Frequently Asked Questions about Soil-biodegradable Plastic Mulches

Nataliya Shcherbatyuk[1], Ben Weiss[2], Yingxue Yu[3], Nayab Gull[4], Aidan Williams[1], Lisa Wasko DeVetter[1], and Carol Miles[1]

KEYWORDS. biobased, biodegradation, certified organic, plastic pollution, soil health

ABSTRACT. Plastic mulch accounts for approximately 16% of agricultural plastics, with approximately 2.5 million metric tons of plastic mulch films used globally each year. Polyethylene (PE) is the most widely used polymer in mulch manufacturing because of its low cost, excellent mechanical strength, and barrier properties that prevent weed growth, optimize soil temperature, and conserve soil moisture for crop growth. However, PE mulch is a growing source of plastic pollution because it is nonbiodegradable, and there is a lack of sustainable end-of-life disposal options, resulting in nearly all PE mulch being burned, buried, stockpiled, or landfilled. Soil-biodegradable plastic mulch (BDM) is an eco-friendly alternative that is designed to be tilled into soil at the end of the growing season, and soil microorganisms degrade it into carbon dioxide, methane, water, and microbial biomass. Generally, BDM has an agronomic performance similar to that of PE mulch (dependent on thickness and color), is applied with the same equipment, and its in situ disposal saves labor as well as removal and disposal costs. Yet, BDM adoption in the United States has been limited because of questions regarding its ingredients, costs, biodegradability, and impacts on soil ecosystems and overall soil health. This article answers these most frequently asked questions regarding BDM. For example, BDM that meets the EN 17033 standard is biodegradable in soil and has not been found to have negative impacts on soil ecology or health. The BDM purchase cost can be twice the cost of PE mulch, but the overall cost tends to be similar because there is no cost to remove or dispose of BDM. Two to 10 years are required for BDM to biodegrade in soil, depending on environmental conditions, such as climate, soil temperature, and soil moisture. Much of the misinformation regarding BDM comes from a lack of adherence by marketers and the scientific community to the definition of biodegradable plastic, leading to the usage of plastics that are not biodegradable, thus resulting in plastic pollution.

Plastics are used extensively in agriculture because of their efficacy, durability, and cost-effectiveness for achieving an array of production goals (United Nations Environment Programme 2022). Approximately 2.5 million metric tons of plastic mulch films are used globally every year, with polyethylene (PE) being the most widely used polymer in mulch manufacturing (FAO 2021). This is because of the durability and flexibility, low cost, excellent mechanical strength, and barrier properties of PE that can prevent weed growth, optimize soil temperature, and conserve soil moisture for crop growth (FAO 2021; Mansoor et al. 2022). Some PE films can also be specially manufactured to be totally impermeable (TIF) or virtually impermeable (VIF) and are used widely for soil fumigation (US EPA 2024). Although PE mulch films play an important role in modern agriculture, they are also a growing source of plastic pollution (FAO 2021; Hofmann et al. 2023; Mazzon et al. 2022). The primary problem with PE mulch is that it is nonbiodegradable and sustainable end-of-life disposal options are lacking, resulting in nearly all PE films being burned, buried, stockpiled, or landfilled (Goldberger et al. 2019; Madrid et al. 2022). Even if more sustainable disposal options were widely available (e.g., recycling), the propensity of PE mulches to tear during field removal renders complete removal a challenge, and fragments can become a source of terrestrial plastic pollution (Li et al. 2023; Madrid et al. 2022; Mazzon et al. 2022). Thus, the widespread usage of PE mulch in agriculture has resulted in substantial accumulation of plastics in agricultural soils in some regions where it threatens soil health (Li et al. 2022; Liu et al. 2014). Recent research has shown that these plastics, after fragmenting into microplastics, may migrate to subsoils, where they become impossible to remove (Li et al. 2022). Additionally, these plastics can pollute water and air, where they contribute to the accumulation of persistent macroplastics, microplastics, and nanoplastics in ecosystems where they could be ingested by wild and domestic animals, thus posing a hazard (Li et al. 2022).

The global impact and environmental risk of PE mulch pollution has led to growing interest in eco-friendly alternatives, with soil-biodegradable plastic mulch (BDM) representing a promising solution (FAO 2021; Goldberger et al. 2019). Made with biodegradable polymers, BDM is designed to be tilled into soil at the end of the growing season, when soil microorganisms degrade it into carbon dioxide, methane, water, and microbial biomass (Yu and Flury 2024). Generally, BDM has agronomic performance similar to that of PE mulch; therefore, growers can achieve weed management, moderation of soil temperature and moisture, and enhancement of crop yield and quality (Huang et al. 2022; Tofanelli and Wortman 2020). The in situ disposal of BDM saves labor and end-of-season removal and disposal costs (Madrid et al. 2022). Furthermore, BDMs are applied with the same equipment as that used for PE mulch, streamlining the transition for farmers and simplifying adoption (Shrestha et al. 2023). However, BDM has lower mechanical strength than PE mulch and requires lower tension on roller bars and pressing wheels during machine laying; greater tensions may result in overly tight application or tearing, resulting in premature deterioration and soil exposure, which leads to increased weed growth (Sintim and Flury 2017; Xiong at al. 2024).

Despite its advantages, BDM adoption in the United States has been limited because of lingering uncertainties about its ingredients, costs, complete biodegradability, and impacts on soil ecosystems and overall soil health (Dentzman and Goldberger 2020; Goldberger et al. 2015; Madrid et al. 2022). The aim of this publication is to address these critical frequently asked questions and concerns about BDM. This article will contribute to bridging the knowledge gap between the scientific community, crop advisors, and growers regarding how BDM can contribute to sustainability goals in commercial agriculture as well as the limitations of BDM usage and areas for continued research.

What is used to make BDM and PE mulch?

Approximately 75% to 95% of BDM mass is polymeric feedstock, with the remainder being additives or minor components (DeVetter et al. 2021). Commercially available BDMs are made with a blend of biobased and synthetic fossil-fuel derived feedstock polymers, and common additives include colorants, pigments, stabilizers, fillers, lubricants, and plasticizers. The most common biobased feedstocks for BDM production are thermoplastic starch (TPS), polyactic acid (PLA), and poly(hydroxyalkanoates) (PHAs) (Yu et al. 2023b). Of these, TPS is extracted from natural materials such as potato (*Solanum tuberosum*), maize (*Zea mays*), and sugarbeet (*Beta vulgaris*) (Yu et al. 2023b), and PHAs are polyester and fatty acid biopolymers produced by genetically modified bacteria and yeast that include poly(hydroxybutyrate) and poly(hydroxyvalerate) (Yu et al. 2023b). Synthetic (i.e., not biobased) biodegradable polymers commonly used for BDMs are polybutylene adipate-coterephthalate (PBAT), polybutylene succinate (PBS), polybutylene succinate adipate (PBSA), and polycaprolactone (PCL) (DeVetter et al. 2021). These synthetic biodegradable polymers are mostly derived from petroleum oil; however, efforts to create bio-based PBAT are underway. The PE mulch is made from synthetic resins created from the polymerization of ethylene molecules. Ethylene is a gas (C_2H_4) that is derived from petroleum oil, which is a nonrenewable resource (Hayes et al. 2019). Because of the high stability of its chemical structure, plastics made from PE do not easily interact with environmental factors and are considered nonbiodegradable; therefore, PE can reside in the environment for a few hundred years and contribute to persistent plastics in ecosystems (US Environmental Protection Agency 2024a, 2024b).

After feedstocks, the remaining mass of BDM includes additives that aid in film manufacturing and in-field performance (DeVetter et al. 2021). Plasticizers, lubricants, antioxidants, antibacterial agents, colorants, and pigments are examples of additives. Depending on the colorants and pigments, commercially available BDMs can be black, clear, green, white, and white-on-black. Black is the most common color of mulch film on the market because it increases soil temperature most effectively and blocks light transmission to the soil, which reduces weed growth (Markets and Markets 2023; Snyder et al. 2015). White mulch with black backing keeps the soil cooler while still preventing weed growth (Gheshm and Brown 2020; Snyder et al. 2015).

What is the brief history regarding BDM?

Since the 1950s, agriculture in the United States has relied on PE mulch for crop production in both small-scale and large-scale horticultural production systems; currently, PE mulch is an important weed management tool for organic crop production (Madrid et al. 2022; Mansoor et al. 2022). Degradable plastic mulch was introduced in the 1980s; however, rather than biodegrade, those mulches disintegrate, that is, they break apart into smaller pieces of plastic (Riggle 1998). In 1990, truly biodegradable plastic mulches were introduced after a call for research and development of biodegradable thermoplastics by the German government. Novamont SpA (Eschborn, Germany) manufactured the Mater-Bi® line (a blend of TPS and PBAT copolyester) in 1991, followed by line extrusion and injection molding grades created by Bayer BAK (Leverkusen, Germany) in 1996 (Novamont 2022). In 2009, the US Department of Agriculture (USDA) Specialty Crop Research Initiative program funded an investigation of BDM. By 2012, BASF (Ludwigshafen, Germany) had produced ecovio® mulch films, which expanded practical application of BDM (BASF 2013). Current research and development efforts are focused on increasing the biobased content of BDM, extending its functional field life, expanding its color options, and reducing its manufacturing costs because price is considered a primary factor that limits adoption.

Are there standards or certifications regulating BDM?

Biodegradability is a key attribute of BDM and is assessed as a product's inherent ability to degrade to carbon dioxide, methane, water, and microbial biomass after being metabolized by microorganisms (Yu and Flury 2024). Inherent biodegradability is determined by tests within a standard. The BDMs that meet international standards must adhere to specifications regarding dimensional, mechanical, ecotoxicity, biodegradation, and optical properties (European Committee for Standardization 2018). Table 1 lists existing biodegradability standards for BDM. The most common standards for BDM in the United States are EN 17033 (2018) for in-soil biodegradation and ASTM D6400 (2012) for compostability. EN 17033 tests biodegradation of BDM feedstocks under aerobic soil conditions, while ASTM D6400 evaluates biodegradability under industrial composting conditions using the ASTM D5338 test method. Tests within both these standards are performed in controlled laboratory settings. EN 17033 ensures that a BDM product meets performance specifications both during crop production and following soil incorporation. For example, BDM feedstocks must reach at least 90% biodegradation within 2 years and includes controlled

Received for publication 24 Mar 2025. Accepted for publication 23 Apr 2025.

Published online 20 Jun 2025.

[1]Department of Viticulture and Enology, Washington State University, Irrigated Agriculture Research and Extension Center, 24106 North Bunn Road, Prosser, WA 99350, USA

[2]Department of Horticulture, Washington State University, Northwestern Washington Research and Extension Center, 16650 State Route 536, Mount Vernon, WA 98273, USA

[3]Department of Environmental Science and Forestry, The Connecticut Agricultural Experiment Station, 123 Huntington Street, New Haven, CT 06511, USA

[4]Department of Crop and Soil Sciences, Washington State University, Northwestern Washington Research and Extension Center, 16650 State Route 536, Mt. Vernon, WA 98273, USA

Funding was provided by the USDA Specialty Crops Research Initiative Award 2022-51181-38325, Agriculture and Food Research Initiative Award 2023-68016-38933, and Organic Research and Extension Initiative 2021-51300-34909 from the USDA National Institute of Food and Agriculture. Additional support was provided by NIFA Hatch projects 7005372, 7003737, and W5188 Multi-State Project. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

We thank the reviewers, especially Markus Flury and Sam Wortman, for their critical examination and feedback.

C.A.M. is the corresponding author. E-mail: milesc@wsu.edu.

https://doi.org/10.21273/HORTTECH05652-25

Table 1. Standards for testing soil biodegradation or compostability of plastic mulch.

Standard organization	Standard name	Comments
European Committee for Standardization (CEN)	EN 17033 (2018) Plastics Biodegradable Mulch Films for Use in Agriculture and Horticulture—Requirements and Test Methods	First international standard directly pertaining to biodegradable mulches by an international organization.
Association Francaise de Normalisation (AFNOR)	NFU 52-001 (2005) Biodegradable Mulches for Use in Agriculture and Horticulture Mulching Products—Requirements and Test Methods	French standard pertaining to biodegradable mulches. This standard has been substituted by EN 17033.
Ente Nazionale Italiano di Unificazione	UNI 11495 (2013) Biodegradable Thermoplastic Materials for Use in Agriculture and Horticulture Mulching Films—Requirements and Test Methods	Italian standard pertaining to biodegradable mulches. This standard has been substituted by EN 17033.
ASTM International	ASTM D6400 (2012) Standard Specification for Labeling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities	Pertains directly to biodegradation under industrial composting conditions and is often misrepresented. International Organization for Standardization (ISO) has equivalent standard.
TUV Austria (formerly Vincotte)	OK Biodegradable SOIL (label)	Certifies that plastic materials will biodegrade fully and will not promote ecotoxicity in the soil.
State Administration for Market Regulation, People's Republic of China	GB/T 41010-2021 Degradability and identification requirements of biodegradable plastics and products	Includes biodegradability and content specifications and tests to ensure no phytotoxicity or ecotoxicity.

laboratory tests for ecotoxicity for plants, invertebrates, and microorganisms. The standard also regulates heavy metal content (e.g., zinc, chromium, copper, lead, nickel, cadmium, mercury) and prohibits the presence of substances of very high concern to ensure the BDM does not have a negative impact on the environment.

While EN 17033 specifies using agricultural or forest soil in the tests, results from standard tests do not always translate to the multitude of agricultural environments in the United States or elsewhere. Other standards regarding BDM, such as EN 14995, EN 13432, ISO 17088, and ASTM D5988-18, also do not include tests that account for the diversity of environments and climates that create variability in BDM biodegradation. For example, Griffin-LaHue et al. (2022) conducted an in-field degradation experiment during which they retrieved visible mulch fragments after 4 years of continuous application. They found that the in-field degradation rate based on calendar time was much slower than the laboratory standards. However, the in-field degradation rate would align better with the laboratory standards if thermal time was used to take into account the differences in temperature over the calendar year. Soil composition (proportions of clay, sand, silt, organic matter) and differing farm practices such as tillage and cover cropping can also influence BDM biodegradability. For example, the degradation of BDM in the Mediterranean climate of Western Washington (*Csb* in the Köppen-Geiger classification) was slower than that in the humid subtropical climate of Knoxville, TN, USA (*Cfa* in the Köppen-Geiger classification) (Beck et al. 2018; Sintim et al. 2020). Growers and crop consultants can assess the degradation rates of BDMs within their own climactic and soil conditions using established in-field burial protocols that assess visual degradation in mesh bags (Madrid et al. 2020).

In Nov 2021, China released standard GB/T 41010-2021 for biodegradable plastic with an implementation date of 1 Jun 2022 (State Administration for Market Regulation 2021). This standard requires biodegradable plastic to have an organic content (defined as volatile solid content) of at least 51% and meet minimum content requirements for heavy metals and other specified substances of very high concern, such as prohibited hazardous substances and substances classified as carcinogenic and mutagenic. The standard has two biodegradability requirements: 1) relative (overall) biodegradability must be at least 90%, and each single organic component of the material with a weight percentage of 1% or more must have an absolute biodegradability of at least 60% and 2) for mixtures and multiple combined materials, the total weight percentage of organic components must be less than 5% and each organic component with a weight percentage of less than 1% must be biodegradable. Biodegradability certification information is not required to be displayed for these components. The standard's biodegradable plastic labeling requirements include the use of the biodegradability mark/logo and the material(s) it is made with, its biodegradation environment (e.g., compost), the product standards or biodegradability measurement standards that the product complies with, and the product name (State Administration for Market Regulation 2021).

Some BDMs may be labeled with a certificate, such as TÜV Austria (formerly Vincotte) OK Biodegradable SOIL (Brunn/Gebirge, Austria) that certifies the feedstock material will fully biodegrade and not cause ecotoxicity in the soil. It is important to note that a certificate is not the same as a standard. For example, authorization of the TÜV Austria OK Biodegradable SOIL certificate is provided by European Bioplastics, an association that represents the interest of the European bioplastics industry.

What is the difference between deterioration, biodegradation, and decomposition?

The two terms "deterioration" and "degradation" are often incorrectly used in reference to BDM. Deterioration is the loss of physical or mechanical strength and is assessed through physical testing or visual observation of rips, tears, and holes as well as microscopic imaging. Degradation is the mineralization or conversion of polymer carbon to carbon dioxide, methane, or microbial biomass that results in changes in the chemical structure, physical properties, or appearance of BDM. Sometimes degradation is used interchangeably with decomposition, which is the breakdown or decay of material into smaller matter by decomposers like worms, fungi, and bacteria. The ASTM defines biodegradable plastics as plastics that degrade from the action of naturally occurring microorganisms in the environment such as bacteria, fungi, and algae. These microorganisms have metabolic pathways that degrade BDM (European Committee for Standardization 2018; Yu and Flury 2024).

What is the difference between biobased and biodegradable?

Biobased materials are derived from biological sources; for BDM, these include plants and microorganisms such as bacteria and yeast. Biodegradable refers to the breakdown of BDM by microorganisms into carbon dioxide, methane, water, and microbial biomass. Biodegradability is not based on biobased content. Synthetic polymers PBAT, PBS, PBSA, and PCL, which are commonly used to make BDM, are fully biodegradable. The USDA National Organic Program organic rule regarding BDM prohibits the use of BDM that is not 100% biobased even if that BDM meets the EN 17033 standard, which ensures biodegradability.

What factors are important for BDM degradation?

The BDM should degrade completely and not contribute to environmental plastic pollution and waste generation. Degradation is impacted by the inherent nature of the BDM polymer(s), additives within the BDM, and environmental factors in the degradation environment. The characteristics of the polymer(s) determine the inherent degradability of BDMs, while additives, especially ultraviolet stabilizers, influence how polymers are exposed to environmental conditions. Environmental factors that affect degradation can be divided into abiotic and biotic factors. Abiotic factors include soil moisture, temperature, pH, oxygen, wind, and ultraviolet radiation that can cause mulch weathering as well as deterioration (Kyrikou and Briassoulis 2007; Rizzarelli et al. 2021). Biotic factors include the microbial communities and their enzymes in the soil environment and the presence or absence of biosurfactants (Li et al. 2022; Shah et al. 2008). Soil temperature, moisture, and microbial composition, along with physicochemical changes of the BDMs resulting from environmental weathering, will influence the rate of BDM degradation (Anunciado et al. 2021; English 2019; Sintim et al. 2019a). In general, BDM degrades more quickly at higher soil temperatures and moisture, and cooler soil temperatures and drier conditions will slow BDM degradation (Anunciado et al. 2021; English 2019; Griffin-LaHue et al. 2022; Sintim et al. 2020). Crops and weeds contribute to the formation of holes and tears in BDM, which can cause the mulch to deteriorate and fragment (Anunciado et al. 2021). Degradation is also increased by farming practices such as tillage and cover cropping, which can reduce fragment size and increase edge area; the greater the edge area, the greater the exposure of BDM fragments to degrading soil microorganisms (Kasirajan and Ngouajio 2012; Serrano-Ruiz et al. 2021; Sintim et al. 2020). Anunciado et al. (2021) found that the addition of compost to soil significantly increased the degradation rate of BDM. In that study, after 16 weeks, BDM in compost-amended soil had 20% to 30% more mass loss compared with those in unamended soil, and the biodegradation of BDMs had the following order from highest to lowest: PLA/PHA > Bio360 > Naturecycle > Organix (Anunciado et al. 2021).

Studies based on visual assessments have shown that it takes several years for BDM to degrade completely in agricultural fields after soil incorporation (Griffin-LaHue et al. 2022; Li et al. 2024; Sintim et al. 2020). In a study that used five BDMs, BioAgri (Mater-Bi® & PBAT; Piracicaba, Brazil), an experimental blend of PLA/PHA (Ingeo® PLA and Mirel™ amorphous PHA; Metabolix, Inc., Cambridge, MA, USA), Naturecycle (starch-polyester blend; Burlington, WA, USA), Organix AG (BASF ecovio® PBAT + PLA; Organix Solutions, Blomington, MN, USA), and WeedGuardPlus (cellulose; Sunshine Paper Co., Aurora, CO, USA), visual assessments of macroscopic BDM fragments (>2.36 mm) revealed that after 4 years of annual BDM application (2015–2018) in Northwest Washington's cool Mediterranean climate, mulch recovery from the soil 1 year after final incorporation ranged from 23% to 64% of the total amount applied (based on area) (Ghimire et al. 2020). Recovery decreased to 4% to 16% (mass basis) 2 years after final mulch incorporation (Griffin-LaHue et al. 2022). In that study, only Naturecycle (a starch–polyester blend BDM) reached less than 10% recovery (90% degradation) within 2 years, while the other BDMs may require 2.5 to 5 years to reach 90% degradation based on a zeroth-order kinetics simulation model (Griffin-LaHue et al. 2022). These results indicate that BDM biodegrades at a steady rate even after repeated consecutive applications and in a relatively cool soil (maximum 16 °C at a 5-cm depth during summers) (2015–2020 average daily temperature, AgWeatherNet 2021, https//weather.wsu.edu).

Do BDMs contribute to microplastic and nanoplastic pollution?

The BDM is designed to deteriorate, fragment, and degrade in the soil; through these processes, micro-particles and nano-particles are formed (Yu et al. 2021). The terms "biodegradable microplastics" and "biodegradable nanoplastics" are used in scientific literature to describe micro-sized and nano-sized particles derived from biodegradable plastic. The terms are defined based on particle size ranges (microparticles are 100 nm to 5000 μm; nanoparticles are 1 to 100 nm) and composition of the polymeric material. Although the definitions are inherently neutral, the terms tend to convey negative connotations attributable to the potential threat of microplastics and nanoplastics to ecosystems and human health (Li et al. 2023; Lim et al. 2020). Studies have shown that BDM generates microplastics in a shorter timeframe than that of nonbiodegradable plastic mulch (e.g., PE), which is to be expected for several reasons. First, nonbiodegradable plastic mulch is retrieved from the field after harvest, whereas the intended end-of-life for BDM is soil incorporation through tillage. Second, biodegradable plastic breaks down in a relatively short timeframe, as mentioned (2–10 years), and fragments and microplastics reside in the soil during this period (Griffin-LaHue et al. 2022). Finally, with repeated annual BDM applications, a certain amount of biodegradable fragments and microparticles may be present in the soil until up to 10 years after the final application (Yu et al. 2021). Thus, while BDM generates greater amounts of microplastics in the soil in the short-term, the residence time of these microplastics is up to 10 years, which is substantially shorter than that of microplastics derived from nonbiodegradable mulch, which can be several hundred years. Given the shorter residence time of biodegradable microplastics and nanoplastics, and their assimilation into microbial communities, their potential negative impact on ecosystems is likely less than that of nonbiodegradable plastic, but research is needed for verification. While some studies have reported the potential for negative effects from biodegradable microplastics, many of these studies used microplastic concentrations far in excess of environmental realities (up to 700-times more than that which would occur with annual mulch application) (Degli-Innocenti 2024). The scientific community must discern studies that use relevant and reasonable concentration rates when investigating a response to biodegradable microplastic and nanoplastic particles. For example, Yu and Flury (2024) showed that with a conservative biodegradation rate of 10% per year for BDM, the maximum plastic mass in soil would be approximately 0.43 g/kg (equivalent to a weight percentage of 0.043% w/w).

Are residues released from BDM degradation?

The biodegradable polymers in BDM biodegrade in soil over a period of a few years; with repeated BDM use, a certain amount of biodegradable polymers will be present in the soil until a few years after the final BDM soil incorporation. The amount of BDM residues present in soil depends on the in-field degradation rate of the BDM as well as the number of BDM applications. Yu et al. (2021) used a linear model to estimate the amount of residual biodegradable polymers in soil following yearly BDM (PBAT-based) applications. Modeling showed that with a degradation rate of 10% per year, residual biodegradable polymers reached a steady concentration after 10 years of yearly BDM application. In contrast, when the model used a degradation rate of 50% per year, the residual biodegradable polymers reached a steady concentration within 2 years. In both model scenarios, once the application of BDM ceased, the amounts of biodegradable polymers and other degradable components of BDM steadily decreased in the soil until all were fully degraded within 2 or 10 years (50% and 10% degradation rates, respectively). In northwest Washington, 2 years after four consecutive BDM applications, only 4% to 16% of the original BDM mass remained (Griffin-LaHue et al. 2022). Skvorčinskienė et al. (2023) found that 100% corn starch-based packing peanuts fully degraded in a moist soil environment within 6 months, whereas the 100% corn starch compostable bag only changed color and had some surface changes, and plastics made from 100% PLA showed signs of deformation, increased rigidity, and loss of color. In that same study, bioplastics made from 90% biobased nylon plus petroleum-based plastics (PCL, PA, PP, PE) and plastic made with 30% polypropylene and 70% corn starch became malleable and soft. It is important to note that compostable plastics require temperatures of 50 to 60 °C to degrade, and PLA is compostable and generally considered to biodegrade slowly in soil because soil temperatures are usually below optimal degradation temperatures. Anunciado et al. (2021) found that under industrial composting, black BDM (ecovio®-based Organix AG; BASF) was slightly more compostable than white-on-black and clear versions of the same BDM product. The authors attributed this difference to the polymeric constituents of the mulch products and suggest that microbial degradation of PHA and starch is greater than that of PLA and PBAT.

The nonbiodegradable components of BDM (e.g., inorganic pigments and fillers) would likely accumulate in the soil after repeated BDM use; however, only a few studies have reported this issue (Li et al. 2022). For example, some studies have shown that BDM (PBAT-based and PHA/PLA-based) can release pigments such as carbon black and TiO_2 (used to make black and white-on-black mulch, respectively) during degradation in compost (Sintim et al. 2019b; Yu et al. 2023b). Although nonbiodegradable components may accumulate in soil, not all components pose a threat to soil and ecosystem health (Abbate et al. 2023; Van Roijen and Miller 2022). For example, some nonbiodegradable components that are commonly used as fillers in BDM, such as calcium carbonate, silica, and clay, are inert and occur naturally in the environment (Zang et al. 2020). Other components, such as silver nanoparticles, despite being anthropogenic and accumulating, would not cause adverse effects if the concentration is low, such as that from BDM degradation (Anjum et al. 2013). However, the long-term fate in the environment of nonbiodegradable components is unknown and, in general, their replacement with degradable components in the manufacture of BDM is recommended.

Another concern regarding BDM fragments and biodegradable microplastics is their potential to adsorb pesticides and other agrichemicals applied to the soil. Beriot et al. (2020) tested the sorption of pesticides with an oxo-degradable plastic mulch containing pro-oxidant additive and a low-density polyethylene mulch; it is important to note that neither of these mulches are soil-biodegradable. The sorption rate for the oxo-degradable plastic mulch was approximately 50% higher than that of the PE mulches for 20 of the 38 pesticide compounds tested. The authors speculated this could be attributable to the PBAT feedstock in the oxo-degradable plastic mulch and its affinity for those pesticidal compounds. It is important to consider that these tests were conducted via laboratory incubation, a technique that is not always comparable to field conditions. Research is needed to determine whether soil-incorporated BDM fragments and biodegradable microplastics adsorb pesticides and whether this impacts the biodegradation rate caused by inhibition of bacteria and fungi colonization. The active ingredient of the pesticides and other absorbed agrichemicals should also be considered.

Could BDM fragments impact plant health?

Concerns have been raised that BDM fragments in soil could negatively impact plant health or crop safety. To date, studies of the phytotoxicity potential of BDMs have used concentrations hundreds of times greater than those encountered in the field; therefore, results are inapplicable to actual field conditions (Degli-Innocenti 2024). Furthermore, experiments have been conducted in containers that limit the soil volume that plant roots can explore, which also does not relate to the natural soil–plant environment. It is crucial to carefully evaluate whether experimental methods are appropriate when interpreting current and emerging literature.

The same considerations apply to studies that assess soil health. For example, Serrano-Ruiz et al. (2021) found that polyhydroxybutyrate-based BDM fragments had greater negative impacts on plant growth and soil health compared with nonweathered BDM or soil without BDM. However, that study used a concentration of 4.5% weathered BDM fragments to soil, which greatly exceeded the 0.0063% concentration likely to be present in agricultural fields after a single application of BDM (Degli-Innocenti 2024). For example, PBAT-based and PL-based BDMs have been shown to degrade to 50 to 125 particles/kg after 3.5 years. Thus, the likelihood of achieving a concentration almost 1000-times greater than that of a single BDM application is essentially impossible (Li et al. 2023). Similarly, Qi et al. (2018) found that macroplastics and microplastics resulting from starch-based plastic mulches containing polybutylene terephthalate, pullulan, and polyethylene terephthalate can cause harmful effects on wheat (*Triticum aestivum*) growth compared with low-density polyethylene. However, this study used a 1% w/w concentration of mulch fragments to soil, and BDMs do not contain these nonbiodegradable polymers. Furthermore, the study was conducted in a controlled environment; therefore, results likely do not directly correlate with field investigations.

Does BDM degradation harm terrestrial and/or aquatic animals?

No studies to date have shown that BDM fragments or biodegradable microplastics pose problems to terrestrial and aquatic life. The EN 17033 (2018) standard requires BDM to be tested for ecotoxicity in soil systems, including toxic effects on plants, invertebrates, and microorganisms. Earthworms (*Lumbricus terrestris*) have been observed on the soil surface foraging on BDM microplastics made with PBAT and dragging fragments into their burrows to be ingested and incorporated into their casts; no acute toxicity after BDM ingestion has been observed (Adhikari et al. 2023; Zhang et al. 2018). Raman spectroscopy furthermore showed that PBAT-based BDM was modified after going through the earthworm gut, while PE did not undergo any modifications or changes after earthworm ingestion (Adhikari et al. 2023). To date, no studies have shown that insects are attracted specifically to BDM as a food source.

There is a concern that biodegradable microplastics may be bioaccumulated in plant tissue and then ingested by animals, including humans (Okeke et al. 2022). No studies to date have been conducted to investigate if biodegradable microplastics are bioaccumulated in plants or to assess if there are effects on livestock, wildlife, or humans that feed on plants grown with BDM. However, Bao et al. (2022) found that biodegradable plastic bags made with PLA, PBAT, and starch that were cut into 2.5-cm × 4-cm strips fragmented into microplastics and nanoplastics at a faster rate than that of PE bags. The authors speculated that biodegradable microplastics and nanoplastics may contribute to air pollution and respiratory diseases in animals, similarly to conventional plastics (Allen et al. 2019; Lim et al. 2021).

EN 17033 does not include ecotoxicity testing in freshwater aquatic or saltwater marine environments because BDM is not intended to be used or disposed of in those environments. However, BDM fragments and biodegradable microplastics may be carried by wind or runoff and be deposited in an aquatic environment. Because BDMs are not designed to degrade in water, this may lead to incomplete degradation and accumulation of biodegradable plastics in aquatic ecosystems (Nizzetto et al. 2016; Rosenboom et al. 2022; Schmidt et al. 2017). Studies have shown that PBAT-based plastics fragmented into microplastics after 10 weeks in freshwater and seawater when incubated in cell culture flasks with ventilated caps (Wei et al. 2021). Another study showed commercially available fruit and vegetable bags (F&V Ecobag; Erreti S.r.l., Solbiate Olona, Italy) made with Mater-Bi® HF03V (Novamont, Novara, Italy), a blend of TPS and PBAT, disintegrated in a simulated marine seafloor environment with a half-life ranging from 72 to 368 d, which was shortest when samples were placed on sediment with the coarsest grain size (Eich et al. 2021). Yu et al. (2023a) found that weathered biodegradable nanoplastics derived from PBAT were highly stable in freshwater, seawater, and soil pore water, suggesting they could migrate readily in aquatic environments.

In studies that investigated the impact of biodegradable plastic on the health of aquatic fauna, Klein et al. (2021) found that incorporating PLA microplastics into freshwater sediments reduced the survival of the freshwater California blackworm (*Lumbriculus variegatus*). However, Magni et al. (2020) found no adverse effects of biodegradable microplastics made with Mater-Bi® (a blend of TPS and PBAT copolyester) on zebra mussel (*Dreissena polymorpha*). The effects of BDM fragments on aquatic organisms will likely depend on fragment size, concentration, potential to block digestive systems, and the potential for feedstock to be metabolized as a food source. Further studies are still needed to assess the potential environmental risks associated with BDM and BDM-derived fragments in aquatic ecosystems.

What impact does BDM have on soil health?

Several studies have explored the impact of continuous application of BDM on soil health, including the chemical, physical, and biological components (Hayes et al. 2019; Serrano-Ruiz et al. 2021; Zhang et al. 2019; Zhou et al.

2023). For instance, Gao et al. (2021) compared the effects of PE and BDMs made from PLA and PBAT on soil properties and potato yield across two winter-planting seasons in Huizhou, Guangdong Province, China. The results showed that BDM residues improved soil bulk density and organic matter content after degradation in soil, and the authors concluded that BDM has the potential to replace PE mulch for potato production. Mazzon et al. (2022) investigated the impact of BDM film (Mater-Bi®) on soil quality, specifically microbial biomass, nitrogen cycling, and the activity of soil enzymes in loamy and sandy soil on two farms in northern Italy. Soil-incorporated BDM resulted in accelerated carbon mineralization, increased nitrogen immobilization, and greater microbial biomass (Mazzon et at. 2022). A comparative 2-year (2015–2016) study in northwest Washington and eastern Tennessee using pie pumpkin (*Cucurbita pepo*) showed that the geographical location and seasonal variations had a greater impact on soil properties, functions, and health indicators than the application and incorporation of BDM (BioAgri®, Naturecycle, Organix, and PLA/PHA-based) after 4 consecutive years of application (Sintim et al. 2019a). Soil collected from that study also showed that microbial community, structure, and function were more impacted by site and time of sampling than by BDM (Bandopadhyay et al. 2020).

Follow-up studies after 4 years of consecutive BDM application at the northwest Washington and eastern Tennessee sites similarly demonstrated no detrimental effects of PE mulch or BDM (BioAgri®, Naturecycle, Organix, and PLA/PHA-based) on soil microbial communities, their activities, or the overall accumulation of soil organic matter (English 2019; Liquet y Gonzalez and DeBruyn 2019). After 4 years of consecutive BDM application, winter wheat was cultivated at the northwestern Washington site for 2 years, and further research showed no negative effects on soil health or groundwater quality (Sintim et al. 2021). Di Mola et al. (2021) studied the impact of soil solarization on soil quality using both BDM (starch-based) and PE mulch in greenhouse conditions. The application of BDM prevented the accumulation of high ammonia concentrations in the soil caused by reduced soil water content and slightly lower temperatures compared with PE mulch. This effect was ascribed to the BDM providing favorable conditions for the growth of nitrifying bacteria (Di Mola et al. 2021).

Huang et al. (2022) focused on the effects of continuous use of biodegradable films on soil health in dryland maize production in northwest China. The results showed that PBAT-based BDM increased the soil carbon: nitrogen ratio and improved the soil nutrient environment. In another field study with maize in northeast China, Xue et al. (2023) found after 4 consecutive years, BDM (PBAT-based) application decreased the accumulation of fungal necromass carbon compared with no mulch and PE mulch, but bacterial necromass carbon and soil total carbon were unaffected. The BDM also decreased the amount of soil dissolved organic carbon. The authors suggested that BDM reduced fungal necromass carbon through changes in substrate availability, soil pH, and fungal community composition, and this would impact long-term soil carbon storage. While long-term field studies are needed to determine the impact of BDM on soil health, current results suggest that BDM has effects similar to those of PE mulch.

Is BDM allowed for use in certified organic production?

The USDA National Organic Program added biodegradable biobased plastic mulch to the list of allowed synthetic substances for organic crop production in Oct 2014. According to the organic standard (7 Code of Federal Regulations, Section 205.601), an acceptable BDM must: 1) not be produced using excluded methods (e.g., genetically modified organisms); 2) meet the compostability specifications of one of the following standards: ASTM D6400, ASTM D6868, EN 13432, EN 14995, or ISO 17088; 3) demonstrate at least 90% biodegradation absolute or relative to microcrystalline cellulose in less than 2 years in soil according to one of the following test methods: ISO 17556 or ASTM D5988; and 4) be biobased with content determined using ASTM D6866. Regarding the biobased percentage, the National Organic Program set a 100% requirement in 2014 but soon recognized that this was impractical in the short term. Public comments submitted to the National Organic Standards Board indicated that a biobased content of 20% to 50% was more feasible. In 2021, the National Organic Standards Board recommended lowering the minimum required biobased content from 100% to 80%, and advised that organic farmers should transition to BDM products with higher biobased content as they become commercially available (National Organic Program 2023; National Organic Standards Board 2021). However, the National Organic Program had not yet changed the rule requiring 100% biobased content by the time of this publication. Research in Italy is underway to test a BDM with 60% biobased content, but no mulch products with more than 20% biobased content are commercially available (Molyneux 2022). It is important to note that biobased content does not correlate with degradation (Bergeson et al. 2024), and the commercial production of biobased polymers is based on using genetically modified bacteria and yeast to increase efficiency and reduce costs. EN 17033 ensures that BDM feedstocks are fully biodegradable without negative impacts, but this standard is not included in the organic rule. It is also noteworthy that BDMs do meet compost standards, but compost made with BDM cannot be applied on certified organic farms in the United States.

What is the cost difference between BDM and PE mulch?

The purchase cost of BDM is generally 1.5-times to two-times more than that for PE mulch, but there are no indirect costs for BDM removal or disposal as there is with PE (Li et al. 2024). However, drip tube or drip tape must still be removed and disposed of if used. The BDM is tilled into the field at the end of the cropping season, and there is no additional cost when tillage is already a common end-of-season activity for farmers (Velandia et al. 2019). Additionally, farm labor can be used for farm activities other than mulch removal.

Can BDM function as fumigation tarp?

BDM is not currently listed by the US Environmental Protection Agency as an approved fumigation tarp for buffer zone reduction credits (DeVetter and Stanghellini 2020). However, BDM can be used after the restricted-entry interval for fumigants has passed, but their application during fumigation is not recommended because fumigation-induced degradation of the BDM may occur.

Are oxo-degradable plastics the same as BDM?

Oxo-degradable plastics (sometimes referred to as photodegradable) are not compostable or biodegradable; therefore, they are not equivalent to BDM. Oxo-degradable plastics are made from conventional materials like high-density polyethylene, low-density polyethylene, or polypropylene that are then combined with starch or other additives that cause the plastic to fragment when exposed to ultraviolet light, heat, or oxygen. These fragments persist in soil and aquatic environments and can move up the food chain, contributing potential ecological harm (Bao et al. 2024; Browne et al. 2008; Feuilloley et al. 2005; Thompson et al. 2004). Oxo-degradable plastic fragments further break down into microplastics, contributing to long-term environmental pollution. Despite being labeled as "biodegradable" by some manufacturers, oxo-degradable plastics fail to meet the soil biodegradability standard EN 17033 and should not be used in agriculture. Many growers who report dissatisfaction with BDM likely used an oxo-degradable plastic mulch because their lower price point can be appealing. Growers are encouraged to test BDM that meets biodegradability standards to determine if it is compatible with their production system.

Conclusions

Plastic mulch is a valuable tool in agriculture worldwide; to reduce its contribution to plastic pollution, BDM can be a suitable alternative. Although the purchase cost of BDM can be two-times that of PE mulch, when PE mulch removal and disposal costs are factored in, BDM can be less expensive because it is tilled into the soil at the end of the growing season. Compared with PE mulch, BDM poses fewer impacts on soil health and both terrestrial and aquatic organisms, and the risk potential appears relatively low for BDM regarding pesticide accumulation. Unlike PE mulch fragments that reside in the environment for dozens or several hundred years, BDM will only reside in the soil for several years (Griffin-LaHue et al. 2022; Li et al. 2024; Sintim et al. 2020). There is misunderstanding regarding the biodegradability of BDM because mulch marketers and some members of the scientific communities have not adhered to the definition of soil-biodegradable plastic. Additionally, inappropriate experimental methods have been used to test biodegradability, thereby resulting in misleading interpretations and outcomes (Qin et al. 2021). Thus, studies have claimed that BDM does not fully biodegrade when the plastic mulch used in the study is not actually biodegradable, or the BDM was tested at almost 1000-times the concentration that would naturally occur in real-world conditions. To eliminate this misinformation, mulch marketed as biodegradable should meet the EN 17033 standard, which verifies that BDM degrades into carbon dioxide, methane, water, and microbial biomass in soils without negatively impacting soil health, depositing heavy metals or substances of very high concern, or otherwise negatively impacting the environment. There is a need for research studies to use meaningful protocols, and publications should adhere to the definition of biodegradable plastics to stop misinformation regarding BDM.

Another misunderstanding in the agricultural community is in regard to the terms "biobased" and "biodegradable." There is a common belief that a BDM must be fully biobased to be fully biodegradable, which is not correct. Synthetic polymers that are commonly used to make BDM (PBAT, PBS, PBSA, and PCL) are fully biodegradable. The USDA National Organic Program organic rule regarding BDM prohibits the use of BDM that does not have 100% biobased content even though they meet the EN 17033 standard. This rule supports the continued use of PE mulch and the plastic pollution it contributes to the environment.

Long-term studies using field-relevant rates are needed to evaluate the impact of BDM fragments, biodegradable microparticles, and potential persistent residues on soil and agroecosystem health and function. Studies are also needed to gain a better understanding of biodegradable polymer technology, address any concerns, and build confidence within the agricultural community. These efforts should occur in parallel with the development of new BDM technologies that meet requirements for organic production, provide multifunctional benefits (e.g., add soil organic matter or essential plant nutrients), and use feedstock materials that promote circular economies. Concurrently, efforts are needed to promote PE mulch recycling in scenarios in which BDM is not a viable option, such as certified organic production or when leasing agreements do not permit BDM use. This encompasses improved PE mulch collection, aggregation, and densification strategies that minimize soil contamination on the mulch to minimize transport cost, reduce tipping fees, and facilitate recycling because of lower contaminant removal cost and risk of equipment damage.

References cited

Abbate C, Scavo A, Pesce GR, Fontanazza S, Restuccia A, Mauromicale G. 2023. Soil bioplastic mulches for agroecosystem sustainability: A comprehensive review. Agriculture. 13(1):197. https://doi.org/10.3390/agriculture13010197.

Adhikari K, Astner AF, DeBruyn JM, Yu Y, Hayes D, O'Callahan BT, Flury M. 2023. Interactions of earthworms with polyethylene and PBAT microplastics in soil: Microplastic characterization and microbial community analysis. ACS Agric Sci Technol. 3(4):340–349. https://doi.org/10.1021/acsagscitech.2c00333.

AgWeatherNet. 2021. Washington State University. AgWeatherNet, Mount Vernon, WA. http://weather.wsu.edu/. [accessed 14 May 2025].

Allen S, Allen D, Phoenix VR, Roux GL, Jiménez PD, Simonneau A, Binet S, Galop D. 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat Geosci. 12(5): 339–344. https://doi.org/10.1038/s41561-019-0335-5.

Anjum NA, Gill SS, Duarte AC, Pereira E, Ahmad I. 2013. Silver nanoparticles in soil–plant systems. J Nanopart Res. 15(9): 1896. https://doi.org/10.1007/s11051-013-1896-7.

Anunciado MB, Hayes DG, Astner AF, Wadsworth LC, Cowan-Banker CD, Liquet y Gonzalez J, EL, DeBruyn JM. 2021. Effect of environmental weathering on biodegradation of biodegradable plastic mulch films under ambient soil and composting conditions. J Polym and Environ. 29(9):2916–2931. https://doi.org/10.1007/s10924-021-02088-4.

Bandopadhyay S, Sintim HY, DeBruyn JM. 2020. Effects of biodegradable plastic film mulching on soil microbial communities in two agroecosystems. PeerJ. 8:e9015. https://doi.org/10.7717/peerj.9015.

Bao R, Pu J, Xie C, Mehmood T, Chen W, Gao L, Lin W, Su Y, Lin X, Peng L. 2022. Aging of biodegradable blended plastic generates microplastics and attached bacterial communities in air and aqueous environments. J Hazard Mater. 434:128891. https://doi.org/10.1016/j.jhazmat.2022.128891.

Bao X, Gu Y, Chen L, Wang Z, Pan H, Huang S, Meng Z, Chen X. 2024. Microplastics derived from plastic mulch films and their carrier function effect on the environmental risk of pesticides. Sci Total Environ. 924:171472. https://doi.org/10.1016/j.scitotenv.2024.171472.

Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data. 5(1):180214–180212. https://doi.org/10.1038/sdata.2018.214.

Bergeson AR, Silvera AJ, Alper HS. 2024. Bottlenecks in biobased approaches to plastic degradation. Nat Commun. 15(1):4715. https://doi.org/10.1038/s41467-024-49146-8.

Beriot N, Zomer P, Zornoza R, Geissen V. 2020. A laboratory comparison of the interactions between three plastic mulch types and 38 active substances found in pesticides. PeerJ. 8:e9876. https://doi.org/10.7717/peerj.9876.

Browne M, Dissanayake A, Galloway T, Lowe D, Thompson R. 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). Environ Sci Technol. 42(13):5026–5031. https://doi.org/10.1021/es800249a.

Degli-Innocenti F. 2024. The pathology of hype, hyperbole and publication bias is creating an unwarranted concern towards biodegradable mulch films. J Hazard Mater. 463:132923. https://doi.org/10.1016/j.jhazmat.2023.132923.

Dentzman K, Goldberger JR. 2020. Plastic scraps: Biodegradable mulch films and the aesthetics of 'good farming' in US specialty crop production. Agric Hum Values. 37(1):83–96. https://doi.org/10.1007/s10460-019-09970-x.

DeVetter L, Stanghellini M. 2020. Soil fumigation and biodegradable plastic mulch application. https://s3.wp.wsu.edu/uploads/sites/2181/2020/09/Soil-Fumigation-and-Biodegradable-Plastic_Final-for-2020.pdf. [accessed 25 Nov 2024].

DeVetter L, Shrestha S, Hayes D. 2021. What is a soil-biodegradable plastic mulch composed of? https://s3.wp.wsu.edu/uploads/sites/2181/2021/07/What-is-in-a-BDM.pdf. [accessed 26 Nov 2024].

Di Mola I, Ventorino V, Cozzolino E, Ottaiano L, Romano I, Duri LG, Pepe O, Mori M. 2021. Biodegradable mulching vs traditional polyethylene film for sustainable solarization: Chemical properties and microbial community response to soil management. Applied Soil Ecology. 163:103921. https://doi.org/10.1016/j.apsoil.2021.103921.

Eich A, Weber M, Lott C. 2021. Disintegration half-life of biodegradable plastic films on different marine beach sediments. PeerJ. 9:e11981. https://doi.org/10.7717/peerj.11981.

English ME. 2019. The role of biodegradable plastic mulches in soil organic carbon cycling (Degree Diss). University of Tennessee, Knoxville, TN, USA. https://trace.tennessee.edu/utk_gradthes/5412/.

European Committee for Standardization. 2018. EN 17033: Plastics-biodegradable mulch films for use in agriculture and horticulture-requirements and test methods. Brussels, Belgium.

Feuilloley P, César G, Benguigui L, Grohens Y, Pillin I, Bewa H, Lefaux S, Jamal M. 2005. Degradation of polyethylene designed for agricultural purposes. J Polym and Environ. 13(4):349–355. https://doi.org/10.1007/s10924-005-5529-9.

Gao X, Xie D, Yang C. 2021. Effects of a PLA/PBAT biodegradable film mulch as a replacement of polyethylene film and their residues on crop and soil environment. Agric Water Manage. 255:107053. https://doi.org/10.1016/j.agwat.2021.107053.

Gheshm R, Brown RN. 2020. The effects of black and white plastic mulch on soil temperature and yield of crisphead lettuce in Southern New England. HortTechnology. 30(6):781–788. https://doi.org/10.21273/HORTTECH04674-20.

Ghimire S, Flury M, Scheenstra EJ, Miles C. 2020. Sampling and degradation of biodegradable plastic and paper mulches in field after tillage incorporation. Sci Total Environ. 703:135577. https://doi.org/10.1016/j.scitotenv.2019.135577.

Goldberger JR, Jones RE, Miles C, Wallace RW, Inglis DA. 2015. Barriers and bridges to the adoption of biodegradable plastic mulches for US specialty crop production. Renew Agric Food Syst. 30(2):143–153. https://doi.org/10.1017/S1742170513000276.

Goldberger JR, DeVetter LW, Dentzman KE. 2019. Polyethylene and biodegradable plastic mulches for strawberry production in the United States: Experiences and opinions of growers in three regions. HortTechnology. 29(5):619–628. https://doi.org/10.21273/HORTTECH04393-19.

Griffin-LaHue D, Ghimire S, Yu Y, Scheenstra EJ, Miles C, Flury M. 2022. In-field degradation of soil-biodegradable plastic mulch films in a Mediterranean climate. Sci Total Environ. 806(Pt 1):150238. https://doi.org/10.1016/j.scitotenv.2021.150238.

Hayes DG, Anunciado MB, DeBruyn JM, Bandopadhyay S, Schaeffer S, English M, Ghimire S, Miles C, Flury M, Sintim HY. 2019. Biodegradable plastic mulch films for sustainable specialty crop production, p 183–213. In: Gutiérrez T (eds). Polymers for agri-food applications. Springer, Cham. https://doi.org/10.1007/978-3-030-19416-1_11.

Hofmann T, Ghoshal S, Tufenkji N, Adamowski JF, Bayen S, Chen Q, Demokritou P, Flury M, Hüffer T, Ivleva NP, Ji R, Leask RL, Maric M, Mitrano DM, Sander M, Pahl S, Rillig MC, Walker TR, White JC, Wilkinson KJ. 2023. Plastics can be used more sustainably in agriculture. Commun Earth Environ. 4(1):332. https://doi.org/10.1038/s43247-023-00982-4.

Huang F, Wang B, Li Z, Liu Z, Wu P, Wang J, Ye X, Zhang P, Jia Z. 2022. Continuous years of biodegradable film mulching enhances the soil environment and maize yield sustainability in the dryland of northwest China. Field Crops Res. 288:108698. https://doi.org/10.1016/j.fcr.2022.108698.

Kasirajan S, Ngouajio M. 2012. Polyethylene and biodegradable mulches for agricultural applications: A review. Agron Sustain Dev. 32(2):501–529. https://doi.org/10.1007/s13593-011-0068-3.

Klein K, Piana T, Lauschke T, Schweyen P, Dierkes G, Ternes T, Schulte-Oehlmann U, Oehlmann J. 2021. Chemicals associated with biodegradable microplastic drive the toxicity to the freshwater oligochaete *Lumbriculus variegatus*. Aquat Toxicol. 231:105723. https://doi.org/10.1016/j.aquatox.2020.105723.

Kyrikou I, Briassoulis D. 2007. Biodegradation of agricultural plastic films: A critical review. J Polym and Environ. 15(2):125–150. https://doi.org/10.1007/s10924-007-0053-8.

Li S, Ding F, Flury M, Wang Z, Xu L, Li S, Jones DL, Wang J. 2022. Macro- and microplastic accumulation in soil after 32 years of plastic film mulching. Environ Pollut. 300:118945. https://doi.org/10.1016/j.envpol.2022.118945.

Li S, Ding F, Flury M, Wang J. 2023. Dynamics of macroplastics and microplastics formed by biodegradable mulch film in an agricultural field. Sci Total Environ. 894:164674. https://doi.org/10.1016/j.scitotenv.2023.164674.

Li X, Zheng G, Li Z, Fu P. 2024. Formulation, performance and environmental/agricultural benefit analysis of biomass-based biodegradable mulch films: A review. Europ Polym J. 203:112663. https://doi.org/10.1016/j.eurpolymj.2023.112663.

Lim D, Jeong J, Song KS, Sung JH, Oh SM, Choi J. 2021. Inhalation toxicity of polystyrene micro(nano)plastics using modified OECD TG 412. Chemosphere. 262: 128330. https://doi.org/10.1016/j.chemosphere.2020.128330.

Liquet y Gonzalez J, DeBruyn J. 2019. Effects of long-term use and incorporation of biodegradable plastic mulch films on soil microbial community structure and activity (Degree Diss). University of Tennessee, Knoxville, TN, USA. https://trace.tennessee.edu/utk_gradthes/5573.

Liu EK, He WQ, Yan CR. 2014. White revolution to white pollution—agricultural plastic film mulch in China. Environ Res Lett. 9. https://doi.org/10.1088/1748-9326/9/9/091001.9:091001.

Mansoor Z, Tchuenbou-Magaia F, Kowalczuk M, Adamus G, Manning G, Parati M, Radecka I, Khan H. 2022. Polymers use as mulch films in agriculture—a review of history, problems and current trends. Polymers Basel. 14(23):5062. https://doi.org/10.3390/polym14235062.

Markets and Markets. 2023. Mulch films market size, share, industry growth, trends report by type (clear/transparent, black mulch, colored mulch, photo-selective mulch, degradable mulch), application (agricultural and horticultural), element (LLDPE, LDPE, HDPE, EVA, PLA, PHA) and region – global forecast to 2028. https://www.marketsandmarkets.com/Market-Reports/mulch-films-market-220908278.html. [accessed 18 Jun 2024].

Madrid B, Zhang H, Miles C, Flury M, Sintim HY, Ghimire S, DeVetter LW. 2020. Assessing degradation of soil-biodegradable plastic mulches. https://smallfruits.wsu.edu/documents/2023/06/mesh-bag-sampling.pdf/. [accessed 14 Jun 2024].

Madrid B, Goldberger JR, Miles C, DeVetter LW. 2022. Risk and uncertainty of plastic mulch adoption in raspberry production systems. Renew Agri and Food Sys. 37(6):660–671. https://doi.org/10.1017/S1742170522000291.

Magni S, Bonasoro F, Torre CD, Parenti CC, Maggioni D, Binelli A. 2020. Plastics and biodegradable plastics: Ecotoxicity comparison between polyvinylchloride and Mater-Bi(R) micro-debris in a freshwater biological model. Sci Total Environ. 720:137602. https://doi.org/10.1016/j.scitotenv.2020.137602.

Mazzon M, Gioacchini P, Montecchio D, Rapisarda S, Ciavatta C, Marzadori C. 2022. Biodegradable plastics: Effects on functionality and fertility of two different soils. Appl Soil Ecol. 169:104216. https://doi.org/10.1016/j.apsoil.2021.104216.

Molyneux CG. 2022. Italy transposes into national law the EU single-use plastic products directive. Inside Energy and Environment. https://www.insideenergyandenvironment.com/2022/01/italy-transposes-into-national-law-the-eu-single-use-plastic-products-directive/. [accessed 19 Jan 2025].

National Organic Standards Board. 2021. Formal recommendation by the National Organic Standards Board (NOSB) to the National Organic Program (NOP): Biodegradable biobased mulch film (BBMF) biobased content percentage. US Department of Agriculture, Washington, DC, USA. https://www.ams.usda.gov/rules-regulations/organic/petitioned-substances/biodegradable-biobased-mulch-films. [accessed 15 Feb 2025].

National Organic Program 2023. Memorandum to the National Organic Standards Board: Work agenda request on biodegradable biobased mulch film (BBMF). US Department of Agriculture, Washington, DC, USA. https://www.ams.usda.gov/rules-regulations/organic/petitioned-substances/biodegradable-biobased-mulch-films. [accessed 18 Feb 2025].

Nizzetto L, Bussi G, Futter MN, Butterfield D, Whitehead PG. 2016. A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments. Environ Sci Process Impacts. 18(8):1050–1059. https://doi.org/10.1039/c6em00206d.

Novamont 2022. Biodegradable and compostable mulch film user manual. Novamont, Novara, Italy. https://agro.novamont.com/public/Documenti/manuale-pacciamatura_EN_LR_senza-logo-FSC.pdf. [accessed 14 May 2025].

Okeke ES, Okoye CO, Atakpa EO, Ita RE, Nyaruaba R, Mgbechidinma CL, Akan OD. 2022. Microplastics in agroecosystems-impacts on ecosystem functions and food chain. Resources, Conservation and Recycling. 177:105961. https://doi.org/10.1016/j.resconrec.2021.105961.

Qi Y, Yang X, Pelaez AM, Huerta Lwanga E, Beriot N, Gertsen H, Garbeva P, Geissen V. 2018. Macro- and microplastics in soil-plant system: Effects of plastic mulch film residues on wheat (*Triticum aestivum*) growth. Sci Total Environ. 645:1048–1056. https://doi.org/10.1016/j.scitotenv.2018.07.229.

Qin M, Chen C, Song B, Shen M, Cao W, Yang H, Zeng G, Gong J. 2021. A review of biodegradable plastics to biodegradable microplastics: Another ecological threat to soil environments? Journal of Cleaner Production. 312:127816. https://doi.org/10.1016/j.jclepro.2021.127816.

Riggle D. 1998. Moving toward consensus on degradable plastic. Biocycle. 39:64–65. https://archive.org/details/sim_biocycle_1998_39_index.

Rizzarelli P, Rapisarda M, Ascione L, Degli Innocenti F, La Mantia FP. 2021. Influence of photo-oxidation on the performance and soil degradation of oxo-and biodegradable polymer-based items for agricultural applications. Polym Degradation and Stability. 188:109578. https://doi.org/10.1016/j.polymdegradstab.2021.109578.

Rosenboom JG, Langer R, Traverso G. 2022. Bioplastics for a circular economy. Nat Rev Mater. 7(2):117–137. https://doi.org/10.1038/s41578-021-00407-8.

Serrano-Ruiz H, Martin-Closas L, Pelacho AM. 2021. Biodegradable plastic mulches: Impact on the agricultural biotic environment. Sci Total Environ. 750:141228. https://doi.org/10.1016/j.scitotenv.2020.141228.

Shah A, Hasan A, Hameed F, Ahmed A. 2008. Biological degradation of plastics: A comprehensive review. Biotechnol Adv. 26(3):246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005.

Schmidt C, Krauth T, Wagner S. 2017. Export of plastic debris by rivers into the sea. Environ Sci Technol. 51(21):12246–12253. https://doi.org/10.1021/acs.est.7b02368.

Shrestha S, DeVetter LW, Miles C, Mejia-Munoz J, Krone P, Bolda M, Ghimire S. 2023. Building agricultural knowledge of soil-biodegradable plastic mulch. HortTechnology. 33(5):455–463. https://doi.org/10.21273/HORTTECH05248-23.

Sintim H, Flury M. 2017. Is biodegradable plastic mulch the solution to agriculture's plastic problem? Environ Sci Technol. 51(3):1068–1069. https://doi.org/10.1021/acs.est.6b06042.

Sintim HY, Bandopadhyay S, English ME, Bary AI, DeBruyn JM, Schaeffer SM, Miles CA, Reganold JP, Flury M. 2019a. Impacts of biodegradable plastic mulches on soil health. Agric Ecosyst Environ. 273:36–49. https://doi.org/10.1016/j.agee.2018.12.002.

Sintim HY, Bary AI, Hayes D, English ME, Schaeffer SM, Miles C, Zelenyuk A, Suski K, Flury M. 2019b. Release of micro- and nano-particles from biodegradable plastic during in situ composting. Sci Total Environ. 675:686–693. https://doi.org/10.1016/j.scitotenv.2019.04.179.

Sintim HY, Bary AI, Hayes D, Wadsworth LC, Anunciado MB, English ME, Bandopadhyay S, Schaeffer SM, DeBruyn JM, Miles C, Reganold JP, Flury M. 2020. In situ degradation of biodegradable plastic mulch films in compost and agricultural soils. Sci Total Environ. 727:138668. https://doi.org/10.1016/j.scitotenv.2020.138668.

Sintim HY, Bandopadhyay S, English ME, Bary A, González JE, DeBruyn JM, Schaeffer SM, Miles C, Flury M. 2021. Four years of continuous use of soil-biodegradable plastic mulch: Impact on soil and groundwater quality. Geoderma. 381:114665. https://doi.org/10.1016/j.geoderma.2020.114665.

Skvorčinskienė R, Kiminaitė I, Vorotinskienė L, Jančauskas A, Paulauskas R. 2023. Complex study of bioplastics: Degradation in soil and characterization by FTIR-ATR and FTIR-TGA methods. Energy. 274:127320. https://doi.org/10.1016/j.energy.2023.127320.

Snyder K, Grant A, Murray C, Wolff B. 2015. The effects of plastic mulch systems on soil temperature and moisture in Central Ontario. HortTechnology. 25(2):162–170. https://doi.org/10.21273/HORTTECH.25.2.162.

State Administration for Market Regulation. 2021. GB/T 41010-2021 Degradability and identification requirements of biodegradable plastics and products (English Version). The Standardization Administration of the People's Republic of China, Beijing, China. https://www.codeofchina.com/standard/GBT41010-2021.html.

Thompson R, Olsen Y, Mitchell R, Davis A, Rowland S, John A, McGonigle D, Russell A. 2004. Lost at sea: Where is all the plastic? Science. 304(5672):838. https://doi.org/10.1126/science.1094559.

Tofanelli MB, Wortman SE. 2020. Benchmarking the agronomic performance of biodegradable mulches against polyethylene mulch film: A meta-analysis. Agronomy. 10(10):1618. https://doi.org/10.3390/agronomy10101618.

United Nations Environment Programme. 2022. Plastics in agriculture – an environmental challenge. https://wedocs.unep.org/bitstream/handle/20.500.11822/40403/Plastics_Agriculture.pdf. [accessed 18 Jun. 2024].

US Environmental Protection Agency. 2024a. Tarps. https://www.epa.gov/soil-fumigants/tarps. [accessed 18 Jan 2025].

US Environmental Protection Agency. 2024b. Impacts of plastic pollution. https://www.epa.gov/plastics/impacts-plastic-pollution. [accessed 11 Feb 2025].

Van Roijen EC, Miller SA. 2022. A review of bioplastics at end-of-life: Linking experimental biodegradation studies and life cycle impact assessments. Resources, Conservation and Recycling. 181:106236. https://doi.org/10.1016/j.resconrec.2022.106236. [accessed 18 Jan 2025].

Velandia M, Galinato S, Wszelaki A. 2019. Economic evaluation of biodegradable plastic films in Tennessee pumpkin production. Agronomy. 10(1):51. https://doi.org/10.3390/agronomy10010051.

Wei XF, Bohlen M, Lindblad C, Hedenqvist M, Hakonen A. 2021. Microplastics generated from a biodegradable plastic in freshwater and seawater. Water Res. 198:117123. https://doi.org/10.1016/j.watres.2021.117123.

Xiong L, Li Z, Shah F, Wang P, Yuan Q, Wu W. 2024. Biodegradable mulch film enhances the environmental sustainability compared with traditional polyethylene film from multidimensional perspectives. Chem Engin J. 492:152219. https://doi.org/10.1016/j.cej.2024.152219.

Xue Y, Zhao F, Sun Z, Bai W, Zhang Y, Zhang Z, Yang N, Feng C, Feng L. 2023. Long-term mulching of biodegradable plastic film decreased fungal necromass C with potential consequences for soil C storage. Chemosphere. 337:139280. https://doi.org/10.1016/j.chemosphere.2023.139280.

Yu Y, Griffin-LaHue DE, Miles C, Hayes D, Flury M. 2021. Are micro- and nanoplastics from soil-biodegradable plastic mulches an environmental concern? J Hazard Mater Adv. 4:100024. https://doi.org/10.1016/j.hazadv.2021.100024.

Yu Y, Astner AF, Zahid TM, Chowdhury I, Hayes D, Flury M. 2023a. Aggregation kinetics and stability of biodegradable nanoplastics in aquatic environments: Effects of UV-weathering and proteins. Water Res. 239:120018. https://doi.org/10.1016/j.watres.2023.120018.

Yu Y, Velandia M, Hayes DG, DeVetter LW, Miles CA, Flury M. 2023b. Biodegradable plastics as alternatives for polyethylene mulch films. Adv Agron. 183:121–192. https://doi.org/10.1016/bs.agron.2023.10.003.

Yu Y, Flury M. 2024. Unlocking the potentials of biodegradable plastics with proper management and evaluation at environmentally relevant concentrations. Npj Mat Sustain. 2(1):1–7. https://doi.org/10.1038/s44296-024-00012-0.

Zang H, Zhou J, Marshall MR, Chadwick DR, Wen Y, Jones DL. 2020. Microplastics in the agroecosystem: Are they an emerging threat to the plant-soil system? Soil Biology and Biochemistry. 148:107926. https://doi.org/10.1016/j.soilbio.2020.107926.

Zhang L, Sintim HY, Bary AI, Hayes D, Wadsworth LC, Anunciado MB, Flury M. 2018. Interaction of *Lumbricus terrestris* with macroscopic polyethylene and biodegradable plastic mulch. Sci Total Environ. 635:1600–1608. https://doi.org/10.1016/j.scitotenv.2018.04.054.

Zhang M, Zhao Y, Qin X, Jia W, Chai L, Huang M, Huang Y. 2019. Microplastics from mulching film is a distinct habitat for bacteria in farmland soil. Sci Total Environ. 688:470–478. https://doi.org/10.1016/j.scitotenv.2019.06.108.

Zhou J, Jia R, Brown RW, Yang Y, Zeng Z, Jones DL, Zang H. 2023. The long-term uncertainty of biodegradable mulch film residues and associated microplastics pollution on plant-soil health. J Hazard Mater. 442:130055. https://doi.org/10.1016/j.jhazmat.2022.130055.