced from bagasse pulp as the main raw material, with a small amount of cotton pulp and starch (Qin et al., 2002). In recent years, the production of cellulosic composites and the related property verification experiments are increasing (Saberi, 2024). For example, jute/cotton mulch is based on cotton stalk fibers and waste cotton fibers as the main raw material, and its decomposition in the soil increases the nitrogen content of the soil and has better water infiltration, which can meet the requirements of agricultural production (Wang et al., 2018).

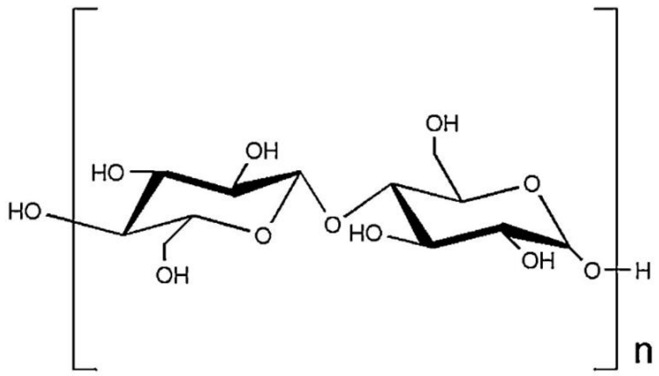


Figure 2 Molecular structural formula of cellulose (Adopted from Heinze, 2016)

2.3 PLA

PLA is a linear macromolecule polymerized from small-molecule lactic acid produced by microbial fermentation of biomass raw materials (sugarcane, sugar beet, straw cellulose, cassava, etc.) and belongs to the class of poly (α-hydroxy ester) (Balla et al., 2021) (Figure 3). PLA is not only degradable and biocompatible, but also can be produced and processed using most common processing equipment, but its own brittleness will bring many defects to its membranes (Hayes et al., 2012). PLA-based biodegradable membranes need to be modified or blended when preparing them (Noda et al., 2004). For example, the use of Al layered dihydroxide in stearate-Mg_3PLA films greatly improved the elongation at break (Mahboobeh et al., 2010); Muller et al. (2017) attempted to prepare a bilayered composite ground film by blending PLA with starch and examined the barrier, tensile, and optical properties of the composite film. The results showed that the composite ground film not only had high ductility and water vapor barrier properties, but also maintained good transparency. Zhang et al. (2018), comparatively studied the mechanical properties and degradation behaviors of PE, starch-polyester and cellulose paper-based membranes in soil. The results showed that under soil weathering, the mechanical properties of starch-polyester and cellulose paper-based membranes were significantly reduced, and even underwent It was found that the mechanical properties of starch-polyester and cellulose paper-based films decreased significantly under soil weathering, and even crushed severely, while PLA/PHA films still had mechanical properties similar to those of PE films.

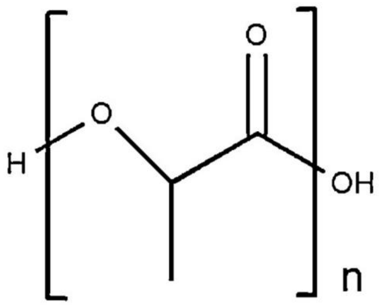


Figure 3 Molecular structure of PLA (Adopted from Qiu et al., 2021)

2.4 PBAT

PBAT is a new type of biodegradable aromatic copolyester, whose repeating structural unit consists of rigid chain segments of butylene terephthalate (BT) and flexible chain segments of butylene adipate (BA) (Kijchavengkul et al., 2008) (Figure 4), so PBAT has the good biodegradability and flexibility of aliphatic polyester, and the good mechanical properties of aromatic polyester (Wongphan et al., 2022). However, due to the fact that PBAT itself is too flexible, the rigidity and stiffness of the made film products are low, and the price is expensive, which limits its application in the agricultural field. Currently, PBAT-based biodegradable mulch films have appeared on the market, and Touchaleaume et al. (2016) conducted experiments on the growth condition of grapes by utilizing PBAT-based mulch films, and although it helped in the growth of grapes, the yield of grapes was basically the same as that of grapes cultivated with traditional PE mulch films after the degradation of the mulch films. Although the comprehensive performance of PBAT-based biodegradable mulch film is enough to be comparable to the traditional PE mulch film, and it can also realize complete biodegradation, the current market price of PBAT-based biodegradable mulch film is 3-5 times higher than that of PE mulch film, so it has not yet been popularized and applied on a large scale in the field of agricultural production.

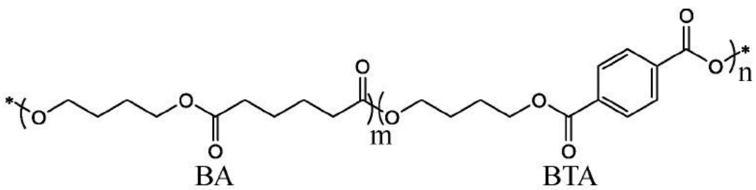


Figure 4 Molecular structure of PBAT (Adopted from Qiu et al., 2021)

3 Effects of Biodegradable Mulch on Soil Microorganisms

3.1 Soil microbial content

Soil microbial biomass is the total amount of living organisms in the soil with a volume of less than 5×10^3 μm^3, which is the most active component of soil organic matter. Among them, microbial biomass carbon is its important component. Microbial biomass carbon (MBC) is an easily accessible nutrient pool in the soil and the driving force of organic matter decomposition and nitrogen mineralization, and is closely related to the nutrient cycling of C, N, P and S in the soil. It can fully reflect the soil nutrient effectiveness status and soil microbial activity.

Liu (2023) conducted a study on the effect of biodegradable film covering on soil microbial C and N content, and found that covering biodegradable film treatment can significantly increase soil microbial carbon, which is 26.5% higher than that of PE film treatment, but the difference between microbial nitrogen and that of covering PE film treatment is not significant, and the microbial carbon and nitrogen of the soil are significantly higher in the film-covering than in the bare-ground non-film treatment (Table 1). However, there was no significant difference in soil urease, cellulase, β-glucosidase, and acid phosphatase activities when covering biodegradable film compared with covering PE mulch. Wu Si's experiment also confirmed that soil microbiomass carbon was significantly higher under biodegradable mulch treatment than PE mulch treatment, but there was no significant difference in soil microbiomass nitrogen.

Table 1 Effects of different treatments on soil microbial carbon and nitrogen (Adopted from Liu, 2023)

Treatment	Soil microbial carbon (mg/kg)	Soil microbial nitrogen (mg/kg)
1	(107.1±4.2) c	(11.8±6.1) c
2	(129.4±6.9) b	(13.2±5.8) b
3	(130.8±6.7) b	(15.5±7.2) ab
4	(155.7±7.4) a	(16.7±4.5) a

Note: Treatment groups 1, 2, 3 and 4 were without mulching, covered with ordinary PE mulch, standard PE mulch, and PBAT+PLA fully biodegradable film, respectively; different lowercase letters after the numbers in the same column indicate significant differences ($p<0.05$)

3.2 Soil respiration intensity

Soil respiration intensity is commonly used to measure the total soil microbial activity. Li et al. (2022) studied the effects of biodegradable mulch on soil microbial abundance, activity and community structure, and the results showed that the soil respiration rate of biodegradable mulch treatment was higher than the trend of uncoated mulch and PE mulch cover treatments, which may be due to the fact that the biodegradable mulch started to break up in the middle of the crop growth period, and the residue was decomposed by the microorganisms in the soil into H_2O and CO_2, which enhanced the intensity of soil respiration, indicating that biodegradable mulch took into account the characteristics of ordinary PE mulch for heat preservation and moisture retention, and compared with ordinary PE mulch, covering biodegradable mulch had a tendency to increase microbial activity, which might have a promotion effect on soil microbial activity under long-term covering.

3.3 Soil microbial community structure

Lu et al. (2023) demonstrated that the soil microbial community structure, species abundance, soil enzyme activity and tomato plant growth at different mulching sites could be improved by covering PBAT/PLA humic acid biodegradable mulch (FZS) compared with PE mulch, and that the mulching of PBAT/PLA humic acid biodegradable mulch (FZS) could help to increase the microbial activity of soil fungi Ascomycota and bacteria Verrucomicrobiota and Bacteroidota species abundance; soil sucrase activity and tomato stem thickness were significantly higher with PBAT/PLA humic acid biodegradable mulch (FZS) than with PE mulch.

Bandopadhyay et al. (2020) demonstrated that several bacterial and fungal organisms were found to be in higher abundance in sandy loam soils compared to PE mulch, and the bacteria were categorized and found to be mainly divided into Methylobacterium, Arthrobacter, and Sphingomonas. This suggests that microorganisms of these genera may be the corresponding degrading colonies. The reduced bacterial set in degradable mulch compared to PE mulch is in line with the experimental prediction that PE, with its non-biodegradable and more hydrophobic surface, may accommodate a wider range of microorganisms without obvious selection.

In summary, in addition to the same premise of heat preservation and moisturization as ordinary PE mulch, degradable mulch will promote the increase of soil microbial amount carbon content, soil respiration intensity, and will indirectly screen out some colonies that are favorable to their own degradation thus changing the community structure of microorganisms in the soil. The above experiments can also prove that biodegradable mulch can meet the needs of crop growth and development, promote its rapid growth, improve yield, and there is no significant difference in yield with ordinary PE mulch.

4 Conclusion

Mulch is a widely used technology in modern agriculture. Its effectiveness in improving physical, chemical and biological soil properties and in containing weeds is well established. Mulch can be made from a variety of materials, of which traditional plastics (i.e., fossil-sourced and non-biodegradable) are by far the most used. However, the subsequent disposal of plastic mulches when they are no longer in use is a serious problem, as they are not always easy to recycle and their residues can fragment until they become "microplastics" that pose a threat to the environment. Another serious problem associated with traditional plastics is their fossilized origin. For these reasons, the use of biodegradable mulch has been slowly gaining popularity in recent years. In crop production, biodegradable mulch maintains the physical properties and moisture of the soil, reducing the need for tillage and irrigation; increased biodiversity improves the habitat for microbial communities in terms of water/air ratios and the thermal state of the soil.

Authors' Contributions

Conceptualization, RC, XA, LZ and CC; Data curation, XA; Formal analysis, RC Funding acquisition, XA; Investigation, RC and TL; Methodology, RC and XL; Resources, RC; Software, XA and RC; Writing-original draft, XA and RC; Writing-review & editing, XA. All authors read and approved the final manuscript.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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