CHAPTER THREE

Biodegradable plastics as alternatives for polyethylene mulch films

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Contents

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Abstract

Plastic mulching is a critical agricultural practice for food production, which provides multiple benefits, including water conservation, weed control, and increased crop yield and quality. However, the application of conventional polyethylene mulch films has led to plastic pollution in the terrestrial environment because mulch residues in fields are difficult to remove and recycle. To address this issue, soil-biodegradable plastic mulch (BDM) films have been introduced to replace conventional polyethylene mulch films, as BDM films are designed to provide desired agronomic outcomes as well as in-situ disposal and degradation. Thus, increasing interests have been expressed toward BDM films in both research and application areas. In this review, we summarize and synthesize current knowledge about BDM films, regarding the history, definition and use, in-field degradation, agronomic performance, environmental impacts, and economic feasibility. In-field research suggests that BDMs show satisfactory agronomical performance but vary considerably in biodegradability among different products and environmental conditions, and generally do not impair soil health. However, laboratory studies indicate that BDMs may negatively impact terrestrial and aquatic ecosystems. Overall, current data indicate that BDMs are a promising alternative of conventional polyethylene mulch films. Questions remain about in-field biodegradation, potential accumulation of BDM residues in soils, release of nonbiodegradable additives, and off-site transport of biodegradable plastic residues (including micro- and nanoplastics) to air and water. We provide recommendations to address these questions and challenges to ensure safe and sustainable use of BDM films in agriculture.

Biodegradable plastic mulch (BDM) films are designed to be degradable in soil after being tilled in at the end of the growing season. Therefore, in this review, we use "biodegradable" and "soil-biodegradable" synonymously when applied to plastic mulch films, implying that soil is the intended end-of-life degradation environment.

1. Introduction

Plastic mulch films are an essential component of modern agriculture, as they provide multiple benefits in agricultural production, including weed and insect control, water conservation, soil temperature modification, and reduction of soil compaction (Sintim and Flury, 2017). These benefits translate to an increase in crop yield and allow growers to plant and harvest earlier, thereby attain a premium price for their products (Kasirajan and Ngouajio, 2012; Martin-Closas et al., 2017). These agronomic benefits, along with the growing population and food demand, explain the popularity and expanding market of plastic mulch films. The market for plastic mulch films is expected to reach $5.7 billion by 2026, with the strongest growth in the Asia-Pacific region (Research and Markets, 2021). Among all plastic mulch films, linear low-density polyethylene (LLDPE) mulch films have been dominating the market as the conventional plastic mulch films, which have superior mechanical properties compared to other plastic polymers in terms of resistance, tensile strength, flexibility, and elongation, as well as overall agronomic performance.

However, the application of plastic mulch films, especially the application of conventional polyethylene mulch films, has led to the accumulation of plastic mulch waste and plastic pollution in soils. In annual cropping systems, polyethylene mulch films should be removed after harvest and disposed of properly. However, removal is not always effective, given that a portion of the mulch film is intentionally buried underground to hold the mulch film in place during use, and this portion can be inadvertently left in the fields during removal. Further, removal is not always feasible due to the fragility of the plastic after exposure to environmental weathering during the growing season, and the plastic tends to break apart and fragment into small pieces that are challenging to recover from soils, especially for thin mulch films. Thin polyethylene mulch films had been extensively used in China (thickness 8 μm), where agricultural soils became heavily polluted with residual plastics that accumulated over time (Huang et al., 2020; Li et al., 2022; Liu et al., 2014). In 2020, the Chinese government banned the use of plastic mulches with the thickness of <10 μm to prevent further pollution of agricultural lands (Mancl, 2022; Ministry of Ecology and Environment of China, 2020).

Even if conventional plastic mulch films can be removed completely, disposal and recycling are costly and often prohibitive. Used plastic mulch films are contaminated with soil, plant debris, and agrochemicals, making them unacceptable to many recycle facilities. Recycling is further challenged by the high cost of long-distance transport from remote collection sites and the high price of the recycled resin, as compared to virgin resin on the open market. Therefore, many growers choose to discard plastic mulch films in local landfills, bury plastic mulch films on site, or burn plastic mulch film waste (Goldberger et al., 2015; Olsen and Gounder, 2001).

Plastic pollution of agricultural soils by polyethylene mulch films has raised concerns about the negative impacts to food production and to our ecosystems. Further, the increasing public awareness of plastic pollution of aquatic and terrestrial environments and the demonstrated accumulation of plastic debris in the environment have led to the promotion of environmentally friendly alternatives, such as biodegradable plastic mulch (BDM) films. These BDM films are designed to provide similar agronomic benefits as conventional plastic mulch films (Fig. 1), but they can completely biodegrade in soils, therefore can be tilled into soils, and do not have to be disposed of after the growing season. As a promising solution for the plastic mulch film waste problem in agriculture, the market for BDM films is expected to grow at a compound annual growth rate (CAGR) of 8.5%, faster than that of conventional polyethylene mulch films (CAGR 7%) during 2021–2026 (Research and Markets, 2022).

While BDM films are a promising alternative to polyethylene mulch films, there remain certain issues that need to be addressed and resolved (Sintim and Flury, 2017). BDM films are tested in laboratory experiments to ensure that they indeed can biodegrade in soil; however, in a natural soil environment, biodegradation may be much slower than in a controlled laboratory setting. When a BDM film is tilled into the soil after harvest, it can take several years to completely biodegrade, and the drier the soil and the cooler the climate, the longer it will take (Griffin-LaHue et al., 2022). During the degradation process, BDM films will deteriorate into micro- and nanoplastic particles (Sintim et al., 2020; Yu et al., 2021), which can potentially cause harm to soil fauna and flora. Micro- and nanoplastics can also move through soil, thereby polluting subsoil or groundwater resources (Yu and Flury, 2021a). Further, BDM films contain additives, such as fillers, dyes, UV stabilizers, and plasticizers, all of which will be

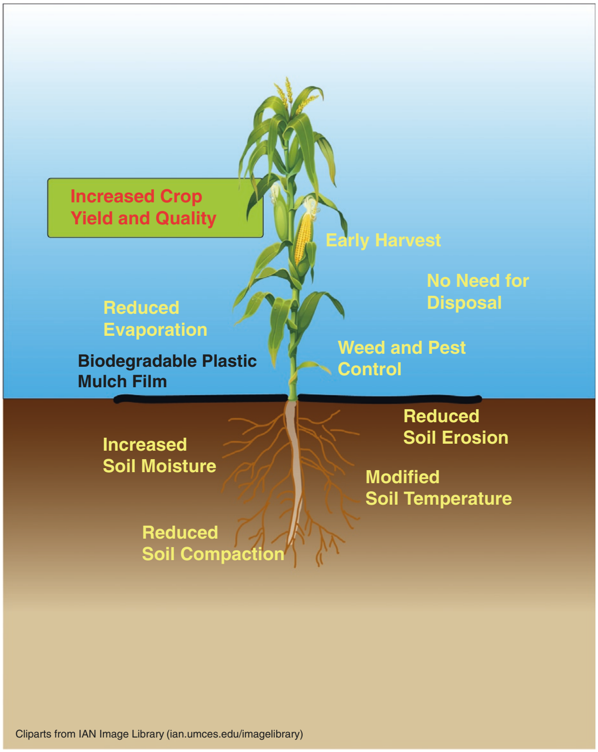


Fig. 1 Benefits of biodegradable plastic mulches used in agricultural cropping systems.

released when the biodegradable plastic polymers degrade. Such release, as demonstrated for carbon black and TiO_2 nanoparticles (Sintim et al., 2019b; Yu et al., 2022), can also potentially cause negative impacts to the soil environment.

As BDM films become more prominent and their use is being promoted by regulatory agencies, research about their properties and performance have increased substantially in recent years and will likely continue to increase in the near future. In this review article, we expand upon previous review articles about BDM films (Kasirajan and Ngouajio, 2012; Martin-Closas et al., 2017; Somanathana et al., 2022) and provide a comprehensive update. We also discuss and include recent meta-analyses on agronomic performance of BDM films (Liu et al., 2021; Tofanelli and Wortman, 2020).

The purpose of this review article is to summarize and critically synthesize current knowledge about BDM films. The specific objectives are to: (1) provide a brief history about BDM films; (2) define BDM films, regarding biodegradability and standards, compositions, material properties, and commercially available products, as well as use and lifecycle; (3) describe the in-field degradation of BDM films, in terms of processes, influencing factors, sampling and quantification, and evidence and modeling of degradation; (4) evaluate the agronomic performance of BDM films; (5) discuss the environmental impacts of BDM films, including effects on soil health and environmental concerns; (6) demonstrate the economic and social aspects of BDM films; and (7) point out challenges and opportunities for the use of BDM films as an alternative to conventional polyethylene mulch films.

2. History of biodegradable plastic mulch films

BDM films were introduced in the 1980s as an alternative to conventional plastic mulch films. However, the first generation of so-called "biodegradable" plastic mulch films was actually photo- or oxodegradable rather than biodegradable, and they disintegrated or fragmented into small pieces of nonbiodegradable plastics. At the time these products entered the market, there were no standards defining biodegradation nor were there widely accepted testing methods to evaluate the behavior of biodegradable products (Hunt, 2019). In response to this need, the American Society for Testing and Materials (ASTM) issued ASTM-D883 "Standard Terminology Relating to Plastics" in 1996 to clearly define "degradation" as "a deleterious change in the chemical structure, physical properties, or appearance of a plastic" irrespective of cause, and "biodegradation" as "results from the action of naturally-occurring microorganisms such as bacteria, fungi, and algae" (ASTM-D883, 2022). Following ASTM-D883, ASTM-D6400 was first released in 1996 to specify the requirements to label plastic products as compostable. Later, EN-17033 and ISO-23517 were released in 2018 and 2021, respectively, to specify the requirements for soil-biodegradable plastic products.

The invention of biodegradable polymers goes back to 1926, when Maurice Lemoigne developed polyhydroxybutyrate (PHB) from the bacterium *Bacillus megaterium* (Lenz and Marchessault, 2005). The earliest commercialization of PHB was started by W.R. Grace & Co. in 1959 with commercial-scale fermentation (Chanprateep, 2010). However, even today, large-scale production of polyhydroxyalkanoate (PHA) is expensive due to the complex fermentation, isolation, and purification processes, limiting the application of PHA in biodegradable plastic products (Fredi and Dorigato, 2021). Following PHB, polylactic acid (PLA) of low molecular weight was developed by Wallace Carothers from DuPont in 1932, and high molecular weight products were further produced by DuPont in 1954 (Lunt, 1998). Advances in large-scale commercial production of biodegradable plastics were made possible with the invention of polybutylene adipate terephthalate (PBAT) by BASF in 1998, marketed under the trademark ecoflex (BASF, 2022). In 2005, the Mater-Bi mulch film, mainly composed of PBAT and starch, was introduced into the north American market by Novamont (2022). In 2007, BASF launched the ecovio, a blend of PBAT with PLA, which was first applied for packing materials and later for BDM films (BASF, 2013). PBAT has similar physical properties as LLDPE and is commonly blended with starch-based plastics, PLA, and PHAs, which lend stiffness to the plastic film (Fredi and Dorigato, 2021). PBAT and PLA are widely used for compostable waste bags, agricultural mulch films, packaging (wrapping) films, cups, bowls, and tableware; for example, a compostable shopping bag is typically 85% PBAT and 15% PLA (Tullo, 2021).

3. What are biodegradable plastic mulch films?

3.1 Biodegradability standards

Biodegradability standards are established to test the intrinsic biodegradability of plastic products and to specify the requirements for labeling of plastic products as "biodegradable" or "compostable" in certain disposal environments. For BDMs, existing standards include EN-17033 (2018) and ISO-23517 (2021) pertaining to disposal via soil incorporation, as well as ASTM-D6400 (2012) and ISO-14855 (2018) pertaining to composting. We note that the preferred end-of-life route for biodegradation of BDMs is soil incorporation, with composting serving as an alternative option.

EN-17033 and ISO-23517 specify that a plastic mulch film is soil-biodegradable if 90% or more of the organic carbon in the whole item or for each organic constituent that is present at ≥1% w/w is converted to CO_2 within 2 years, either in absolute terms or relative to a positive control (e.g., microcrystalline cellulose), when the product is tested with a standardized laboratory test conducted under ambient soil conditions (20–28°C) according to ASTM-D5988 or ISO-17556 (ASTM-D5988, 2018; ISO-17556, 2019). This "90% mineralization" is also the criterion specified in ASTM-D6400 and ISO-14855 for a plastic mulch film to be labeled as "compostable in aerobic municipal and industrial composting facilities," with the test period being 180 days under industrial composting conditions (e.g., 58°C and mature compost). The selection of 90% mineralization is intentional, given that part of the organic carbon (typically 10%–40%) in plastic products is assimilated as biomass, even when the biodegradation is 100%.

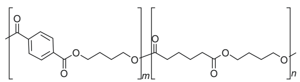
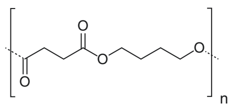
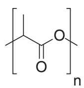
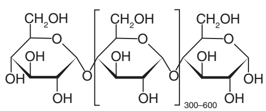
In addition to these standards, BDMs can also be certified with ecolabels that are issued by for-profit or nonprofit companies or governments. Ecolabels, such as "OK Biodegradable SOIL" from TÜV-Austria (2022b) or "BPI compostable" by the Biodegradable Products Institute (BPI), are designed to recognize the environmental sustainability of BDMs and thus to attract environmentally conscious consumers, suppliers, and other stakeholder groups.

3.2 Polymers and additives

Table 1 lists major biodegradable polymers, their chemical structure, and mechanical and thermal properties. The chemical structure imparts the flexibility, strength, and biodegradability of polymers. PBAT is a fossil fuel-based copolymer made of 1,4-butanediol (B), adipic acid (A), and terephthalic acid (T), whose properties are attributable to the aromatic group and the aliphatic chain. PBAT is flexible and possesses good strength and a higher elongation at break value than most other biodegradable polymers. The butylene adipate group in PBAT enables its good soil biodegradability. Polybutylene succinate (PBS) is a bio-based copolymer, which is made of 1,4-butanediol and succinic acid. PBS has greater biodegradability, thermal properties, melt processability, and chemical resistance than other aliphatic polyesters, and the ester group in PBS allows it to degrade when exposed to water.

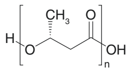
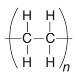
It is desirable for BDMs to have similar mechanical properties as LLDPE films, especially good tensile strength and the ability to maintain stability when stretched. EN-17033 specifies that the tensile strength of BDMs has to be $\geq$18 MPa in the machine direction and $\geq$16 MPa in the cross-direction for films with the thickness of $\geq$15 μm (EN-17033, 2018). The elongation at break is the ability of a film to be stretched during laying in the field without breakage. While LLDPE has a high elongation at break (>700%), most biodegradable polymers possess lower values, except for

Table 1 Major biodegradable polymers and their chemical structure, mechanical, and thermal properties in biodegradable plastic mulch films.

Polymer	Chemical structure	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (MPa)	Elongation at break (%)	Melting point (°C)	Glass transition (°C)	Reference
Polybutylene adipate terephthalate (PBAT)		1.25	15–36	20–136	670	110–125	−30	Al-Itry et al. (2012), Ferreira et al. (2019), Wei et al. (2019), Ludwiczak et al. (2021)
Polybutylene succinate (PBS)		1.23–1.26	20–33.7	320–707	7.6–21.5	105–115	−32 to 78	Someya et al. (2004), Hu et al. (2017), Kurokawa et al. (2018), Ayu et al. (2020)
Polylactic acid (PLA)		1.21–1.25	21–60	205–3500	3–20	130–180	55–60 for amorphous, 60–80 for semi-crystalline	Van de Velde and Kiekens (2002), Farah et al. (2016), and Avérous and Kalia (2016)
Starch		NA[a]	0.2–21.8	2–55	11–320	151	NA	Merino et al. (2018), Merino et al. (2019), Gazonato et al. (2019), and Chen et al. (2020b)

Continued

Table 1 Major biodegradable polymers and their chemical structure, mechanical, and thermal properties in biodegradable plastic mulch films.—cont'd

Polymer	Chemical structure	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (MPa)	Elongation at break (%)	Melting point (°C)	Glass transition (°C)	Reference
Polyhydroxyalkanoates (PHA) Short-chain length PHA, e.g., poly(3-hydroxybutyrate), poly(4-hydroxybutyrate), poly(3-hydroxyvalerate)		1.18–1.25	40	3500	3–1000	50–180	−50 to 9	Sudesh et al. (2000) and Anjum et al. (2016)
Medium-chain length PHA, e.g., poly (3-hydroxyhexanoate), poly (3-hydroxyoctanoate)		NA	1–10	11–25	20–300	61	−39 to −53	Anjum et al. (2016), Dartiailh et al. (2021)
Linear low-density polyethylene (LLDPE)		0.919–0.924	33.4	118	730–1219	124	−145	Cho et al. (1998), Luyt et al. (2006), Shinoj et al. (2011)

[a]*NA*, not available.
Linear low-density polyethylene is included in the table as a reference.

PBAT (>700%) (Table 1). PBAT is therefore the most commonly employed polymer in BDMs. PBAT also shows satisfying strength in terms of tensile strength (15 to 36 MPa) and Young's modulus and remains stable in the presence of environmental weathering conditions, especially when black colorants are added (Coltelli et al., 2008; Shah et al., 2008). Compared to PBAT, PBS has a higher Young's modulus but a lower elongation at break.

It is common for PBAT and PBS to be blended with other polymers to improve physicochemical properties or biodegradability (Siegenthaler et al., 2012). For instance, thermoplastic starch, which is formed by blending with plasticizers, improves biodegradability (e.g., Mater-Bi, Table 2). In addition, two of the most abundantly produced biopolymers, PLA and PHA, are commonly used for blending. Both polymers are fully biobased and biodegradable; however, PLA does not degrade well in soil due to the polymer's high glass transition temperature (>55°C).

To further enhance BDM properties or increase durability during deployment, additives are included in the feedstock (Table 2) (Mormile et al., 2017). Several additives, such as filler, plasticizer, and slip additives, enhance the processing of the film during heating and extrusion. Regarding the quantity, most of the additives are added at <1% w/w, with the exception of fillers, which are added at significant levels (up to 5% w/w).

3.3 Biodegradable vs biobased

There is often a confusion between the terms "biodegradable" and "biobased." These terms refer to different stages of the life scenario of a material: "biodegradable" refers to the end-of-life of a material, whereas "biobased" refers to the beginning-of-life. "Biodegradable" describes the ability of a material to degrade into CO_2, CH_4, and biomass in a natural or engineered environment (e.g., soil, water, compost, anaerobic digester). "Biobased" means that the material is derived from living organisms or their by-products, such as from corn, sugarcane, or bacteria.

These two terms are not necessarily mutually exclusive when applied to a polymer (Fig. 2): a polymer can be both biodegradable and biobased (e.g., starch, PLA), can be biodegradable but not biobased (e.g., PBAT), can be biobased but not biodegradable (e.g., polypropylene), or can be neither biodegradable nor biobased (e.g., polyethylene) (Saranya Ramesh Kumar and Babu, 2020). A plastic material often consists of blends of different polymers and thus can contain both biodegradable and biobased polymers.

Table 2 Common additives in biodegradable plastic mulch films.

Additive type	Purpose	Additives example	Reference
Antibacterial	Prevent biofilms	Zinc pyrithione, silver nanoparticles	Pittol et al. (2017) and Singh et al. (2012)
Antioxidant	Prevent oxidation during manufacture and exposure to sunlight	Hindered amine light stabilizer	Ram (1997)
Colorant[a]	Control soil temperature; counteract solar degradation; control penetration of UV radiation; provide aesthetic appearance	Carbon black, TiO_2	Lamont (1999), Mitchell et al. (2004), Kijchavengkul et al. (2008a), Kasirajan and Ngouajio (2012), and Maughan and Drost (2016)
Filler	Reduce cost; improve processing; resist abrasion; control density, dimensional and thermal stability; provide optical effects	$CaCO_3$, wood, silica, glass, clay	Callister and Rethwisch (2020)
Nucleating agent	Control stiffness and hardness; improve tensile strength; control pore size and distribution	Dibenzylidene sorbitol, phosphate esters	Murphy (2001)
Plasticizer	Improve flexibility and processing properties by reducing rigidity and fracture stress	Glycerol, sorbitol, triethyl citrate, and oligomers	Dufresne et al. (2000), Coltelli et al. (2008), Shah et al. (2008), Andersson et al. (2010), and Jiang et al. (2015)
Slip additive (lubricant)	Improve flow and processing	Erucamide, oleamide	Natarajan et al. (2014)
Stabilizer	Prevent photodegradation or photocross-linking caused by UV radiation	Carbon black, ZnO, TiO_2, MgO, $CaCO_3$, $BaSO_4$, Fe_2O_3	Yousif and Haddad (2013)

[a]Colorants render BDMs into black, white, silver, brown, green, or yellow; no colorant is added into clear BDMs, which are used to increase the soil temperature (Lamont, 1999; Melek and Atilla, 2009).

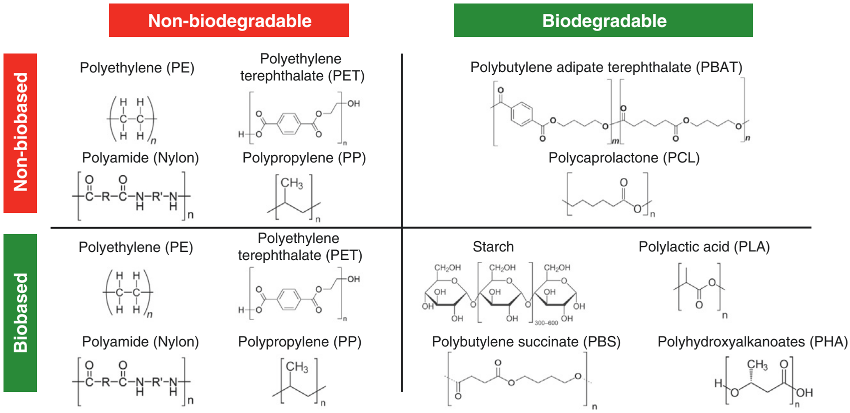


Fig. 2 Quadrant showing the relationships between "biodegradable" and "biobased" for a series of typical polymers. Nonbiodegradable polymers can be biobased, i.e., made of substances derived from living organisms, whereas biodegradable polymers can be made from nonbiobased source materials.

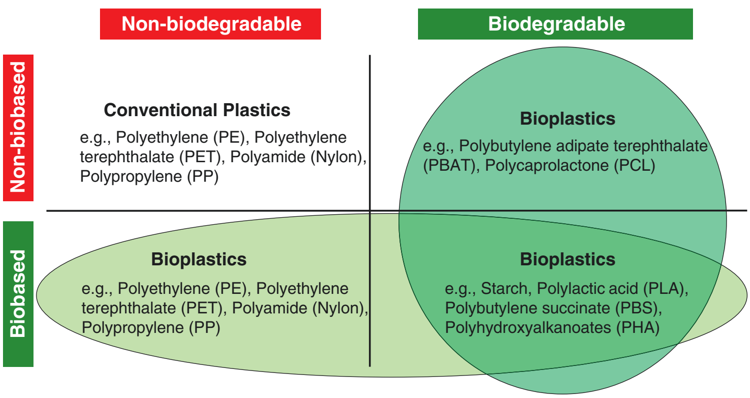


Fig. 3 Bioplastics in relation to biodegradable and biobased materials. Bioplastics consists of biodegradable, biobased, or both types of polymers. Conventional plastics do not contain either biodegradable or biobased polymers. *Adapted from European Bioplastics, 2018. Factsheet: What are Bioplastics? Material Types, Terminology, and LabelsAn Introduction. European Bioplastics, Berlin, Germany. https://www.european-bioplastics.org/bioplastics.*

Such a plastic is often called "bioplastic" (European Bioplastics, 2018), as opposed to conventional plastics, which are both nonbiodegradable and nonbiobased (Fig. 3).

Plastics that partially contain biobased materials are often also denoted as biobased, but the fraction of biobased material may not always be disclosed.

Standards are available to measure the biobased content of a material based on the C-14 method (ASTM-D6866, 2022), and certifications exist for labeling products based on the percentage of biobased content (TÜV-Austria, 2022a; USDA, 2022). Certain regulations require that the material contains a specified amount of biobased substances; e.g., the USDA National Organic Program (NOP) and the National Organic Standards Board (NOSB) require that biodegradable plastics are only allowed to be used in certified organic agriculture if their biobased polymer content is 100% (National Organic Program, 2022).

3.4 Commercially available products

On the market, many mulch films are advertized as "biodegradable," but only a few commercial products meet standards of biodegradability in soils (e.g., TÜV Austria OK Biodegradable SOIL, EN-17033, and ISO-23517). Examples of commercially available polymers used to manufacture BDMs are listed in Table 3. Additional brand names may be available through other converters that use the same or similar polymers. Most commercial BDMs are black, but can be manufactured in other colors including green, white, and clear. However, color changes can influence the performance of BDMs in the field due to the use or exclusion of certain additives. Products that do not meet standards of biodegradation should not be considered biodegradable and may in fact be photo- or oxo-degradable.

3.5 Use of biodegradable plastic mulch films in different cropping systems

BDMs have been evaluated in a variety of annual and perennial cropping systems. Regardless of the cropping system, a commercially viable BDM should perform similarly or better than polyethylene mulch in terms of in-field durability, weed suppression, and crop yield and quality enhancement to be well adopted by growers (Miles et al., 2017).

BDMs have been used for annual crops, such as corns, cucumbers, melons, and tomatoes, due to their widespread and increasing dependence on conventional plastic mulch. BDMs are also being increasingly explored and used for perennial fruits during crop establishment (Zhang et al., 2021). Perennial fruits are traditionally grown in unmulched systems; yet, BDMs have been demonstrated to promote raspberry (*Rubus idaeus* L.) crop establishment within the sensitive 10–18 months after planting while minimizing the use of herbicides and hand-weeding (Zhang et al., 2019b, 2020c).

Table 3 Examples of commercially available polymers and product names used to manufacture biodegradable plastic mulches (Sources: Guerrini et al., 2019; Hayes et al., 2012, 2019; Kijchavengkul et al., 2010; Kijchavengkul and Auras, 2008; Manzano et al., 2019; Martín-Closas and Pelacho, 2011; Tullo, 2012; van der Zee, 2021).

Product name(s)	Polymer(s)	Manufacturer
Biocycle	Blends of PHA and sucrose	PHB Industrial (Brazil)
Bio-Flex	PLA co-polyester blend	FKUR, Willich (Germany)
Biolice	PBAT	Limagrain (France)
Biomax TPS	Starch + thermoplastic starch	DuPont (USA) and Plantic (Australia)
Biomer	PHA	Biomer (Germany)
Biopar	TPS blended with co-polyester	United Biopolymers (Portugal)
BioPBS	PBS	MCPP (Division of Mitsubishi Chemicals, Japan)
Biocosafe/Biosafe	Thermoplastic starch blended with PBAT, PBS, and/or PBSA	Xinfu Pharmaceutical Co (China)
DaniMer (formerly ReNew and Meredian)	PHA	Danimer Scientific (USA)
ecoflex	PBAT blended with starch	BASF (Germany)
ecovio	ecoflex + PLA	BASF (Germany)
Envio	ecoflex + PLA + starch	BASF (Germany)
EnPol	PBS	IRE Chemical (Korea)
GreenBio (trade name is SoGreen)	PHA	Tianjin GreenBio Materials (China)
Ingeo	Starch + PLA; PBS + PLA	Nature Works (USA)
Mater-Bi	PBAT blended with starch	Novamont (Italy)

Improved establishment can increase the earliness and volume of yields, which in-turn help growers recoup costs of plastic mulch films (Zhang et al., 2019b). Double cropping is another new application of BDMs whereby two crops are harvested from the same area without soil disturbances (i.e., tillage) between crop cycles. Recent research has shown yields to be the same between BDMs and polyethylene mulch films in a double-cropping system using strawberry (*Fragaria* × *ananassa* Duch.) and lettuce (*Lactuca sativa* L.) (Wang et al., 2022b).

One barrier of using BDMs in commercial systems is the need to sometimes fumigate soil for suppression of soil-borne pests and diseases. Growers that fumigate often use virtually or totally impermeable films or "tarp" to improve fumigant retention in soils and reduce emissions. Buffer zones are also required during and after fumigation around an application site and tarps can reduce buffer zones. Fumigation tarps are tested and approved by the United States Environmental Protection Agency by active ingredients in soil fumigants. Presently, no BDMs are approved as fumigation tarps and as such are not approved for buffer zone reduction credit in the United States (DeVetter and Stanghellini, 2021). Designing BDMs to meet requirements for effective soil fumigation will expand their application to a wider diversity of cropping systems that depend on this practice.

3.6 General life cycle of biodegradable plastic mulch films

As illustrated in Fig. 4, the general life cycle of BDMs includes production, application, weathering, in-situ disposal (tillage), and biodegradation. Commercial BDMs are made using a combination of biobased and nonbiobased (fossil fuels) polymers that represent 75–95% of BDM mass (DeVetter et al., 2021b). Polymers are subsequently blended with additives (e.g., plasticizers, lubricants, fillers, pigments) and either extruded or blown into a film. For agricultural applications, BDMs are usually sold as rolls of a film that can be laid using the same mulch laying machine as polyethylene mulch films, and the application time is similar after initial equipment adjustments are made to optimize film tension and laying.

Once in the field, environmental factors, such as solar radiation, wind, and rainfall, contribute to the initial weathering that weakens the polymers in the BDMs throughout the growing season. By the end of growing season when the crop is terminated, BDMs are in-situ disposed of and tilled into the soil using customary tillage implements available to growers. Tillage incorporates BDMs into soils and creates smaller fragments that eventually become micro- and nanoplastics that are colonized by soil microorganisms. Biodegradation is achieved by the metabolic activities of soil microorganisms that convert polymers in the film to CO_2, H_2O, and microbial biomass under aerobic or anaerobic conditions (Hayes et al., 2019; Kasirajan and

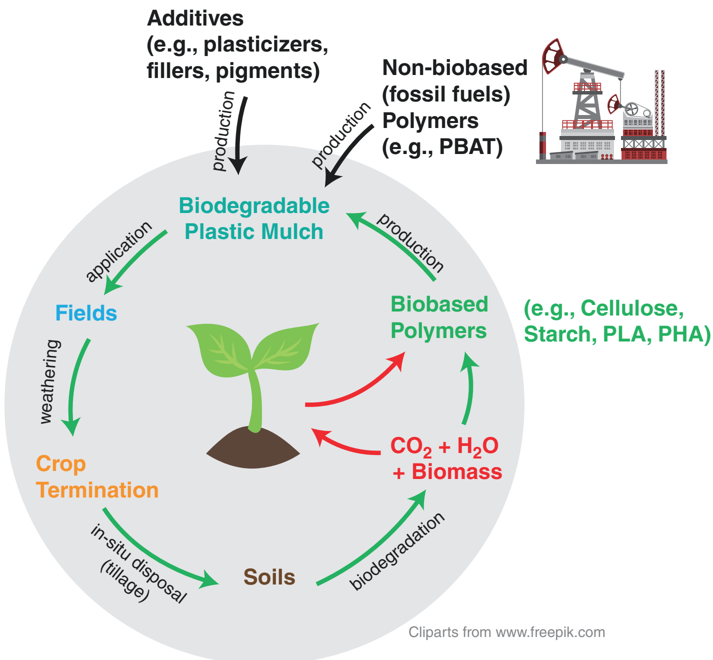


Fig. 4 General life cycle of biodegradable plastic mulch films. Biobased polymers have a circular life cycle, while nonbiobased polymers originate from fossil fuels.

Ngouajio, 2012). Whether biodegradation is aided by cover crops that alter soil microbial communities, application of biological stimulants, or increased tillage that breaks BDMs into smaller fragments remains open to further research. BDMs may also be removed by hand and composted on farm or at a municipal composting facility, but this is not recommended as BDMs break easily upon field removal and field removal would be an expensive and labor-intensive process. BDMs should not go into the recycling stream as they will contaminate recyclates.

4. In-field degradation of biodegradable plastic mulch films

4.1 In-field degradation processes

The in-field degradation processes of BDMs can be divided into three steps: (1) abiotic fragmentation; (2) colonization, biofragmentation, and

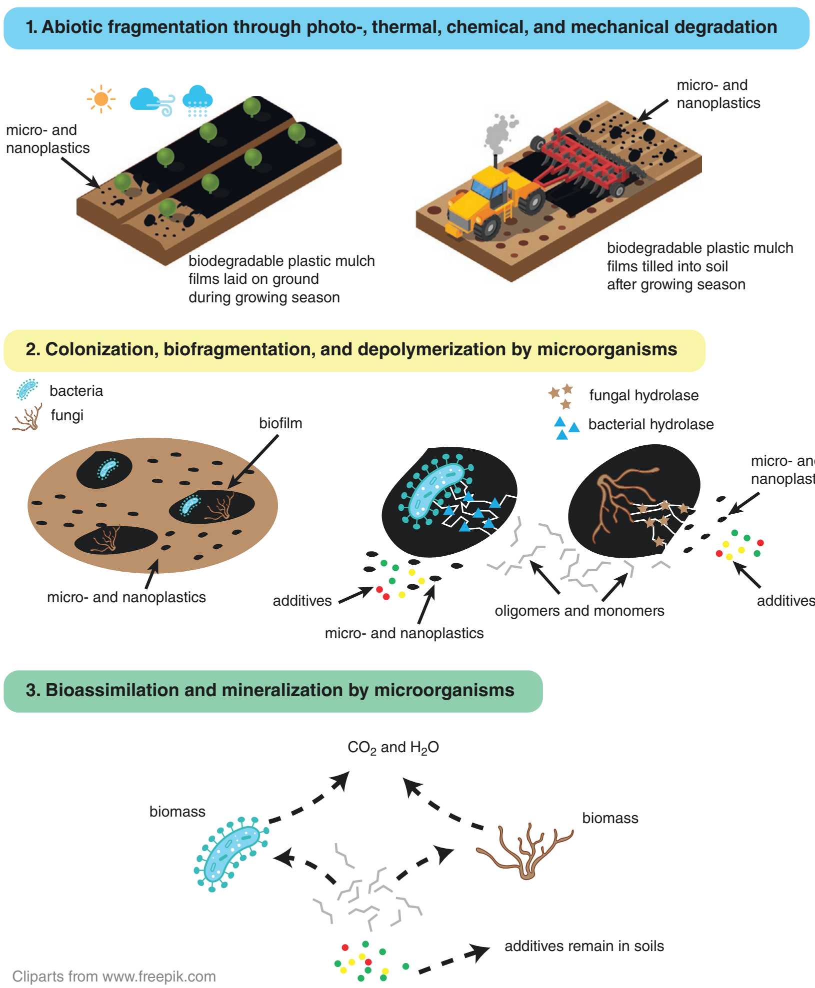


Fig. 5 Schematic of in-field degradation processes of biodegradable plastic mulch films showing the three major steps: (1) abiotic fragmentation; (2) colonization, biofragmentation, and depolymerization; and (3) bioassimilation and mineralization. While these steps are shown separately, they are interconnected and can occur simultaneously.

depolymerization; and (3) bioassimilation and mineralization (Fig. 5) (Haider et al., 2019; Sander, 2019). Although illustrated separately, these steps are strongly interconnected and can occur simultaneously during the in-field degradation of BDMs. Below, we discuss each step individually in detail to examine the underlying mechanisms.

Abiotic fragmentation of BDMs happens through photo-, thermal, chemical, and mechanical degradation when BDMs are laid on the ground during the growing season and when BDMs are tilled into soils after usage. Photodegradation occurs when BDMs are exposed to UV radiation, which causes photoionization and chain scission, contributing to embrittlement of BDMs (Lucas et al., 2008). Heat exposure of BDMs in the field can affect the organization of macromolecules in semicrystalline polymers when the temperature is higher than the glass transition temperature (e.g., −30°C for PBAT, 55°C for PLA) (Deng et al., 2018), which facilitates further chemical and biological degradation (Iovino et al., 2008). Chemical degradation occurs when BDMs are exposed to O_2, O_3, H_2O, agrochemicals, and pollutants in the environment. Oxidation of BDMs by O_2 and O_3 breaks covalent bonds in the polymers, which can be synergetic to photodegradation, leading to cross-linking reactions and/or chain scissions. Abiotic hydrolysis is facilitated when water diffuses into a polymer structure, attacking hydrolyzable bonds and reducing molecular weight. Mechanical degradation is caused by compression, tension, and shear forces exerted by external load, snow, rainfall, and tillage, leading to fragmentation of BDMs (Lucas et al., 2008). Abiotic fragmentation leads to deterioration of BDMs at the molecular level and the formation of micro- and nanoplastics.

After BDMs are placed in the field, soil microorganisms start to colonize BDM surfaces and form biofilms (Fig. 6), initiating biodegradation through

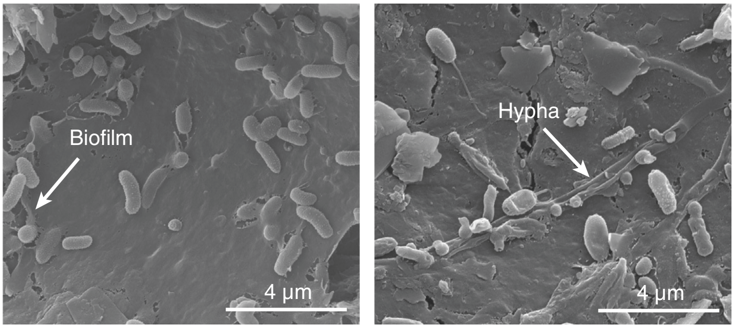


Fig. 6 Scanning electron microscopy images of the surface of biodegradable plastic mulch films (left: Organix, made of PBAT and PLA, manufactured by BASF; right: Naturecycle, starch-polyester blend) colonized by fungi and bacteria after soil burial for 5 years (Griffin-LaHue et al., 2022). *Reprinted from Griffin-LaHue, D.E., Ghimire, S., Yu, Y., Scheenstra, E.J., Miles, C.A., Flury, M., 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. Sci. Total Environ. 806, 150238. https://doi.org/10.1016/j.scitotenv.2021.150238, Copyright (2022), with permission from Elsevier.*

biofragmentation and depolymerization. Both fungi and bacteria can colonize BDM surfaces, while fungus-colonization is thought to be more prevailing, because fungi can use hyphae to grow between soil particles and film surfaces, thus reaching the film without direct contact (Sander, 2019; Sang et al., 2002). The formation of hyphal networks is also expected to facilitate further colonization by bacteria, as motile bacteria can reach film surfaces through these "fungal highways" (Kohlmeier et al., 2005; Warmink and Van Elsas, 2009). After colonization, microorganisms can degrade BDMs through mechanical and enzymatic actions (Gu, 2003). Microorganisms adhere onto BDM surfaces with extracellular substances, such as polysaccharides and proteins, which imbibe into pores and cracks on films, exerting mechanical stress to induce biofragmentation (Bonhomme et al., 2003). More importantly, microorganisms secrete extracellular enzymes, which catalyze hydrolysis and promote the depolymerization of the polymer chain, leading to the formation of oligomers and monomers.

In the last step, oligomers and monomers are assimilated by soil microorganisms as carbon sources and mineralized into CO_2 and biomass (Sander, 2019; Zumstein et al., 2018). The most direct approach to study bioassimilation and mineralization is to quantify the conversion of polymer-derived carbon to CO_2, which is the common criterion for standard laboratory tests to indicate biodegradable plastics (ASTM-D5988, 2018; EN-17033, 2018; ISO-23517, 2021). In addition, the incorporation of polymer-derived carbon into biomass can be tracked by carbon isotope labeling (Zumstein et al., 2018). Theoretically, all of the polymer-derived carbon should be converted into CO_2 and microbial biomass at the end of in-field degradation, but this process can take years depending on the properties of BDMs and the environmental conditions.

4.2 Factors affecting in-field degradation

In-field degradation of BDMs is a consequence of abiotic and biotic degradation processes. The biodegradation is controlled by both intrinsic (physical and chemical properties of BDM films) and extrinsic (environmental conditions) factors (Fig. 7).

The properties of BDMs are primarily controlled by their polymeric composition and additives, which determine the molecular weight, crystallinity, and hydrophobicity of BDMs. Generally, a higher degradation rate is correlated with lower molecular weight, lower crystallinity, and less hydrophobicity of BDMs (Brodhagen et al., 2015; Lucas et al., 2008).

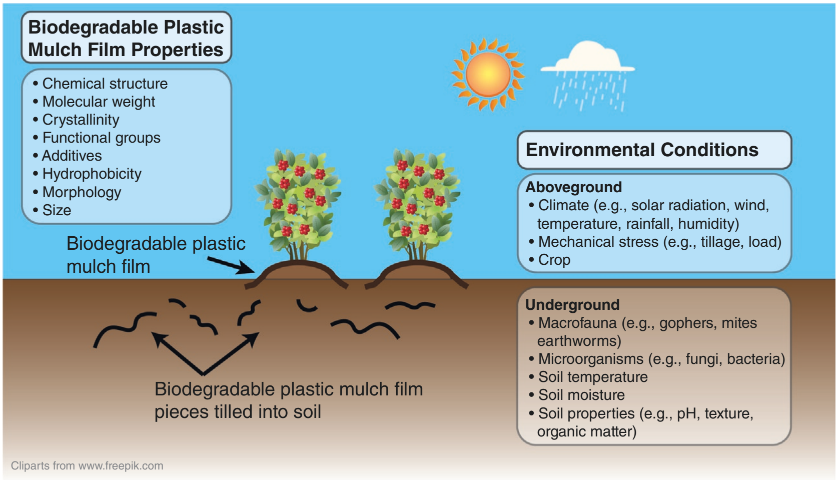


Fig. 7 Factors affecting in-field degradation of biodegradable plastic mulch films, grouped into intrinsic (biodegradable plastic mulch film properties) and extrinsic (environmental conditions) factors.

Lower molecular weight increases the accessibility of polymer chains in BDMs by moisture and enzymes, and the smaller polymer molecules are more easily hydrolyzed or utilized by microbes (Kasirajan and Ngouajio, 2012; Kijchavengkul et al., 2008b). Lower crystallinity of BDMs is more likely to promote biodegradation, as microorganisms are more capable of degrading more loosely packed chemical structures in the amorphous regions of polymers (Mohanan et al., 2020; Mueller, 2006). As a result, the crystallinity of a film increases as the degradation proceeds, which can hinder future degradation (Lucas et al., 2008; Mueller, 2006). The hydrophobicity of BDMs affects the hydrolysis of polymers, and the less hydrophobic a BDM film is, the more likely it will permit water, enzymes, and aqueous solutes to contact the polymers, promoting chain scission, molecular weight reduction, and degradation (Brodhagen et al., 2015; Kasirajan and Ngouajio, 2012).

The polymeric composition is the ultimate factor controlling the in-field degradation of BDMs. Among common biodegradable synthetic polymers, PHA has the highest biodegradability in soils, followed by PBAT, and PLA has the lowest (Anunciado et al., 2021a; Brodhagen et al., 2015; Miles et al., 2017). However, the biodegradability of these pure polymers does not directly represent the biodegradability of BDMs because BDMs are generally blends of synthetic and natural polymers with different types of additives (Akhir and Mustapha, 2022; Brodhagen et al., 2015).

Additives regulate how polymers in BDMs are exposed to the degradation environment, and thus can either promote or hinder biodegradation depending on the properties of the additives. For instance, natural fillers, such as carbon black, organic fertilizers, and silica rice ash, were found to promote the sorption of water and thus facilitate hydrolysis and further biodegradation of a PBAT/PLA blend BDM (Harada et al., 2019). On the other hand, UV stabilizers, such as carbon black and TiO_2 nanoparticles, are added to plastic materials to prevent premature photodegradation and thus slow down overall degradation (Souza et al., 2018, 2019; Zheng and Nowack, 2021).

In addition to polymeric composition and additives, the total surface area considerably affects the in-field degradation of BDMs. As degradation begins at the surface of BDMs, a larger total surface area leads to a faster degradation, which is related to the size, thickness, and morphology of BDM pieces (Chinaglia et al., 2018; Tosin et al., 2019). The size reduction of BDMs is commonly achieved through mechanical stress, such as tillage and abrasion, or through environmental weathering, where photodegradation, thermal degradation, and hydrolysis break down chemical bonds in polymers, causing embrittlement and fragmentation of BDMs.

Environmental conditions controlling the weathering process of BDMs include climate (e.g., solar radiation, temperature, wind, rainfall, and humidity), macrofauna, microorganisms, soil moisture, soil temperature, and soil pH (Fig. 7). The intensity of solar radiation, especially UV radiation, is positively correlated with the reactivity of electrons in polymers, thus controlling the extent of photodegradation. Temperature, including air and soil temperature, affects both thermal degradation and biodegradation. Generally, a higher temperature in warmer regions leads to a higher degradation rate, due to the increased chemical and enzymatic hydrolysis, as long as there is sufficient soil moisture to provide a conducive environment for chemical and microbial reactions (Anunciado et al., 2021a; Sintim et al., 2020). Similarly, soil pH and redox potential also affect chemical and enzymatic hydrolysis and the ultimate biodegradation rate in soils (Lucas et al., 2008).

Environmental conditions already start to affect the degradation of BDMs during manufacture and continue to affect the final bioassimilation and mineralization of BDM films by microorganisms. Indoor storage has been found to cause embrittlement and a slight decrease in the elongation of PLA/PHA and PBAT BDMs (Anunciado et al., 2021b; Hayes et al., 2017). Further, upon field application, BDMs experience more mechanical stress if they are laid out by machinery than if they are laid out by hand. During the usage of BDMs in fields, environmental weathering from UV, heat, and water contributes to embrittlement and depolymerization. The embrittlement and depolymerization further lead to a reduction in film dimensions and molecular weight, thus increasing the total surface area and the amount of polymer molecules accessible to microorganisms (Anunciado et al., 2021a; Kasirajan and Ngouajio, 2012).

The biodegradation process is proliferated by higher microbial activity as well as by a better contact between microorganisms and plastic surfaces. Earthworms are known to ingest and egest plastic particles, thereby incorporating the plastics into the microbially enriched cast (Adhikari et al., 2023; Cui et al., 2022). This intense mixing with soil and microbes is likely to enhance biodegradation, and the passage through earthworm intestines also leads to grinding and chemical degradation of the BDM particles (Adhikari et al., 2023; Zhang et al., 2018); therefore, earthworms have been proposed as a mean to enhance biodegradation (Khaldoon et al., 2022; Sanchez-Hernandez et al., 2020).

4.3 Sampling and quantification of film residues

4.3.1 Soil sampling method

The in-field degradation of BDMs has been assessed by quantifying the surface area or the weight of film residues at different times after soil incorporation (Cowan et al., 2013; Ghimire et al., 2020a; Griffin-LaHue et al., 2022). Generally, soil samples are taken from the field, and film residues are extracted from soil samples by sieving (Cowan et al., 2013; Ghimire et al., 2020a; Griffin-LaHue et al., 2022). However, the recovery rate has been found to be highly variable and to depend on the size of soil samples taken. For example, Cowan et al. (2013) collected three cylindrical soil cores (10.2 cm in diameter and 15.2 cm in depth) and recovered a total BDM surface area twice the original surface area after 132 days of soil incorporation. Using the same-sized sampler (10.2 cm in diameter and 15.2 cm in depth), Ghimire et al. (2017) found that the recovered BDM surface area varied from 2% to 95% with five soil cores within 16 days after soil incorporation, and the average recovery increased from 40% with five cores to

70% and 62% with 15 and 128 soil cores, respectively. In another study, Ghimire et al. (2020a) collected 24 soil samples with 1m × 1 m blocks and then reduced each sample to 1/8 of the original size using the quartering method, and they found that the recovered BDM surface area was nearly 100% with slight variations right after incorporating BDMs into soils.

Results of these studies reveal that BDM recovery rate can be improved considerably by taking a larger amount of soil sample. This is reasonable because a larger amount of soil yields a bigger sample support, which is more likely to be representative of the whole field in terms of film residues (Webster and Oliver, 1990, 2001). It has been pointed out by Yu and Flury (2021b) that to accurately quantify the amount of plastics in a field, the amount of soil samples taken from the field should reach or exceed the representative elementary volume. For discrete particles like microplastics, the representative elementary volume increases hyperbolically as the amount of plastics in soils decreases (Yu and Flury, 2021b). As the representative elementary volume is constant for a given plastic concentration under a certain distribution, the number of samples required to accurately quantify plastic particles decreases with increasing individual sample size (Fig. 8A and B). For example, to quantify a plastic concentration of 100 particles/m^2 when the plastic particles are distributed uniformly, three 1m × 1 m samples would be sufficient to measure the plastic concentration with a 10% relative error, while 514 samples would be needed if 8-cm-diameter cores were used. This shows that taking soil samples with 1m × 1 m blocks is highly efficient. Further, the amount of soil samples can be readily reduced by the quartering method to a reasonable size for future extraction and quantification of mulch residues (Fig. 8C and D) (ASTM-C702/C702M, 2018).

In reality, the amount of soil taken to quantify BDM film residues should not only exceed the theoretical representative elementary volume under the uniform distribution but also be properly increased based on the distribution of film residues in the field. This is because the distribution of film residues is rarely uniform but rather highly random. After usage, BDM residues are tilled into soil and thus are approximately uniformly distributed right after soil incorporation (Fig. 8E). However, as BDM residues continue to degrade in the field, multiple small film pieces will be generated around the original large piece (Fig. 8F), making the distribution no longer uniform but rather clustered. In such a case, the amount of soil samples has to be properly increased (Fig. 8B) to accurately quantify BDM residues in the field.

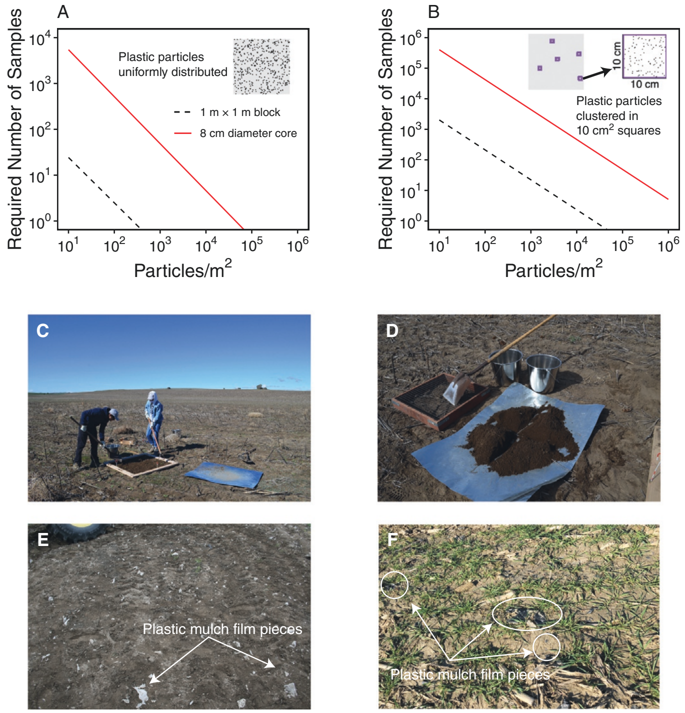


Fig. 8 Demonstration of theoretical and practical representative sampling of biodegradable plastic mulch film residues. Theoretically calculated number of different sized samples (8-cm-diameter cores or 1 m × 1 m blocks) required to quantify plastic concentrations for (A) uniformly distributed plastic particles and for (B) plastics particles arranged in random clusters of 100 particles per cluster (10% relative error). Demonstration of (C) sampling plastics with 1 m × 1 m blocks and (D) reducing soil amount with the quartering method. Distribution of plastic mulch film residues in a field (E) right after soil incorporation and (F) several months after soil incorporation. *Panels (A) and (B): Adapted from Yu, Y., Flury, M., 2021b. How to take representative samples to quantify microplastic particles in soil? Sci. Total Environ. 784, 147166. https://doi.org/10.1016/j.scitotenv.2021.147166.*

4.3.2 Meshbag method

The high uncertainty and variability of BDM film recovery rate can be avoided with the meshbag method, where BDM residues are enclosed into nondegradable meshbags and buried into the soil (Fig. 9A). Then, the meshbags are retrieved from the field at predetermined time intervals (Fig. 9B), and film residues are quantified with image analysis (Fig. 9C and D). The meshbag method is often used in ecological studies to quantify litter degradation (Pena et al., 2013). While meshbags may hinder the access

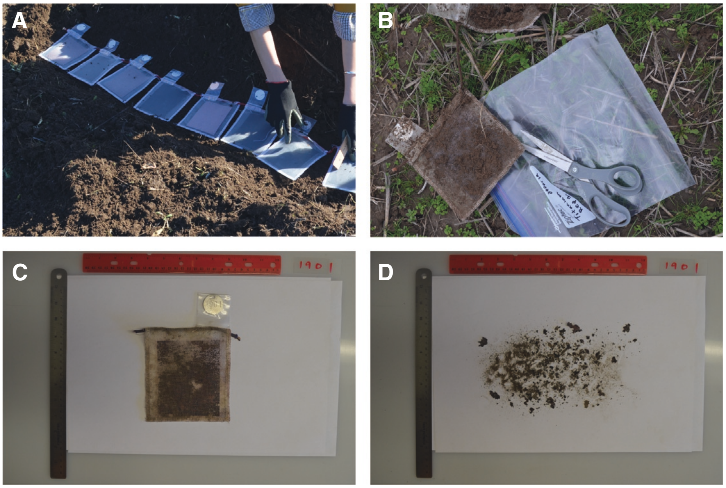


Fig. 9 Meshbag method to assess in-field degradation of biodegradable plastic mulch films in soils. (A) Enclosure of biodegradable plastic mulch films into nylon meshbags and burial into ground; (B) recovery of meshbag and biodegradable plastic mulch residues from the field and (C,D) image analysis of biodegradable plastic mulch residues in the lab.

of organisms to the BDMs to some extent, the use of meshbags allows an accurate recovery of film residues without having to extract film resides from soil. A readily biodegradable sample, e.g., cellulose mulch film, is often used as a positive control to verify the viability of the method (Sintim et al., 2020).

4.3.3 Assessment of degradation

The BDM residues recovered by the soil sampling method or the meshbag method can then be analyzed for the surface area or weight (Griffin-LaHue et al., 2022; Sintim et al., 2020). When the surface area is quantified, film residues recovered from soils are cleaned to remove adhering soil particles, spread on a flat surface, and photographed with a digital camera, and then the total surface area of film residues is determined by the image analysis (Sintim et al., 2020; Zhang et al., 2020b). When the degradation is quantified by the weight loss, film residues are thoroughly washed in water, air-dried, and weighed (Ghimire et al., 2017; Griffin-LaHue et al., 2022). The accuracy of both quantification methods can be impaired by the adhering soil particles, while the surface area loss method can be further interfered by the folding and wrinkling of BDM film residues and the settings of image processing software (Ghimire et al., 2017). Nonetheless, it is important to note that both methods are an approximation of the actual biodegradation of BDMs, which can only be quantified accurately by measuring the conversion of carbon from the plastic polymers into CO_2 and biomass (Sander, 2019; Zumstein et al., 2018).

4.4 Evidence of in-field degradation

In-field degradation of different types of BDMs has been reported from different climatic regions (Griffin-LaHue et al., 2022; Li et al., 2014b; Sintim et al., 2020). Li et al. (2014b) quantified the degradation of two commercial BDMs made of PBAT and starch (e.g., BioAgri Ag-Film, BioBag, Palm Harbor, FL, USA, and BioTelo Agri, Dubois Agrinovation, Waterford, ON, Canada) using the meshbag method and found 2% of both films remaining in Texas, 52% and 49% remaining in Tennessee, and 99% and 89% remaining in Washington state, respectively, after a period of 2 years. Sintim et al. (2020) reported that the surface area of four different BDMs reduced to 61–83% in Tennessee and 26–63% in Washington state after 3 years of soil incorporation. Griffin-LaHue et al. (2022) monitored the in-field degradation of BDM films successively applied for 4 years in Washington state and found that mulch recovery continuously decreased and dropped to 4–16% of total mulch mass 2 years after the final soil incorporation. Significant differences in degradation rates are often observed among different types of BDMs (Griffin-LaHue et al., 2022; Sintim et al., 2020). These results indicate that climate is a key factor for mulch degradation and that mulch properties can be tuned to facilitate biodegradation.

4.5 Modeling of in-field degradation

Other than the direct quantification of BDM film residues after soil incorporation, the in-field degradation has also been assessed with modeling. One common model is based on the Arrhenius equation, which considers the degradation rate coefficient (k, mol m^{-2} s^{-1}) based on temperature (T, K) as (Laidler, 1984):

$$k = A \exp\left(-\frac{E_a}{RT}\right), \tag{1}$$

where A is the pre-exponential factor (mol m^{-2} s^{-1}), E_a is the activation energy of the reaction (J mol^{-1}), and R is the universal gas constant (8.31 J mol^{-1} K^{-1}). To use the Arrhenius equation, the degradation rate is calculated from experimental data at different temperatures and then A and E_a are fitted. With this approach, Pischedda et al. (2019) estimated that a BDM film piece (1 cm × 1 cm × 15 μm) made from Mater-Bi HF03V1 (Novamont, Italy) needed 82 days to completely degrade at 14°C in soil.

In addition, the degradation of BDM films can be described with a surface erosion process (Göpferich, 1996; Von Burkersroda et al., 2002), where the degradation rate is proportional to the total surface area of BDMs (Chamas et al., 2020; Yu et al., 2021):

$$\frac{dC}{dt} = -k\,\mathrm{SA} \tag{2}$$

where C is the amount of BDM films in soil (mol), t is the time (s), k is the degradation rate coefficient (mol m^{-2} s^{-1}), and SA is the surface area (m^2). This zeroth-order degradation model has been used to fit in-field degradation data by Griffin-LaHue et al. (2022), who predicted that BDMs would take 21–58 months, depending on the BDM type, to reach 90% degradation in a field in northwestern Washington state with a cool Mediterranean climate.

Results of these studies support that BDM films indeed undergo in-field degradation, but the degradation rate is highly variable, and the time needed for 90% in-field degradation is generally longer than the 2-year standard as defined in biodegradability tests (ASTM-D5988, 2018; EN-17033, 2018; ISO-23517, 2021). This is because under field conditions, soil moisture does not remain constant nor optimal, and soil temperature rarely reaches 20–28°C, as prescribed in the biodegradability tests. Consequently, it is not suitable to use calendar time to compare the in-field degradation with the biodegradability standards. In contrast to calendar time, thermal time has been found to provide a better agreement between the in-field and the laboratory degradation rates (Griffin-LaHue et al., 2022). Thermal time (τ) can be calculated as (Campbell and Norman, 1998):

$$\tau = \sum_{i=1}^{n} \left(\frac{T_{\mathrm{max,i}} + T_{\mathrm{min,i}}}{2} - T_{\mathrm{base}} \right) \Delta t, \tag{3}$$

where $T_{\mathrm{max,\,i}}$ and $T_{\mathrm{min,\,i}}$ are daily maximum and minimum soil temperatures at a given day i, $(T_{\mathrm{max,\,i}} + T_{\mathrm{min,\,i}})/2$ represents the average daily temperature, n is the total number of days, Δt is the time increment, i.e., 1 day, and T_{base} is the base temperature, which can be taken, in this case, to be 0°C because microbial activity is suppressed considerably at subzero temperatures (Sintim et al., 2020). In the study of Griffin-LaHue et al. (2022), four out of five tested BDM films would reach full degradation within 17,568 cumulative

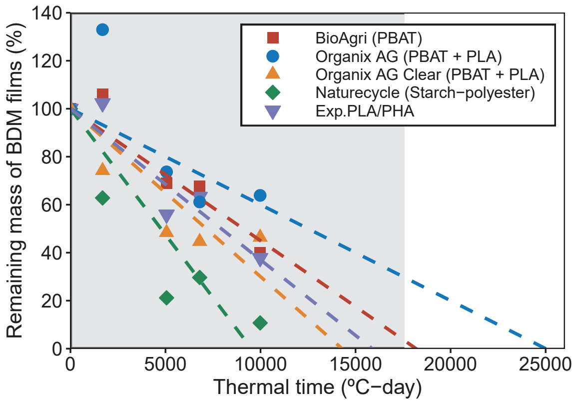


Fig. 10 Quantification of in-field degradation of different biodegradable plastic mulch films (key polymers in parentheses) as remaining mass over thermal time. A zeroth-order model (dashed lines) was fitted to the experimental data to extrapolate the complete degradation of biodegradable plastic mulch films. The shaded area indicates a thermal time less than the defined thermal time needed to reach 90% degradation (17,568 cumulative °C-days in a 24°C incubation) in standard biodegradability tests. Figure adapted from Griffin-LaHue et al. (2022). Reprinted from Science of the Total Environment, 806, Griffin-LaHue, D., Ghimire, S., Yu, Y., Scheenstra, E. J., Miles, C. A. and Flury, M., In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate, 150238, Copyright (2022), with permission from Elsevier.

°C-days, which corresponds to 2 years of calendar time at 24°C in biodegradability tests, when predicted with a zeroth-order degradation model (Fig. 10).

5. Agronomic performance of biodegradable plastic mulch films

Agronomic performance of BDMs refers to how BDMs affect parameters such as crop yield and quality, earliness of harvest, weed and insect control, nutrient cycling and uptake efficiency, water conservation, and soil microclimate (Fig. 1). In addition, an important agronomic parameter is how easy a mulch film can be handled and managed during its application in the field. We will discuss these parameters in turn, benchmarking the performance of BDMs against that of polyethylene mulch film and against no mulch use, i.e., bare soil.

5.1 Soil microclimate

Plastic mulch films affect the soil microclimate by modifying the solar radiation and heat absorption on the surface and the gas and energy exchange across the soil-atmosphere interface. The most important consequence of these modifications is a change in soil temperature, and depending on the color of the mulch, the soil temperature can increase or decrease. Black mulches increase, while white mulches decrease the soil temperature. The highest temperature benefits are usually obtained with clear mulches because shortwave light can easily penetrate the mulch, but then the outgoing longwave radiation cannot escape. Increased soil temperature allows early planting and extends the length of the growing season in cool climates, whereas decreased soil temperature alleviates heat stress in warm climates.

Recent meta-analyses show that BDMs are less effective than polyethylene mulch films in modifying soil temperatures, but nonetheless provide expected benefits when compared to bare soil (Liu et al., 2021; Tofanelli and Wortman, 2020). Soil temperature was found to be about 4% lower under BDM films compared to polyethylene mulch films (Liu et al., 2021; Tofanelli and Wortman, 2020), but still about 3% higher than under bare soil (Fig. 11). Liu et al. (2021) found that soil temperatures were 0.9°C lower under BDMs than under polyethylene.

The less pronounced effect of BDM films on soil temperature compared to polyethylene can be explained by their thickness and durability. BDM films are usually thinner than polyethylene mulch films (19 μm vs 28 μm on average in the meta-analysis by Tofanelli and Wortman (2020)) and therefore retain less heat and have a higher gas permeability (Sintim et al., 2022). Further, BDMs tend to deteriorate during the growing season, leading to bare soil exposure and loss of the warming effect. However, the more developed plant canopy at the later stages of the growing season leads to shading of the soil surface and plastic mulches, which then have less effects on soil temperatures. Indeed, Sintim et al. (2019a) observed the most pronounced soil temperature differences between BDMs and polyethylene mulch films at the beginning of the growing season, with larger differences in a cool climate (Washington state) than in a warm climate (Tennessee).

However, if the thickness of the BDM and the polyethylene mulch films is the same, then BDM films can have an equivalent or even better warming effect than polyethylene mulch films. Wang et al. (2021) found that soil temperatures were higher under BDMs than under polyethylene at the

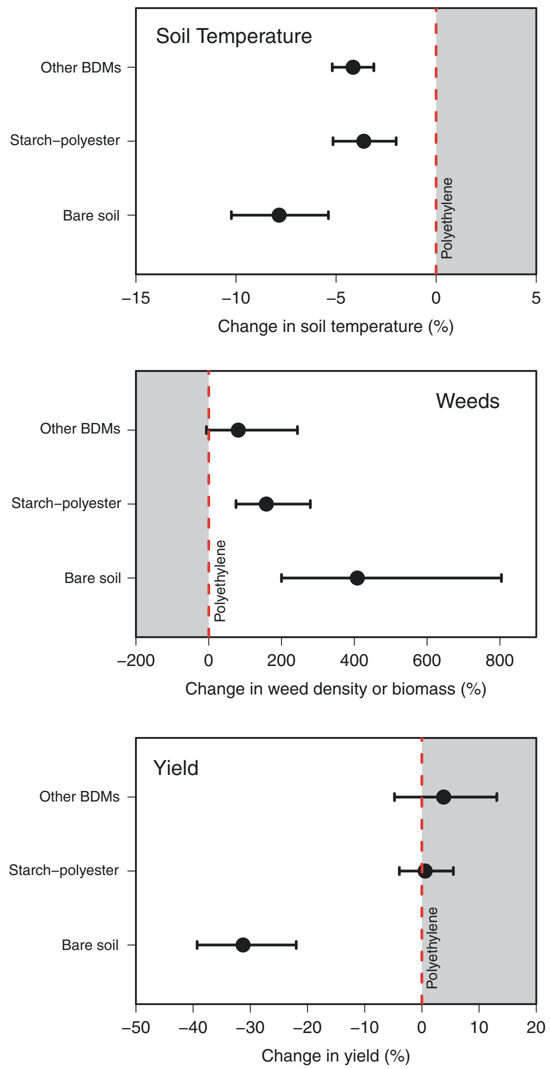


Fig. 11 Change in soil temperature, weed density or biomass for bare soil and biodegradable plastic mulch film relative to polyethylene mulch film. *Shaded area* represents a positive response relative to polyethylene mulch film. *Symbols* represent means, and error bars are 95% confidence intervals determined by bootstrapping. "Other BDMs" denote less common, often experimental mulches manufactured from biodegradable or biobased polymers. *Adapted from Tofanelli, M.B.D., Wortman, S.E., 2020. Benchmarking the agronomic performance of biodegradable mulches against polyethylene mulch film: a meta-analysis. Agronomy 10, 1618. https://doi.org/10.3390/agronomy10101618. Distributed under Creative Commons CC-BY 4.0.*

beginning of the growing season in a corn cropping system, but the differences disappeared later in the growing season, likely due to shading by the crop canopy.

In practice, BDMs are often designed to be thinner than polyethylene mulch films because a thinner film can more readily be degraded, whereas a thicker film in the case of polyethylene allows for better removal after the growing season. As shown in Section 5.7, the difference in soil temperature between BDM and polyethylene mulch films, however, does not translate to differences in yield.

5.2 Soil moisture and water conservation

Polyethylene mulch films are often used to conserve soil moisture, particularly in semiarid regions. Polyethylene mulch film is a highly effective barrier for evaporation (Sintim et al., 2022), and, unless crops are irrigated, soil moisture under plastic is consistently higher than under bare soil (Gao et al., 2019). When crops are being irrigated, then less water is needed when plastic mulch film is placed on top of irrigation drip lines. This water conservation benefit has led to increased yield and a drastic increase in the use of plastic film mulching in China, particularly in the northwestern Provinces (Ingman et al., 2015; Yan et al., 2014), making China the largest user of plastic mulch films worldwide.

BDMs are also an effective evaporation barrier; however, not as good as polyethylene mulch films. How good a plastic mulch film is at preventing evaporation depends on its permeability to water vapor transmission, and the vapor transmission rate is proportional to the vapor diffusivity (or diffusion coefficient) and the inverse of the film thickness:

$$\mathrm{WVT} = C_v \frac{\mathrm{D_{H_2O}}}{d}, \tag{4}$$

where WVT (g $\mathrm{cm^{-2}\ s^{-1}}$) is the water vapor transmission rate, i.e., the amount of water vapor passing through the film per cross section and time, C_v (g $\mathrm{cm^{-3}}$) is the water vapor concentration, $\mathrm{D_{H_2O}}$ ($\mathrm{cm^2\ s^{-1}}$) is the vapor diffusion coefficient for the plastic material, and d (cm) is the thickness of the plastic film. Sintim et al. (2022) measured the vapor diffusion coefficient for a typical PBAT-based BDM to be $\mathrm{D_{H_2O}} = 40 \times 10^{-7}\ \mathrm{cm^2\ s^{-1}}$ and that of a polyethylene mulch film to be $\mathrm{D_{H_2O}} = 4 \times 10^{-7}\ \mathrm{cm^2\ s^{-1}}$, indicating water vapor moved 10 times faster through the BDM as compared to the polyethylene mulch film. As the thickness (d = 18 μm) of the BDMs was less than that of polyethylene mulch ($d = 25$ μm), the resistance to vapor flow of the BDM was about 14 times less than that of the polyethylene mulch film (Sintim et al., 2022). A similar difference was reported by Martin-Closas et al. (2008b), who found that vapor transmission through a BDM (15 μm) was 12 times faster than through a polyethylene mulch film (15 μm). Touchaleaume et al. (2016) tested four different BDMs (40 μm) and found them to be three to six times more permeable than a polyethylene mulch film (40 μm) when new. After 4.5 months of field exposure, the vapor permeability of the polyethylene mulch film decreased while that of BDMs increased (Touchaleaume et al., 2016). Water vapor transmission rates of several BDMs were reported to be 10–20 times larger than those of polyethylene mulch films (Liu et al., 2021), and even about two orders of magnitude higher in a study by Briassoulis and Giannoulis (2018).

Differences in diffusivities can be translated into considerable water savings when soil was completely covered with polyethylene mulch films compared to BDMs (Sintim et al., 2022). However, when plants were present, the differences in water savings were not as pronounced (Sintim et al., 2022) because plant transpiration becomes a more dominant mechanism of water loss and planting holes decrease differences in mulch vapor diffusivity.

Field measurements of soil moisture have indeed not shown a difference between BDMs and polyethylene mulch films (Liu et al., 2021; Tofanelli and Wortman, 2020). Even if polyethylene mulch films were to increase soil moisture, transpiration would also increase if the soil is wetter, and this would cause the differences between polyethylene mulch films and BDMs to diminish. Further, as pointed out by Tofanelli and Wortman (2020), soil moisture data are often confounded by other factors such as weed pressure, root growth, and irrigation. Sintim et al. (2021) found no consistent differences in soil water content between BDMs and a polyethylene mulch film in a cool Mediterranean and a subtropical climate under drip irrigation. Similarly, Wang et al. (2021) found no differences in evapotranspiration rates in a humid continental climate under rainfed conditions in 1 year, but reduced evapotranspiration rates under a polyethylene mulch film in a second year.

A modeling study by Saglam et al. (2017) demonstrated that both BDMs and polyethylene mulch films reduce evapotranspiration as compared to bare soil, and that the soil water dynamics is similar under the two types of plastic mulches. Deterioration of BDMs in the later stages of the growing season caused enhanced evapotranspiration and also allowed rainfall to penetrate the soil.

Overall, experimental and modeling data suggest that BDMs are equivalent to polyethylene mulch films in terms of their effects on soil moisture dynamics and water conservation. Although BDM intrinsic properties (vapor diffusion coefficient and film thickness) make them more permeable for vapor flow, there is no evidence that BDMs in practice are less effective in water conservation than polyethylene mulch films.

5.3 Weed control

Weed control is an important function of plastic mulch films, as it eliminates the need to use herbicides. Polyethylene mulch films have been used successfully to control weed growth. In organic agriculture, where synthetic herbicides are prohibited, polyethylene mulch films play an important part in weed control (Corbin et al., 2013; Ghimire et al., 2018a). Currently, regulations in the United States for the use of BDMs in organic agriculture require BDMs to be at least 80% biobased (National Organic Standards Board, 2021), a requirement that commercial BDMs currently do not satisfy.

BDMs have been shown to effectively control weeds, as long as their spectral transmission properties and their durability in the field are similar to those of polyethylene mulch films. The meta-analysis by Tofanelli and Wortman (2020) indicates that overall, weed control of BDMs is not as effective as that of polyethylene mulch films (Fig. 11), although the data set for this analysis was rather small. Nonetheless, several studies support that BDMs can be equivalent to polyethylene mulch films in terms of weed control (Moreno et al., 2008; Ngouajio et al., 2008; Wang et al., 2022a).

However, if BDMs prematurely deteriorate, then weed control is compromised and agronomic performance is diminished. For instance, premature breakdown of a white BDM caused extensive weed pressure in a tomato (*Solanum lycopersicum*) trial as compared to a black BDM and a polyethylene mulch film that were more intact (Ngouajio et al., 2008). White BDMs also tend to show higher weed pressure because they are more translucent than black BDMs (Miles et al., 2012).

5.4 Nutrient cycling

Plastic mulching has been shown to enhance the nutrient cycling (Sintim et al., 2021). Sintim et al. (2021) observed less nitrate leaching from the rootzone under both BDMs and a polyethylene mulch film in a pumpkin

(*Cucurbita pepo* L.) and a corn (*Zea mays* L.) cropping system. This was in part attributed to more nitrate uptake because the plants produced more biomass under plastic mulching than under bare soil conditions (Sintim et al., 2021).

5.5 Durability

Plastic mulch films provide their benefits by covering the soil surface. Polyethylene has excellent material properties (tensile strength, elongation, thermostability) and usually remains intact during the growing season, unless the film is too thin so that it readily rips and tears apart. To the contrary, BDMs tend to have smaller tensile strength and break apart physically more readily. Percent elongation, a measure of how elastic a plastic film is, of polyethylene mulch films is larger than that of BDMs (Hayes et al., 2017), and thus polyethylene does not as readily fragment.

BDMs tend to fragment, rip, and tear during the growing season, and bare soil will be gradually exposed (Ghimire et al., 2018b, 2020a). Different BDMs have different material properties (Hayes et al., 2017) and thus will have different susceptibility for soil exposure (Ghimire et al., 2020a; Moore and Wszelaki, 2019). Premature deterioration of BDMs will negatively impact their agronomic performance; however, current commercial BDM products seem to have sufficient durability to ensure adequate and comparable performance compared to polyethylene mulch films. Deterioration of BMDs later in the growing season, after plants have been established, is usually not a problem, as the benefits of plastic mulches are most prevalent during the initial phases of the growing season when plants are more susceptible to water and weed stress.

5.6 Early crop development

Plastic mulching allows early planting and leads to early crop development and harvest. Growers can thus bring their crop to the market early and get a premium price (Martin-Closas et al., 2017). The scientific literature indicates that early crop development is similar between BDMs and polyethylene mulch films (Martin-Closas et al., 2017). Little differences in early development were observed for tomatoes grown with BDMs and polyethylene mulch films (Candido et al., 2008; Martin-Closas et al., 2008a), suggesting that BDMs provide equal benefits as polyethylene mulch films.

5.7 Crop yield and quality

Crop yield is a key driver for the use of plastic mulch films. Conventional polyethylene mulch films have been shown to increase crop yields as compared to bare soil by up to 30% (Gao et al., 2019; Tofanelli and Wortman, 2020), and a consistent yield increase has been reported from different geographic regions and for different crop types (Liu et al., 2021; Tofanelli and Wortman, 2020). In addition, plastic mulching has also been found to increase crop quality (Ghimire et al., 2018b; Kasirajan and Ngouajio, 2012).

BDMs have been reported to provide the same benefits as polyethylene mulch films in terms of yield (Table 4). In meta-analyses, where hundreds of observations were analyzed (Liu et al., 2021; Tofanelli and Wortman, 2020), yields obtained with BDMs were not different from yields obtained with polyethylene mulch films (Fig. 11). And remarkably, this equivalent performance in terms of yield was independent of geographic region and crop type (Liu et al., 2021; Tofanelli and Wortman, 2020), suggesting that BDMs are a viable alternative to polyethylene mulch films when assessed for yield.

For instance, no differences in the yield of tomatoes were observed between a BDM and a polyethylene mulch film in a continental Mediterranean climate (Martin-Closas et al., 2008a). Ghimire et al. (2018b) tested experimental and several commercial BDMs against a polyethylene mulch film in two different climatic regions, a cool Mediterranean climate in Washington state and a subtropical climate in Tennessee, and found no yield differences for pumpkin (*C. pepo* L.) among the mulch treatments at each of the locations. Similarly, no yield differences for sweet corn (*Z. mays* L.) were observed in Washington state (Ghimire et al., 2020b) and for peppers (*Capsicum annuum* L.) in Tennessee (Moore and Wszelaki, 2019). In a humid continental climate in northeastern China, corn yield did not differ between BDM and polyethylene mulch treatments (Wang et al., 2021).

The finding of equivalent yield between BDMs and polyethylene mulch films can be explained by the previously discussed similar effects of the two types of plastics on soil temperature, soil moisture, and weed control. Although BDMs deteriorate during the growing season and expose bare soil (Ghimire et al., 2018b; Moore and Wszelaki, 2019), thereby reducing the beneficial effects on soil microclimate, weed control, and water conservation later in the growing season, this apparently does not affect crop yield if the plants are already well established by the time the mulches deteriorate and so no additional benefits from the mulches are provided.

However, if a BDM deteriorates too early or is too thin to provide effective weed control, then yield will be negatively affected. In a trial

Table 4 Yield response to biodegradable plastic mulches compared to polyethylene mulch.

Crop	Latin name	Duration of study[a]	Location	Mulch type	Thickness of BDM (μm)	Mulch color	Yield response	Reference
Corn	*Zea mays* L.	3	China	BDM 1 (high biodegradation)	8	Clear	Yields did not differ between BDM 3 and PE; BDM 2 provided the highest yield, higher than PE	Yin et al. (2019)
				BDM 2 (moderate biodegradation)	8	Clear		
				BDM 3 (low biodegradation)	8	Clear		
				PE	8	Clear		
Corn	*Z. mays* L.	2	Washington, USA	BioAgri	18	Black	Yields were comparable among mulch types; clear Organix mulch had smaller yields, caused by deterioration and increased weed pressure	Ghimire et al. (2020b)
				Organix	18	Black		
				Naturecycle	25	Black		
				PE	25	Black		
				Organix	13	Clear		
Corn	*Z. mays* L.	2	China	ecovio BDM	8	Black	Yields did not differ among all treatments; protein, fat, N, and P content higher under black mulching	Wang et al. (2021)
				ecovio BDM	8	Clear		
				PE	8	Black		
				ecovio BDM	8	Clear		
Cotton	*Gossypium hirsutum* L.	2	China	BDM 1 (PBAT-based)	10	Clear	PE was best in water conservation; PE had the highest yields overall, but some BDMs performed similar to PE; PE also had highest soil warming; BDMs increased yield compared to no mulching	Wang et al. (2019b)
				BDM 2 (PBAT-based)	10	Clear		
				BDM 3 (PBAT-based)	12	Clear		
				BDM 4 (PBAT-based)	10	White		
				PE	8	Clear		

Continued

Table 4 Yield response to biodegradable plastic mulches compared to polyethylene mulch.—cont'd

Crop	Latin name	Duration of study[a]	Location	Mulch type	Thickness of BDM (μm)	Mulch color	Yield response	Reference
Lettuce	*Lactuca sativa* L.	2	Italy	Mater-Bi	12	Black	Yields did not differ between BDM and PE, but harvesting time in the winter cycle was 5 days later for BDM than for PE; no differences in harvesting time in the spring cycle	Di Mola et al. (2022)
				PE	50	Black		
Melon	*Cucumis melo inodorus*	1	Italy	Mater-Bi	18	Black	Clear mulches had higher yields than black mulches; yields were similar between clear BDM and PE and between black BDM and PE	Incalcaterra et al. (2004)
				Mater-Bi	18	Clear		
				PE	50	Black		
				PE	50	Clear		
Melon	*Cucumis melo* L. var. *reticulatus*	2	Italy	Mater-Bi	15	Black	Green BD had higher yields than PE because the green BDMs reached higher soil temperatures; yield of black BDM was lower than that of PE	Filippi et al. (2011)
				Mater-Bi	15	Green		
				PE	50	Black		
Oilseed rape	*Brassica napus* L.	3	China	BDM	8	White	Yields and water-use efficiency were equivalent between BDM and PE	Gu et al. (2017)
				PE	8	White		
Pepper	*Capsicum annuum* L.	2	Tennessee, USA	Bio360	18	Black	Yields were similar in year 1 among mulches, except for Naturecycle, which had lower yield; yield in year 2 was negatively affected by weed growth in all treatments	Moore and Wszelaki (2019)
				Organix	18	Black		
				Naturecycle	25	Black		
				PE	25	Black		
				Organix	18	Black		
				Organix	18	White-on-black		

Pumpkin	*Cucurbita pepo* L.	2	Washington, Tennessee, USA	BioAgri	18	Black	Yields in Washington were highest for PE, BioAgri, and Naturecycle; yields in Tennessee were equivalent among treatments	Ghimire et al. (2018b)
				Organix	18	Black		
				Naturecycle	25	Black		
				PE	25	Black		
Raspberry	*Rubus idaeus* L.	2	Washington, USA	BASF	13	Black	BDMs and PE suppressed weeds, similarly improved yield and plant growth	Zhang et al. (2019a)
				BASF	15	Black		
				Novamont	13	Black		
				Novamont	15	Black		
				PE	23	Black		
Strawberry	*Fragaria×ananassa*	1	Portugal	Biomind	31	White-on-black	Yields for all BDMs were significantly lower than for PE, which was attributed to lower soil temperatures observed with PE mulch at the beginning of the trial	Andrade et al. (2014)
				Mater-Bi	20	White-on-black		
				Mater-Bi	25	White-on-black		
				PE	40	White-on-black		
Strawberry	*Fragaria×ananassa* Duch.	2	Portugal	Mater-Bi	18	Black	BDM performed similarly compared to PE in terms of yield and fruit quality	Costa et al. (2014)
				Mater-Bi	20	Silver-on-black		
				Mater-Bi	20	White-on-black		
				PE	35	Black		
Strawberry	*Fragaria×ananassa*	1	Spain	10 different mulches	20	Black	Some BDMs produced similar yields as PE, some BDMs produced less yield, attributed to weed pressure under these BDMs during the growing season	Giordano et al. (2020)
				2 polylactic acid/ copolyester	25			
				8 starch-based BDMs	35			
				PE	40			

Continued

Table 4 Yield response to biodegradable plastic mulches compared to polyethylene mulch.—cont'd

Crop	Latin name	Duration of study[a]	Location	Mulch type	Thickness of BDM (μm)	Mulch color	Yield response	Reference
Strawberry	*Fragaria×ananassa* Duch.	1	Italy	Mater-Bi N5	18	Black	No yield differences among mulch treatments; new Mater-Bi N5 mulch had better mechanical strength and the commercial Mater-Bi N15 and thus is more suitable for longer soil coverage	Morra et al. (2022)
				Mater-Bi N18	18	Black		
				PE	50	Black		
Strawberry/ Lettuce	*Fragaria×ananassa* Duch./*Lactuca sativa* L.	2	Washington, USA	Organix (ecovio)	25	Black	BDMs performed similarly compared to PE in terms of yield, weed suppression, soil temperature modification, despite deterioration of the BDMs during the growing season	Wang et al. (2022a)
				PE	25	Black		
Tomato	*Lycopersicon esculentum*	1	Spain	Mater-Bi	15	Black	No significant differences observed in yields	Martin-Closas et al. (2008b)
				Biofilm	17	Black		
				Bioflex	15	Black		
				PE	15	Black		
Tomato	*L. esculentum*	1	Spain	Mater-Bi	15	Black	No significant differences observed in yields	Martin-Closas et al. (2008a)
				PE	15	Black		
Tomato	*Solanum lycopersicum*	2	Michigan, USA	BDM made of PBAT (ecoflex)	25	Black	Yields were similar among the black mulches; white BDMs degraded earlier and weed pressure caused yields to be less than under the black mulches in 1 year	Ngouajio et al. (2008)
				BDM made of PBAT (ecoflex)	35	Black		
				BDM made of PBAT (ecoflex)	25	White		
				BDM made of PBAT (ecoflex)	35	White		
				PE	25	Black		

Tomato	*S. lycopersicum* L.	1	Spain	Mater-Bi	14	Black	Yields were similar between BDM and PE	Moreno et al. (2008)
				PE	15	Black		
Tomato	*S. lycopersicum* "Celebrity"	1	Washington, Tennessee, Texas, USA	BioAgri	20	Black	No yield differences among treatments in Texas and Tennessee; BioAgri had the highest yields in Washington	Miles et al. (2012)
				BioTelo	20	Black		
				NatureWorks	640	White		
				PE	30	Black		
Watermelon	*Citrullus lanatus*	1	Texas, USA	BDM: EcoPoly Solutions	25	Black	Yields were similar between BDM and PE, but the fruit size differed between mulches	Othman and Leskovar (2022)
				PE	35	Black		
Wine grape	*Vitis vinifera* L. cv. Chardonnay	3	France	Mater-Bi CF04P	40	Not specified	BDM and PE produced higher yields than bare soil; no significant differences in fruiting production between mulch treatments	Gastaldi et al. (2013)
				PE	40	Not specified		
Wine grape	NA[b]	1	France	Mater-Bi CF04P	40	Black	Fruiting yield equivalent among all mulch treatments	Touchaleaume et al. (2016)
				Bioflex F2110	40	Black		
				PPC/PBAT blend	40	Black		
				PE	40	Black		
Zucchini	*Cucurbita pepo* L.	1	Italy	Mater-Bi MB15	15	Black	Plants grown in open field and greenhouse; yields were not different between BDM and PE, but yields were higher in greenhouse than in open field	Di Mola et al. (2019)
				PE	50	Black		

[a]Number of growing seasons.
[b]Not available.

with strawberry (*Fragaria* × *ananassa*), 10 different BDMs were tested against a polyethylene mulch film, and only the two thickest BDMs (40 μm) provided yields equivalent to that of the polyethylene (Giordano et al., 2020). Thinner BDMs (20 and 25 μm) were not as effective in weed control and led to lower yields (Giordano et al., 2020). Morra et al. (2022), however, found that a thin BDM (18 μm) provided equivalent strawberry yields compared to a polyethylene mulch film (50 μm).

Crop quality is generally not affected by the type of plastic used if the plastic provides adequate pest and environmental controls. The total soluble solid (TSS) of the crop, a measure of the amount of sugars and soluble minerals, has been found not to differ between BDM and polyethylene films in tomato (Martin-Closas et al., 2008a), melon (*Cucumis melo* L.) (Rangarajan and Ingall, 2006), pumpkin (*C. pepo* L.) (Ghimire et al., 2018b), and sweet corn (*Z. mays* L.) (Ghimire et al., 2020b). Other crop quality indicators, such as kernel alignment or protein and nutrient content in sweet corn, also do not appear different between BDM and polyethylene films (Ghimire et al., 2020b; Wang et al., 2021). Similar results regarding crop quality were reported for strawberry (*Fragaria* × *ananassa*), where TSS was not affected by the plastic type, nor were there differences in other quality parameters, such as total protein, total phenols, and antioxidant activity (Giordano et al., 2020).

For heavy crops, such as melons or pumpkins, that make direct contact with plastic mulch films, it has been observed that BDMs can adhere to the surface of the crops and thereby negatively impact marketability (Ghimire et al., 2018b; Martin-Closas et al., 2017; Velandia et al., 2020b; Zhang et al., 2020a). As BDMs are designed to degrade over time, such mulch adhesion is much more likely than in the case of polyethylene mulch films, whose material properties are much sturdier.

6. Environmental impacts of biodegradable plastic mulch films

6.1 Effect on soil health

BDMs can have both positive and negative impacts on the soil environment. During the growing season, BDMs serve as a physical barrier to regulate the exchange of air, water, and heat between the soil and the atmosphere and thus provide numerous benefits to the environment (Fig. 1), which also translate to desired agronomic outcomes as discussed in the previous section. However, as BDMs deteriorate over time, these benefits diminish, and

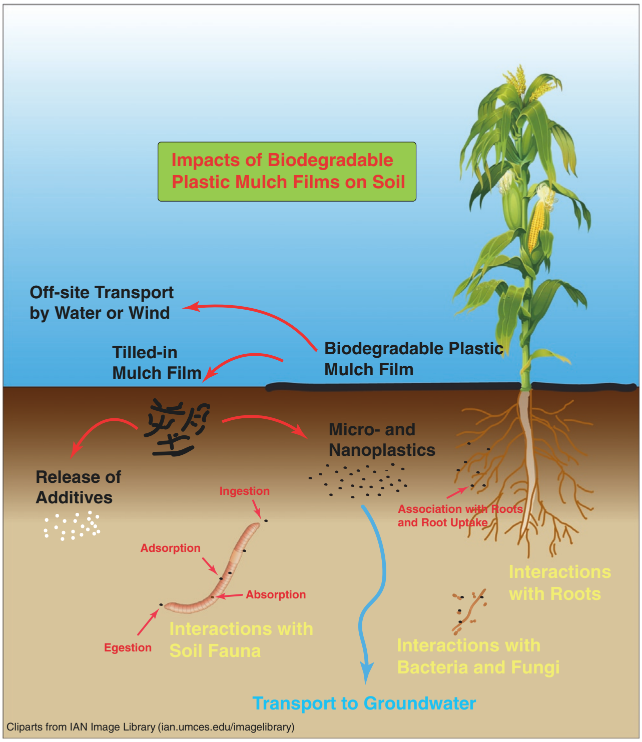


Fig. 12 Potential impacts of biodegradable plastic mulch films on the soil environment.

BDM residues become unwanted anthropogenic substances or even may become pollutants in the environment, raising concerns about their potential environmental impacts (Fig. 12).

6.1.1 Soil physical and chemical properties

During the growing season, BDMs protect soil from disturbances, such as rainfall, hail, and animal traffic, thereby reducing soil erosion, minimizing compaction, and facilitating root growth (Shah and Wu, 2020). This can also translate to increased soil aggregate stability and enhanced infiltration rate (Sintim et al., 2019a, 2021). After BDMs are tilled into the soil at the end of the growing season, these protective benefits will disappear, and the soil surface returns to direct exposure to atmospheric conditions.

The effect of BDM residues after soil incorporation on soil properties has been assessed with in-situ field studies. These studies show that, generally, BDM residues have negligible effects on soil physical and chemical properties, at least over short-term periods of less than 4 years (Sintim et al., 2021).

For example, no significant differences between no-mulch and BDM were observed for bulk density, organic matter content, soil pH, and soil nutrient content, except for nitrate (more nitrate was taken up by plants under the BDM treatments) (Sintim et al., 2021). When soil properties were grouped into soil health indicators, no significant differences were observed between no-mulch and BDMs for hydraulic and nutrient indicators (Sintim et al., 2019a). Soil properties and soil health indicators were more strongly affected by sampling time (spring vs fall) than by BDM treatment (Sintim et al., 2019a).

6.1.2 Soil biological properties

The effect of BDMs on soil biological properties is also different before and after soil incorporation. During the growing season, BDMs act as a surface barrier to regulate microclimate in soils, increasing soil temperature, but reducing evaporation and gas exchange. The increased soil temperature tends to enhance soil microbial activity in cool seasons and reduces soil microbial activity in warm seasons (Bandopadhyay et al., 2020b). Sintim et al. (2021) found a decrease in burst CO_2-C and thus a reduced soil microbial activity in soils covered by BDMs, which was attributed to the increased soil temperature under BDMs. Zhang et al. (2019c) compared microbial community structure of soils covered with BDMs and soils without cover, and they reported that microbial community structure varied significantly, with more BDM-degrading bacteria, such as *Sphingomonas*, *Bacillus*, and *Streptomyces*, found in soils covered with BDMs.

After soil incorporation, BDMs become an input of carbon and additives, as well as agrochemicals that adhered to the films. To date, BDM incorporation has been found to have minor impacts on overall soil biological properties. For example, Kapanen et al. (2008) found no changes in the diversity of ammonium oxidizers nor in the reproduction of the *Enchytraeidae* annelids 1 year after BDMs were incorporated into soils. Li et al. (2014a) tested soil quality in terms of microbial biomass carbon and β-glucosidase after BDMs were incorporated in soil for 18 months and found that BDMs had minor effects on soil quality and the effects were more dependent on cropping system and time of incubation. Moore-Kucera et al. (2014) analyzed the fungal and bacterial communities after 6 months of BDM incorporation at three different locations and found that geographical location, rather than BDM treatment, significantly affected soil microbial community structure. Sintim et al. (2019a) reported no significant changes in soil biological indicators (i.e., organic matter, soil respiration, extracellular enzyme activities C:N and C:P) in a 2-year study in Washington state and Tennessee. Bandopadhyay et al. (2020b) found that the incorporation of BDMs only had limited effect on soil microbial community structure and function over 2 years in Washington state and Tennessee. The relatively unaffected soil microbial community structure and function under BDM treatments are illustrated in Fig. 13, where bacterial community composition clustered according to location and season regardless of the BDM types (Bandopadhyay et al., 2020b).

Despite the limited impacts of BDMs on overall soil biological properties, soil microbial community composition on surfaces of BDMs has been reported to be different from that of the surrounding soil. For example, Muroi et al. (2016) found that fungi belonging to the phylum Ascomycota were enriched on BDM surfaces after 7 months of incubation. Bandopadhyay et al. (2020a) reported an enrichment of soil fungi, while a lowering of bacterial richness on BDM surfaces compared to the bulk soil. Li et al. (2023) collected BDM residues from a farmland after more than 2 years of application, and they found that the structure of bacterial communities on BDM surfaces was distinctively different from that in soils, with more Proteobacteria, phylum Actinobacteriota, and Nocardioidaceae found on BDM surfaces. As pointed out by Bandopadhyay et al. (2018), when tilled into soils, BDMs are an input of carbon, and despite being an overall insignificant amount of carbon (Ding et al., 2021), BDMs can cause enhancement of microbial activity and enrichment of fungal taxa as soil microbes are normally exposed to carbon-limited conditions.

6.2 Environmental concerns about biodegradable plastic mulch films

The environmental concerns about BDMs are commonly related to the intentional incorporation and the subsequent degradation of BDMs in soils. As BDM residues do not disappear instantaneously but rather gradually degrade over time, questions remain about whether the biodegradation process would contribute to CO_2 and other greenhouse gas emission and affect soil carbon stock. In addition, due to the uncertainty and complexity associated with the degradation of BDM in soils, concerns have arisen about generation of biodegradable micro- and nanoplastics, release of additives, and off-site transport of these substances to air and water.

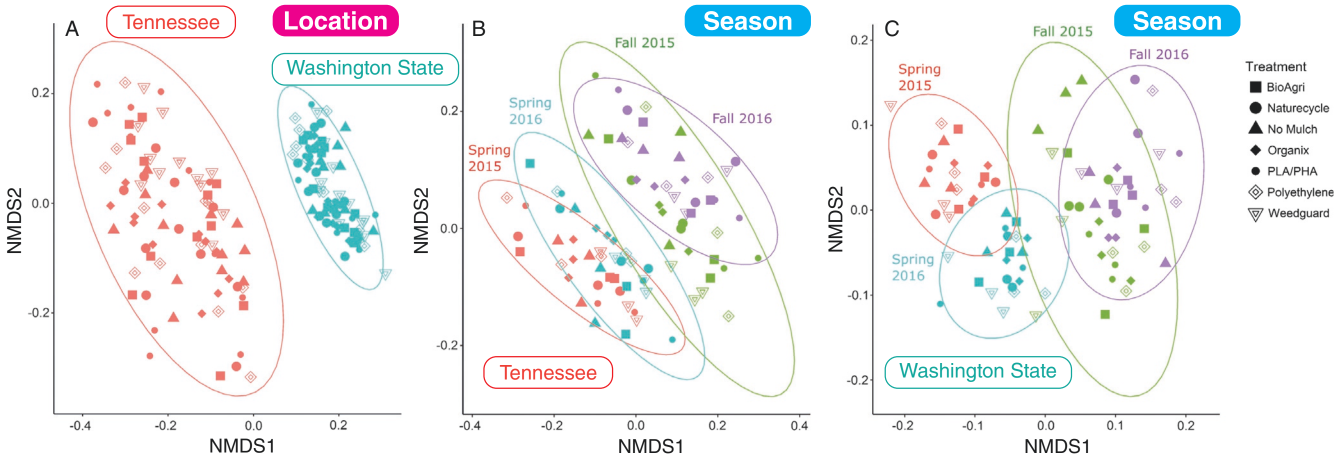


Fig. 13 Bacterial community composition affected by biodegradable plastic mulch film treatment, location, and season as demonstrated by nonmetric multidimensional scaling (NMDS) ordination of Bray–Curtis dissimilarities of OTU relative abundances. (A) Differences between two field locations (Tennessee and Washington state), communities grouped from all sampling seasons; (B) differences among four sampling seasons in Tennessee; and (C) differences among four sampling seasons in Washington state. *Ellipses* show clustering at 95% confidence. *Adapted from Bandopadhyay, S., Sintim, H.Y., DeBruyn, J.M., 2020b. Effects of biodegradable plastic film mulching on soil microbial communities in two agroecosystems. PeerJ 8, e9015. https://doi.org/10.7717/peerj.9015. Distributed under Creative Commons CC-BY 4.0.*

6.2.1 Greenhouse gas emission and soil carbon stock

The biodegradation process of BDMs in soil involves soil microorganisms metabolizing carbon in BDMs into CO_2 and biomass, thus inevitably leads to CO_2 emission. For instance, Inubushi et al. (2022) added PBAT BDM film pieces (<5 mm) into soil and found that, after 4 weeks of incubation at 30°C, CO_2 and N_2O emissions increased compared the no-BDM added soil. Similarly, Rauscher et al. (2023) found that CO_2 emission increased when PBAT microplastics were added into a sandy loam and a loamy soil, with the smaller PBAT particles (50–200 μm) emitting 10–13% more CO_2 than the larger PBAT particles (63–1200 μm). These results suggest that the incorporation of BDMs into soils contributes to CO_2 emission; however, CO_2 emission from BDMs merely indicates that BDMs indeed undergo biodegradation in soils, which is the merit of BDMs and should not be considered as an environment hazard. In addition, the contribution of BDM films to CO_2 emission should be evaluated with the consideration of their agronomical and environmental benefits.

Although BDMs can increase CO_2 emission, they seem to have negligible impacts on soil carbon stock. For example, English (2019) measured soil carbon pools over 2 years after incorporating different mulch films into soils and found that BDM treatments did not affect soil carbon pool compared to no-mulch treatment, but increased soil carbon pool compared to the polyethylene mulch treatment. Ding et al. (2021) calculated the direct carbon input from BDMs over a period of 20 years to be tens of g C m^2, which is several orders of magnitude less than the absolute carbon pool in topsoil (thousands of g C m^2), and thus concluded that the incorporation of BDMs into soils does not substantially affect soil carbon stock.

6.2.2 Generation of biodegradable micro- and nanoplastics

During the life cycle of BDMs, biodegradable micro- and nanoplastics are inevitably generated. These biodegradable micro- and nanoplastics may reside in soils for a certain period of time depending on the degradation rate, and a constant amount of biodegradable micro- and nanoplastics may remain in soils when BDMs are repeatedly applied on farmland (Yu et al., 2021). Like conventional micro- and nanoplastics, biodegradable micro- and nanoplastics can affect soil physical, chemical, and biological properties, disturb soil biota, and act as a carrier for facilitating the migration of other contaminants.

Studies have shown that biodegradable micro- and nanoplastics can significantly impact soil ecosystems when incorporated into soils in forms of artificially created fragments. For example, Boots et al. (2019) found that when PLA microplastics were added at 0.1% w/w into soil containing earthworms (*Aporrectodea rosea*), the germination and shoot length of perennial ryegrass (*Lolium perenne*) were decreased. Qi et al. (2020a) studied the effect of macro- and micro-sized BDM film pieces (5 mm^2 and 50–1000 μm in size, respectively) on soil physicochemical and hydrological properties of a sandy soil at different concentrations (0–2% w/w) after 1 month of incubation, and they found that BDM film pieces at >1% w/w decreased soil bulk density, increased saturated hydraulic conductivity and field capacity, but did not affect pH, electrical conductivity, and aggregate stability. Further, the incorporation of macro- and micro-sized BDM film pieces (5 mm^2 and 50–1000 μm in size, respectively) at 1% w/w impaired wheat (*Triticum aestivum*) growth in a sandy soil (Qi et al., 2018, 2020b).

In addition, biodegradable micro- and nanoplastics can interact with soil fauna, such as earthworms and nematodes, which may cause redistribution of plastic particles in the soil through bioturbation. Sforzini et al. (2016) exposed earthworms (*Eisenia andrei*) to soil samples that were incubated with 1.25% w/w BDM powder for 6 months and found no toxic effects on the survival and reproduction rate of earthworms after 28 days. Boots et al. (2019) found that the biomass of earthworms (*A. rosea*) decreased when PLA microplastics were incorporated in soils at 0.1% w/w. Zhang et al. (2018) reported that earthworms (*Lumbricus terrestris*) ingested BDM pieces and dragged them into their burrows. Similarly, when earthworms (*L. terrestris*) were exposed to BDM in microplastic form, they were found to ingest the microplastics and incorporate the plastics into their cast (Adhikari et al., 2023). No acute toxicity of BDMs on earthworms was observed in these studies after exposure of 20 days (Adhikari et al., 2023) and 50 days (Zhang et al., 2018).

Biodegradable micro- and nanoplastics can be transported to deeper soil layers by water flow, and their further biodegradation can be slowed due to decreased microbial activity in deeper soil layers. In addition, biodegradable micro- and nanoplastics may also facilitate the transport of adherent pollutants (Zhou et al., 2022). Fei et al. (2022) studied the transport of PLA microplastics in saturated porous media and found that PLA microplastics had a higher mobility than polyvinyl chloride microplastics due to their more negative surface charge and higher colloidal stability. Additionally, studies have shown that biodegradable microplastics made of PBAT or PLA tend to absorb organic compounds, such as phenanthrene, hydrocarbons, and antibiotics, more readily than conventional microplastics made of polyethylene, polystyrene, and polyvinyl chloride (Fan et al., 2021; Song et al., 2021; Zuo et al., 2019).

Although biodegradable micro- and nanoplastics can negatively affect soil ecosystems, significant impacts have only been reported at unrealistically high concentrations (>0.1% w/w), which have not been observed for BDMs in agricultural soils to date. Further, the environmental impacts of biodegradable macro-, micro-, and nanoplastics are highly dependent on their residence time in soils, and short-lived biodegradable plastics in suitable degradation environments are less of a concern to soil ecosystems. Thus, to accurately assess the environmental impacts of BDMs, it is necessary to conduct long-term in-field studies to determine the degradation and accumulation dynamics of BDM residues, and to better characterize the content and properties of biodegradable macro-, micro-, and nanoplastics in soils.

6.2.3 Release of additives

Although biodegradable polymers can eventually biodegrade and convert into biomass and CO_2 in soils, additives, such as plasticizers, antioxidants, and pigments, are inevitably released into soil when BDMs biodegrade. For example, Sintim et al. (2019b) found that during composting of BDMs, micro- and nanoparticles, likely carbon black, a common colorant and UV stabilizer in BDMs, were released after 18 weeks when BDMs reached >99% macroscopic degradation. Similarly, Yu et al. (2022) reported that TiO_2 particles, which are added as a white colorant and UV stabilizer, were released from a BDM during 40 weeks of composting (Fig. 14). Although these additives were released into compost, they will transfer to soils when compost is applied as a soil amendment, and potentially migrate through soils (Yu et al., 2022).

Currently, data are still scarce about the direct release of additives from BDMs to soils, but it has been documented that additives can migrate from conventional plastics to soils. For example, Li et al. (2020) found that the content of phthalate acid esters in soils was positively correlated with the intensity of plastic mulch film application in agricultural soils. Viljoen et al. (2022) reported that phthalate acid esters leached from plastic mulch films to soils, and the degradation of phthalate acid esters was slowed down by their physical trapping within the plastic matrix. Tun et al. (2022) found that plastic waste contributed to the contamination of dumping site soils with phthalate plasticizers and butylated hydroxytoluene

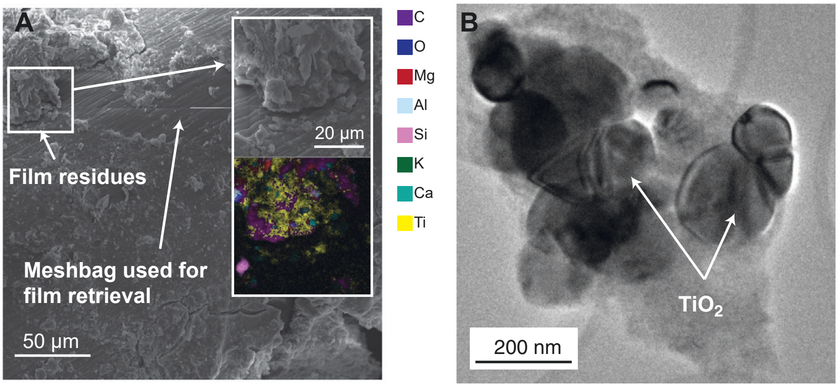


Fig. 14 TiO_2 particles released from a biodegradable plastic mulch film after 40 weeks of composting. (A) Scanning electron microscopy images of film residues on a meshbag used for film retrieval after composting, with inset showing magnified morphology of film residues and corresponding energy dispersive X-ray mapping; (B) transmission electron microscopy images of released TiO_2 particles. *Reprinted (adapted) with permission from Yu, Y., Sintim, H.Y., Astner, A.F., Hayes, D.G., Bary, A.I., Zelenyuk, A., Qafoku, O., Kovarik, L., Flury, M., 2022. Enhanced transport of* TiO_2 *in unsaturated sand and soil after release from biodegradable plastic during composting. Environ. Sci. Technol. 56, 2398–2406. Copyright 2022 American Chemical Society.*

antioxidant. Serrano-Ruíz et al. (2018) studied the effect of BDM extracts on the plant development using mineral solutions and found that BDM film extracts reduced the germination rate and plant biomass of both lettuce (*L. sativa* L.) and tomato (*Lycopersicon esculentum* Mill). Therefore, it is conceivable to postulate that if the same additives are used in BDMs, BDMs would have a comparable environmental impact to soil ecosystems as conventional plastic mulch films.

6.2.4 Off-site transport to air and water

Wind and water can translocate BDMs from agricultural fields to the atmosphere, nearby water bodies, and other nonagricultural ecosystems (Fig. 15). Studies have shown that BDMs do not degrade well in the atmosphere or aquatic environments due to limited microbial activity. For example, Liao and Chen (2021) found no significant weight loss of PLA, PBAT, and PBAT/PLA BDMs after being exposed to air under solar radiation for 6 months, when photodegradation solely dominated the degradation process. Similarly, PBAT films were reported to lose only 4.7% of their original weight after being immersed in various water bodies, including

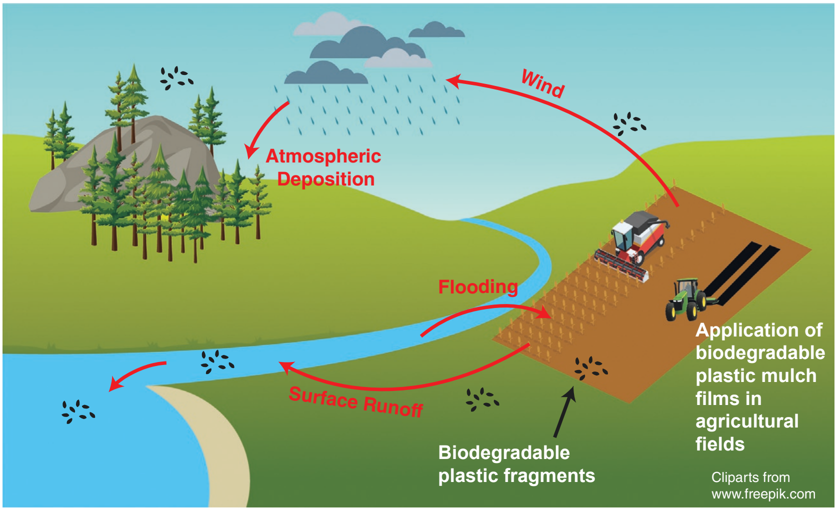


Fig. 15 Off-site transport of biodegradable plastic fragments from farmland to the atmosphere, aquatic environments, and wilderness areas.

river and sea water, for 56 weeks (Wang et al., 2019a). Nakayama et al. (2019) immersed biodegradable films in seawater at Osaka in Japan for 6 weeks and found that poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) and poly(butylene succinate/adipate) films lost 85–100% of their original weight, while PBAT films only lost 6.1%. Although BDMs generally show low degradability in water bodies, studies have shown that the degradation of a BDM made of Mater-Bi can be enhanced when the plastics are in contact with marine sediments, where the microbial activity is higher than that in free water bodies (Eich et al., 2021; Tosin et al., 2012). Other than the limited degradation, BDMs have been reported to generate numerous microplastics in air and water, with a considerably faster generation rate than conventional polyethylene plastics (Bao et al., 2022; Wei et al., 2021).

Impacts of biodegradable microplastics to aquatic systems have been investigated recently. For example, Seeley et al. (2020) found that the presence of PLA microplastics promoted nitrification and denitrification and altered microbial community composition in salt marsh sediment. Magni et al. (2020) compared the sublethal effects of conventional (polyvinyl chloride) and biodegradable (Mater-Bi) microplastics on *Dreissena polymorpha* mussel at 1 mg/L for 14 days, and no adverse effects were observed. Klein et al. (2021) studied the toxicity of PLA microplastics at a concentration of 0.5% w/w in freshwater sediments with the freshwater oligochaete *Lumbriculus variegatus* and found that the survival of the oligochaete was reduced due to the chemicals associated with the plastic particles, but not the polymer itself. Zimmermann et al. (2020) reported that PLA microplastics at 500 mg/L reduced the survival of planktonic crustacean *Daphnia magna*. Further, PLA microplastics showed comparable toxicity to *D. magna* as conventional polyvinyl chloride microplastics (Zimmermann et al., 2020).

Studies about the impacts of BDMs to the atmosphere are still missing, but BDMs are likely to contribute to air pollution similar to conventional plastics. Conventional microplastics have been identified in the atmosphere in both indoor and outdoor environments, even in remote mountains (Allen et al., 2019; Klein and Fischer, 2019; Stanton et al., 2019). Although it is still unclear to what extent airborne micro- and nanoplastics affect human health, studies have shown that once inhaled, micro- and nanoplastics can potentially cause irritation and inflammation in the respiratory system (Chen et al., 2020a). For example, Lim et al. (2021) found that inhalation exposure of rats to polystyrene microplastics led to increased expression of inflammatory proteins. Xu et al. (2019) studied the effect of polystyrene nanoplastics on human alveolar epithelial A549 cells and found that polystyrene nanoplastics induced significant upregulation of proinflammatory cytokines and proapoptotic proteins.

It is unavoidable that BDMs will translocate from soils to air and water, but their environmental impacts to the atmosphere and the aquatic environment depend on the extent of the off-site transport. The off-site transport is affected by BDM properties, conditions of application and disposal environments, as well as management practices. Since wind and water are major carriers, off-site transport of BDMs is likely to be associated with soil erosion and soil disturbance, such as tillage. Research is still needed to quantify the off-site transport potential of BDMs, with the consideration of the dynamic degradation of BDMs in soils.

7. Economics of biodegradable plastic mulch films

7.1 Price, market size, and future perspectives

Generally, BDM films cost more than conventional polyethylene mulch films, with BDMs two to three times more expensive than polyethylene mulches (Velandia et al., 2018; Yang et al., 2023). The differences in price between BDMs and polyethylene mulches vary depending on the feedstock used (e.g., Mater-Bi, ecovio, ecoflex) to produce BDMs, film thickness, supplier, location, and availability (Marí et al., 2019; Velandia et al., 2018). Based on prices gathered in January 2023 from various input suppliers in the United States, we estimate that a 4 × 4000 feet^2 roll of BDM with a thickness of 15 μm (0.75 mil) is, on average, 86% more expensive than a 4 × 4000 feet^2 roll of polyethylene mulch with a thickness of 25 μm (1 mil), excluding shipping costs.

The global BDM market size in 2022 was estimated to be between \$45 and \$63 million, and the market is expected to grow at a CAGR of 3.2–8.5% in the coming 6–7 years, depending on the source and methodology used in the market research (Business Research Insights, 2022; Global Info Research, 2022; Grand View Research, 2022; Research and Markets, 2021). The BDM market is expected to grow especially in regions where the use of conventional plastic is being discouraged, such as North America and Europe (Market and Market, 2022; ReportLinker, 2022). Demand growth for BDMs is likely to be uneven across regions due to differences in policies that promote the use of BDMs (e.g., subsidies), regulations that discourage the use of polyethylene mulches, availability, and feasibility of plastic end-of-life alternatives (e.g., recycling), and available information about performance and long-term impacts of BDMs on soil health.

7.2 Economic feasibility of adoption at the farm level

The economic feasibility of adopting BDMs has been evaluated in terms of price of BDMs, labor cost, as well as removal and disposal cost savings. It was shown that the higher price of BDMs compared to that of polyethylene mulches is the top factor hindering the economic feasibility of adopting BDMs in different crop systems and regions (Marí et al., 2019; Velandia et al., 2020b). Velandia et al. (2020b) found that differences in labor cost in the United States, specifically differences in wage rates across the country, could significantly impact the economic feasibility of adopting BDM films. However, disposal costs and options for disposal seem to have a minimum impact on the economic feasibility of adopting BDMs (Marí et al., 2019; Velandia et al., 2020b). These costs represent a small percentage of the total costs associated with polyethylene mulch use. The highest cost associated with polyethylene mulch use is the removal of it at the end of the season. Velandia et al. (2020b) estimated that removal and disposal of polyethylene mulch could take on average 42 h per hectare (17 h per acre), according to data from a 2019 Tennessee fruit and vegetable farm survey. The reduction of removal and disposal labor represents cost savings when transitioning from polyethylene mulches to BDMs. However, none of these studies incorporated the long-term benefits associated with the use of BDMs in the economic feasibility analyses, such as yield gains and reduced environmental damages. When including these benefits, the use of BDMs may become more favorable.

7.3 Farmer perceptions and willingness to pay for BDM films, and policy implications

Studies evaluating farmers' perceptions of and preferences for BDMs suggest that the higher price of BDMs, compared to polyethylene mulches, is the most common barrier to adopting BDM films (Goldberger et al., 2019; Velandia et al., 2020a; Yang et al., 2023). Another element of concern for farmers is the unpredictable breakdown of BDMs during the growing season, specifically whether BDMs will degrade too fast or too slow, depending on crop and production system needs (Goldberger et al., 2015; Madrid et al., 2022; Velandia et al., 2020c). Additional barriers to BDM adoption identified by other studies include uncertainty associated with the economic feasibility, compatibility with production practices, and in-field degradation of tilled-in BDM fragments (DeVetter et al., 2021a; Madrid et al., 2022).

Given that the price of BDMs has been perceived by farmers as a barrier to adoption, previous studies have shown that farmers would be willing to pay for BDMs if prices were lower than the current market prices (Velandia et al., 2020c; Yang et al., 2023) A subsidy can be provided to fill the gap between market price and farmer willingness to pay for BDMs, as a policy strategy to promote the adoption of BDMs. In certain regions in Spain, there are subsidies in place to promote the adoption of BDMs (Madrid et al., 2022). However, Marí et al. (2019) commented that subsidies were too low to guarantee the economic feasibility of BDM adoption in the Spanish region they studied.

Different policies (e.g., subsidies, tax credits, new standards for biodegradability of BDMs) can have different impacts on the adoption of BDMs. Therefore, farmer preferences for those policies and the effectiveness of these policies in promoting the adoption of BDM films depend on various factors, such as cropping systems, plastic waste generated on the farm, and proximity to a collection site for waste disposal (De Lucia and Pazienza, 2019).

8. Challenges and recommendations

BDMs are a viable alternative to conventional polyethylene mulch films. The agronomic performance of BDMs has been shown to be equivalent to that of polyethylene mulch films, and further improvements in material properties will make BDMs even more attractive for growers. However, the purchase cost of BDMs is greater than that of polyethylene mulch films and therefore growers are hesitant to switch to BDMs. But if costs of removal and disposal of polyethylene mulch films are considered, then the use of BDMs is economically beneficial.

There is, however, an uncertainty about the duration and completeness of in-field biodegradation under different climatic and soil conditions. While intrinsic biodegradability of BDM polymers is ensured by controlled laboratory tests and standards, a manufactured BDM with additional additives may not degrade as readily under actual field conditions, where soil temperature, moisture, and microbial activity vary in space and time. Further, not-yet degraded BDM pieces may be blown away by wind or carried off site by runoff water, and end up in environments that are less conducive to biodegradation (e.g., aquatic or marine ecosystems). Additives from BDMs are being released during biodegradation of the plastic polymers themselves and these additives could pose environmental hazards.

We consider BDMs an important and essential component of sustainable agriculture and integral part of reducing plastic pollution. Replacement of polyethylene mulch films with BDMs will alleviate pollution of soil with plastic residues and help to curb waste generation and disposal problems of agricultural plastics. Nonetheless, while we support the promotion and use of BDMs, we provide the following recommendations to ensure their successful and sustainable use:

- Ensure that BDMs completely degrade and leave no harmful residues in agricultural fields. Biodegradation is dependent on film material composition as well as local climate and soil conditions, so a BDM may biodegrade well in one location but not in another. The in-situ degradation of a BDM therefore needs to be tested and verified under the local conditions where the BDM is being used, and protocols and standards should be developed for such tests. Further, all additives in a BDM need to be verified to cause no harmful effects to soil health.

- Provide both economic and social incentives for growers to adopt and use BDMs. Economic incentives can comprise of subsidies provided by government agencies, when growers use BDMs instead of polyethylene mulch films. Economic incentives can also include the cost savings for growers because they do not need to remove BDM residues from the field but rather incorporate BDM residues directly into soils after the growing season. Regulatory agencies can allow growers to label their crops to be eco-friendly when they use BDMs, which may promote consumers to buy more agricultural products grown with BDMs.
- Discourage growers from using polyethylene mulch films. Disposal cost can be added upfront when growers purchase polyethylene mulch films, which not only minimizes the price gap between BDMs and polyethylene mulch films, making BDMs more competitive, but also prevents growers from discarding polyethylene mulch film residues inappropriately. Added disposal costs can also be passed onto manufacturers of polyethylene mulch films through enactment and enforcement of extended producer responsibility laws.
- Promote the use of BDMs in organic farming. Organic farming is a major consumer of polyethylene mulch films, and currently no BDM meets the criteria for use in certified organic agriculture in the United States. The main issue with BDM films in organic farming is the intentional input of nonbiobased biodegradable plastic residues into soil after harvest, where an underlying concern is the complete degradation of BDMs. This can be resolved by assessing the biodegradability of BDM at a given farm and demonstrating the effects BDMs have on soil health. If BDMs are proven to completely biodegrade at a given farm in a reasonable timeframe and maintain or promote soil health, then the BDMs should be allowed in organic farming. Another option to promote BDM use in organic agriculture is to increase the percentage of biobased ingredients in the feedstocks to better match the biobased requirements.
- Engineer BDMs that can be used during soil fumigation for emission reduction. Many growers still practice chemical or biological soil fumigation where retention of compounds that suppress soil pests and pathogens is essential. Furthermore, totally or virtually impermeable BDMs will benefit growers that use fumigants in areas where emissions need to be controlled for air quality purposes.
- Educate growers and crop consultants about BDMs, including (1) outlining expectations for in-field performance when deployed and how it will differ from polyethylene mulch films, (2) impacts on crop yields, (3) effects on soil health, and (4) economics. Some growers are not aware

of BDMs or are reluctant to use them because of prior negative experience with mulch films falsely advertized as biodegradable. Farmer and crop consultant education will encourage more growers to try this alternative mulch technology and contribute to adoption.

Abbreviations/Glossary

BDM Biodegradable plastic mulch.
Biodegradable A substance that can be degraded into CO_2, CH_4, biomass in a natural or engineered environment, such as soil, water, compost, or anaerobic digester, in a given time frame.
Biobased A material that is derived from renewal resources, i.e., from living organisms, such as corn, sugarcane, or bacteria. The carbon should be fixed from CO_2 recently.
Bioplastics Plastics that are either biodegradable, biobased, or have of both characteristics.
Conventional plastics Plastics that are neither biodegradable nor biobased.
LLDPE Linear low-density polyethylene.
mil Unit for plastic mulch thickness, 1 mil = 1/1000 inch.
Nonbiobased A material that is derived from nonrenewable resources, such as fossil fuels.
Nonbiodegradable A substance that cannot be degraded into CO_2, CH_4, biomass in a natural or engineered environment, such as soil, water, compost, or anaerobic digester.
NOP National Organic Program.
NOSB National Organic Standards Board.
OTU Operational Taxonomic Unit.
PBAT Polybutylene adipate terephthalate.
PBS Polybutylene succinate.
PCL Polycaprolactone.
PE Polyethylene.
PET Polyethylene terephthalate.
PHA Polyhydroxyalkanoates.
PLA Polylactic acid.
TSS Total soluble solids.

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