

Suitability of Biodegradable Plastic Mulches for Organic and Sustainable Agricultural Production Systems

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Abstract. Biodegradable plastic mulch has the potential to be a sustainable technology in agricultural production systems if the mulch performs equally to polyethylene (PE) mulch and biodegrades completely into constituents that do not harm the soil ecology or environment. Reduced labor costs for removal and disposal, and reduced landfill waste add further appeal to the sustainability of biodegradable plastic mulch. Biodegradable paper mulch has been allowed in certified organic production systems in the United States for many years, while the National Organic Program (NOP) added biodegradable biobased plastic mulch to the list of allowed synthetic substances for organic crop production in Oct. 2014. Although biodegradable plastic mulch may meet the NOP biodegradability requirements (90% biodegradation within 2 years), currently no products have been approved for use in certified organic production because, so far, none meet the requirement of being completely biobased. Additionally, while the synthetic manufacturing processes that are used to make biodegradable plastic mulch are allowed by the NOP, the use of genetically modified organisms (GMOs) in the feedstocks, including their fermentation, is not allowed. Organic growers are advised always to check with their certifier before applying a product as some biodegradable mulch manufacturers and marketers erroneously advertise their product as “organic.” Looking forward, if biodegradable plastic mulch meets the NOP requirement of 90% biodegradation after 2 years, there is a possibility that 10% of plastic mulch residuals will persist (if the mulch contains nonbiodegradable ingredients); in this case, after 8 years of annual biodegradable mulch application, plastic residuals in the soil would exceed twice the amount of mulch applied per year. The current methods used by the NOP to test mulch biodegradation are laboratory based and it is uncertain if the results accurately represent field conditions. Reliable field sampling methods to measure residual mulch fragments in the soil need to be developed; however, it is unlikely such field tests will measure CO₂ evolution, and thus will not be a true measure of biodegradation. Additional testing is needed under diverse field conditions to accurately quantify the rate and extent of biodegradation of mulch products that are marketed as biodegradable.

Biodegradable plastic mulch was introduced in the 1990s as an alternative to PE mulch, which has been used in agriculture

worldwide since the early 1960s to control weeds, conserve soil moisture, modify soil temperature, shorten time to harvest, and increase crop yield and quality (Kasirajan and Ngouajio, 2012; Kyrikou and Briassoulis, 2007; Miles et al., 2012; Sarnacke and Wildes, 2008). Plastic mulch is more flexible, easier to apply mechanically, and less expensive than natural mulches (e.g., straw, woodchips). However, PE mulch removal and disposal can be costly (Galinato et al., 2012; Galinato and Walters, 2012; Ghimire and Miles, 2016), and there are only a handful of agricultural plastic recyclers that will accept PE mulch due to the large amount of soil contamination (up to 70% by weight). It is estimated that less than 10% of agricultural PE mulch generated in the United States is currently recycled, with the majority being landfilled or burned in the field at the end of

the growing season (G. Jones, personal communication; Grossman, 2015; Levitan and Barros, 2003). Although PE mulch recycling is well established in central Europe, in many other regions of the world, PE mulch is tilled into the field or is dumped in adjacent areas, creating a significant waste issue (Liu et al., 2014; PlasticsEurope, 2015; Scarascia-Mugnozza et al., 2011).

Biodegradable plastic mulch that performs similar to PE mulch during the cropping season and can be tilled into the field at the end of the season without compromising soil quality or the environment could be an asset for sustainable agriculture. It is worth noting that if biodegradable mulch enters the plastic recycling stream it will contaminate the recycled feedstock, resulting in unusable end product; thus, on-site disposal of biodegradable mulch is most desirable. Although there are several plastic mulch products on the market that are advertised as biodegradable, none of these have been evaluated in long-term studies to determine the rate and extent of biodegradation under agricultural field conditions. Until research addresses this information gap, growers and agricultural professionals must rely on information regarding the constituents of mulch as well as feedback provided by mulch manufacturers to anticipate how the mulch will biodegrade in fields after soil incorporation.

Organic and sustainable growers are particularly interested in the opportunity to use a biodegradable plastic mulch (Goldberger et al., 2015). PE mulch has long been allowed for use in organic crop production [U.S. Department of Agriculture (USDA), 2014a]; however, it was only on 30 Oct. 2014 that the USDA NOP passed a final rule that added biodegradable biobased plastic mulch to their list of allowed synthetic substances [7 Code of Federal Regulations (CFR), Section 205.601; USDA, 2014b]. Before this, the only synthetic biodegradable mulch allowed in certified organic production was paper mulch. On 22 Jan. 2015, the NOP clarified that the polymer feedstocks used to make biodegradable mulch must be completely biobased (USDA, 2015). According to the new rule, the primary requirements for a mulch to be considered biodegradable and biobased are that a mulch film must:

1. Reach at least 90% biodegradation in the soil within 2 years or less as evaluated using standardized tests such as International Organization for Standardization (ISO) 17556 or ASTM International D5988.
2. Fulfill criteria for being biobased as evaluated using standardized tests such as ASTM D6866.
3. Meet compostability specifications of either ASTM D6400, ASTM D6868, European Standards (EN) 13432, EN 14995, or ISO 17088 (7 CFR, Section 205.2).

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4. Be produced without organisms or feedstock derived from excluded methods [7 CFR, Section 205.601(b)(2)(iii)].

The objective of this paper is to broaden the understanding of biodegradable plastic mulch and its potential suitability for organic and sustainable cropping systems. The definition of “biobased” is reviewed along with the composition, manufacturing methods, and use of minor additives in biodegradable mulches. Further, biodegradation of common mulch feedstocks in general, and expected in-soil biodegradation potential in particular, are discussed, along with potential for accumulation of mulch residuals in the soil after repeated applications. Although the focus is on certified organic systems, how biodegradable mulches may complement or detract from the sustainability of conventional and other alternative production systems is also addressed.

Common Biobased and Synthetic Biodegradable Plastic Feedstocks

Although biodegradation of plastic mulch varies with climate (temperature, moisture, and solar radiation) and soil type, the rate and amount of biodegradation depends to a great extent on the feedstocks that are used in the product formulation. Biodegradable plastic feedstocks can be biobased or derived from fossil fuels, or a blend of the two. Biobased feedstocks are derived from renewable resources, that is, plant and/or animal mass derived from carbon dioxide recently fixed by photosynthesis (ASTM, 2012). ASTM D6866, the most commonly used standardized testing method in the United States for biobased certification, uses radiocarbon analysis to measure the level of carbon-14 (^{14}C) in a material as a percent of the weight of total carbon. Products that contain ^{14}C are considered biobased as this carbon isotope is only found at trace levels in fossil fuels. For this ASTM standardized test, only the feedstocks used to make the biodegradable plastic require radiocarbon analysis, whereas other minor ingredients (e.g., plasticizers, nucleating agents, lubricants, and colorants/dyes) do not need to be tested.

Biobased polymers that are used for feedstocks in biodegradable mulch can be divided into three categories: 1) extracted directly from natural materials, such as the polysaccharides starch and cellulose; 2) produced by chemical synthesis from biologically derived monomers, such as polylactic acid (PLA) formed by synthetic polymerization of lactic acid, commonly derived from plants via fermentation; and 3) produced by microorganisms, such as polyhydroxyalkanoates (PHA) (Jamshidian et al., 2010). The most common biobased feedstocks used to make biodegradable plastic mulches are starch, PLA, and PHA (Table 1).

Starch is a natural polysaccharide composed of straight-chain amylose and short-chain, branched amylopectin. Starch used to

make biodegradable plastic is frequently derived from corn (*Zea mays*), sugar beet (*Beta vulgaris*), switchgrass (*Panicum virgatum*), and sugarcane (*Saccharum officinarum*). High-amylose starch is processed into thermoplastic starch (TPS) by extrusion with water and organic alcohols (usually glycerol, a biobased coproduct from biodiesel manufacturing) at relatively high temperatures (Van Soest et al., 1995). Starch sourced in the United States may be derived from GMOs, specifically corn or sugar beets, which is not permitted in certified organic agriculture as GMOs are an excluded method (USDA, 2013). Currently, biobased mulches are not tested for GMOs as it is unsure whether broad-spectrum qualitative polymerase chain reaction tests will be informative as DNA may be degraded after fermentation and processing to the point where GMO status is nonquantifiable.

Plasticizers are additives, which improve the mechanical and flow properties of the plastic during processing, and can affect postextrusion characteristics of the plastic. The primary plasticizers that are added to TPS are alcohol (principally glycerol), polyoxyalkenes, and surfactants (Shanks and Kong, 2012). TPS costs less than other starch feedstocks, and thus, currently is the most common biobased feedstock used in biodegradable plastic mulches (Averous, 2004; Clerici, 2012; D. Mathes, personal communication). Chemically modified starch contains organic acyl groups esterified to free hydroxyls of starch, and improves the stability of the plastic end product by diminishing hydrogen bonding and moisture sensitivity.

PLA, discovered in 1932, is a thermoplastic polyester derived from starch. To produce PLA, starch is fermented by yeasts (e.g., *Saccharomyces* sp.) or other microorganisms to produce lactic acid, which is then polymerized synthetically through a series of reaction steps. PLA can be produced relatively inexpensively in large quantities compared with other biobased biopolymers (Hayes et al., 2012; Jamshidian et al., 2010). PHA is a polyester created by a natural, one-step bacterial fermentation of plant sugars and/or lipids. Over 90 genera of bacteria can produce PHA (Kim et al., 2007). Poly(hydroxybutyrate) and poly(hydroxyvalerate) are the two most important commercial PHAs. PHA copolymers or copolymer-starch blends tend to degrade more rapidly than PLA-based products (Gilmore et al., 1993). Advances in biosynthesis and processing methods, along with investments in commercial facilities, have lowered the price and increased the worldwide supply of PHA. Although PLA can be produced without using GMOs in the fermentation process, most commercially available PLA and PHA are produced through fermentation using genetically modified (GM) yeast and bacteria for increased productivity (Khemani and Scholz, 2012; Reemmer, 2009). The NOP rule (USDA, 2014c) states that synthetic biodegradable plastic mulch must be produced without GMOs; thus, this prohibits

Table 1. Trade names of biodegradable plastic mulches and their primary constituents, and their polymeric feedstocks.

Trade name	Polymer/polymer blend ²
Bio360	Mater-Bi [®] (starch + PCL) + PBAT
BioAgri [®]	Mater-Bi [®] (starch + PCL) + PBAT
Biocycle [®]	Sucrose/PHA blend
Bio-Flex [®]	PLA/copolyester
Biomax [®] TPS	Starch + TPS
Biomer L [™]	PHA
Bionolle [™]	PBS
Biopar [®]	Starch copolyester
Biosafe [™]	PBAT/starch blend; PBS; PBASA
Eastar Bio [®]	PBAT/starch blend
EcoFilm [™]	Unspecified plastic
Ecoflex [®]	PBAT + starch blend
Ecovio [®]	PLA + PBAT/starch
EcoWorks [®]	Unspecified plastic
EnPol [®]	PBS
Envio	PBAT + PLA + starch blend
GreenBio [®]	PHA
Ingeo [®]	Starch + PLA; PBS + PLA
Mater Bi [®]	PCL + starch blend
Mirel [™]	PHA
Naturecycle	TPS/copolyester blend
Paragon	Starch + TPS
ReNew	PHA
Skygreen [®]	Terephthalic acid copolyester

²PBAT = polybutylene adipate terephthalate; PBS = polybutylene succinate; PBASA = PBS-coadipic acid; PCL = polycaprolactone; PHA = polyhydroxyalkanoate; PLA = polylactic acid; TPS = thermoplastic starch.

the use of polymer feedstocks produced from or with GMOs.

The most common fossil fuel-based polymers used to make biodegradable plastic mulch are poly(butylene-adipate-*co*-terephthalate) (PBAT), poly(ϵ -caprolactone) (PCL), poly(butylene succinate) (PBS), and poly(butylene succinate adipate) (Table 1). PBAT is fully biodegradable under composting conditions and has high elasticity, wear, and fracture resistance, as well as resistance to water and oil. PCL has a relatively low melting point (60 °C) and is often mixed with starch to increase biodegradability. PBS is a thermoplastic polyester with physicochemical properties that are comparable to polypropylene. All of these synthetic polymers provide functionality, flexibility, and affordability to plastic films, and are degraded by bacteria and fungi commonly found in soil (Eubeler et al., 2009; Kawai, 1995; Mohan and Srivastava, 2010; Swift, 1993). As a result, these synthetic polymers serve as the major components of biodegradable plastic mulches.

All currently available commercial products are manufactured by blending fossil fuel-based and biobased feedstocks (Briassoulis, 2004; Ghanbarzadeh and Almasi, 2013; Kasirajan and Ngouajio, 2012). Now, commercially available biodegradable plastic mulch products have a maximum of 10% to 20% biobased content (OMRI, 2015). Although butanediol, succinate, and adipate feedstocks can potentially be derived naturally, and it is possible to manufacture biobased PE, their use in agricultural plastics is currently considered too expensive. Biobased

sources for the polymers are, however, being used in other commercial products; for example, in Brazil, sugarcane residues are converted into ethanol, which is then converted into ethylene oxide that is used to make polyethylene terephthalate for beverage bottles (Bomgardner, 2014).

Biodegradable Mulch Manufacturing and Minor Additives

Biodegradable plastic mulch is manufactured using conventional plastic film-processing technologies (Hayes et al., 2012). This includes the addition of minor additives such as plasticizers and lubricants to enhance the flow of molten polymer through the processing machinery, nucleating agents to control mechanical properties, and colorants/dyes. The minor additives used in commercial biodegradable mulches may or may not be produced using GMOs; however, it is difficult to determine their identity and concentration in a given mulch product as this information is proprietary to a mulch manufacturer.

Although the NOP Policy Memo 15-1 (USDA, 2015) states that the polymer feedstocks used in biodegradable mulch films must be completely biobased, processing aids and pigments are not required to be biobased. It is not clear which additives are processing aids exempted from the biobased requirement, and which additives provide a functional effect in the finished product and therefore could be considered as feedstocks. The uncertainty regarding the need for additives to be biobased has resulted in organic certifiers forming different interpretations regarding this issue. Clarification is needed for manufacturers who are targeting organic agriculture, as well as for certifiers and growers who need to comply with NOP policy.

Mulch Deterioration and Biodegradation

For biodegradable plastics, deterioration is generally characterized by aboveground disintegration (via mulch laying and during use) and belowground biodegradation. Factors that influence aboveground deterioration, or weathering, include temperature, sunlight, moisture, and mechanical stresses (e.g., wind-blown soil particles that cause abrasion), as well as interactions among these factors (Hakkarainen, 2002; Ho et al., 1999; Krzan et al., 2006; Singh and Sharma, 2008). These processes can enhance biodegradation by decreasing the material's molecular weight (Hablott et al., 2014; Kijchavengkul et al., 2008; Lucas et al., 2008).

The first plastic mulches marketed as "biodegradable" were actually photodegradable films consisting of a mixture of starch and a nonbiodegradable polymer (e.g., PE); under prolonged exposure to sunlight, chemical bonds susceptible to photodegradation are cleaved, causing the mulch to fragment into pieces of plastic (Riggle, 1998). Because only the starch component can undergo biodegradation,

photodegradable plastic mulches are not biodegradable. Oxo-degradable plastic mulch contains PE and other nonbiodegradable synthetic polymers with transition-metal salts (e.g., cobalt, nickel, manganese, and iron) that promote partial degradation of the polymers, which is manifested by embrittlement and fragmentation of the plastic. Because of these transition metals, oxo-degradable products may be harmful to soil health and the environment (Thomas et al., 2010). Oxo-degradable PE products can potentially undergo cross-link formation, making the plastic more resistant to breakdown and enhancing their persistence in the environment, thereby raising further concerns (Davis et al., 2005; Feuilleley et al., 2005; Thomas et al., 2010). It is important to note that today there are still photodegradable and oxo-degradable plastic mulches that are erroneously labeled as "biodegradable" by their manufacturers.

In the soil, fungi, bacteria, algae, and other macro- and microorganisms contribute to biodegradation. Biodegradation occurs under aerobic and anaerobic conditions (Hickey, 2005). Under both conditions, microorganisms secrete enzymes that cleave the molecular chains of polymers and then incorporate the resulting small molecules into their cells for the support of microbial metabolism. This process of biodegradation provides microbial cells with both carbon and chemical energy for growth and reproduction (Maier et al., 2009). Complete biodegradation encompasses the breakdown of a polymeric product into carbon dioxide and water through oxidative respiration, with some components of the mulch being incorporated into microbial biomass (Lucas et al., 2008).

The rate and extent of biodegradation of plastic mulch depends upon feedstocks as well as soil-related conditions. All of the biodegradable testing procedures cited by the NOP are laboratory-based procedures that test mulches or their feedstock components using ideal temperatures, moisture levels, and organic matter substrates to hasten biodegradation (ISO 17556 or ASTM D5988). Under colder soil temperature conditions (especially during winter months), the rate of biodegradation is reduced as microbial activity slows or ceases. In contrast, biodegradation under composting conditions tends to be more rapid as mesophilic and thermophilic microorganisms are active under the high temperature conditions (40–60 °C). Thus, even though a biodegradable mulch product may fulfill the NOP biodegradation criteria, there is no assurance that the mulch will actually biodegrade at the same rate or extent under field conditions.

Field tests to date indicate that biodegradable mulches may not meet the 90% biodegradation rate within 2 years at some locations. However, it is important to note that in most field tests biodegradation per se is not being measured (CO₂ evolution is not monitored), but rather, soil samples are visually assessed for mulch and the level of biodegradation is inferred based on the visual

presence or absence of mulch fragments in the samples. For example, in a collaborative agricultural field experiment in Knoxville, TN; Lubbock, TX; and Mount Vernon, WA; a commercial paper mulch was no longer visible in samples at all three sites after 1 year, and so complete biodegradation was assumed. In contrast, in the same study after 2 years, the average loss of two commercial biodegradable plastic mulches was 52% at Knoxville, 98% at Lubbock, and 6% at Mount Vernon (Li et al., 2014). In general, weathering factors such as high temperature, sunlight, and moisture pre-soil incorporation, and soil factors such as moisture and biological activity can promote biodegradation (Feuilleley et al., 2005; Kyrikou and Briassoulis, 2007; Li et al., 2014; Yousif and Hasan, 2015), and these results indicate that the relationship between biodegradation and environmental factors is complex. It is also worth noting that according to the NOP rule 205.200, which pertains to maintaining or improving natural resources on the farm, if the biodegradable mulch accumulates over time in the soil (i.e., does not reach 90% biodegradation within 2 years), the grower would likely be in noncompliance and would need to stop using biodegradable mulch until mulch residues are no longer evident in the soil.

Given there is limited data available regarding biodegradation of plastic mulch under agricultural field conditions at this time, one possibility is to estimate the biodegradation potential of a plastic mulch based on published biodegradation potentials for the mulches' ingredients. Table 2 provides a summary of comparative in-soil biodegradation rates of the primary feedstocks and ingredients used to make biodegradable plastic mulch. PLA and PBAT, very common feedstocks, have low and moderate-low expected biodegradation rates, respectively, whereas PHA, an increasingly popular feedstock, possesses a moderate biodegradation rate (Brodhagen et al., 2015; Vroman and Tighzert, 2009). If a mulch does not biodegrade relatively quickly or completely, such as found by Li et al. (2014) at two out of three sites, residual mulch fragments will accumulate in the soil.

In many agricultural systems, mulch is used for a single growing season, and in some cases, mulch is applied to the same field year after year. Under this scenario, there is likely to be accumulation of nonbiodegradable plastic residuals. For example, if 200 kg·ha⁻¹ of mulch is applied each year (based on mulch dimensions 1.8 m width and 0.0254 mm thickness, and bed spacing of 1.8 m center-to-center, common for mulch application), and if 15% of the mulch is assumed to degrade during the growing season due to weathering, at the end of the first growing season, ≈85% of the applied mulch (170 kg·ha⁻¹) would remain and be incorporated into the soil. If it is further assumed that the mulch will biodegrade a total of 45% after 1 year (half of 90% biodegradation that is assumed by the end of 2 years), then at

Table 2. Common feedstocks and ingredients used to make biodegradable mulch, their carbon source, method of synthesis, and estimated comparative rate of biodegradation in the soil (adapted from Brodhagen et al., 2015).

Feedstock/ingredient ²	Carbon source	Synthesis	Estimated comparative rate of biodegradation in soil ³
Cellulose	Biobased	Biological	High
PBAT	Fossil fuel	Chemical	Low moderate
PBS	Fossil fuel	Chemical	Low moderate
PBSA	Fossil fuel	Chemical	Low moderate
PCL	Fossil fuel	Chemical	Moderate
PHA	Biobased	Biological	Moderate
PLA	Biobased	Biological and chemical	Low
Starch	Biobased	Biological	High
Sucrose	Biobased	Biological	High
TPS	Biobased	Biological	High

²PBAT = polybutylene adipate terephthalate; PBS = polybutylene succinate; PBSA = PBS-co-adipic acid; PCL = polycaprolactone; PHA = polyhydroxyalkanoate; PLA = polylactic acid; TPS = thermoplastic starch.

³Estimated rate of biodegradation in soil is comparative for the listed feedstocks/ingredients; as no studies have evaluated actual biodegradation of these materials under soil conditions, comparative values are based on estimates provided in the literature and summarized by Brodhagen et al. (2015).

the end of the second year when the second application of biodegradable mulch is tilled into the soil, there will be $\approx 280 \text{ kg}\cdot\text{ha}^{-1}$ of mulch in the soil ($110 \text{ kg}\cdot\text{ha}^{-1}$ remaining from year-1 application plus $170 \text{ kg}\cdot\text{ha}^{-1}$ from year-2 application), or 140% of the annual amount of mulch applied. If 10% of the mulch was to persist due to nondegradable plastic components, then every year thereafter there would be an additional 10% of nondegraded plastic mulch residues accumulating in the soil (Fig. 1). In this scenario, after 8 years of annual application, plastic mulch residuals in the soil would exceed twice the amount of mulch applied per year. Thus, it is worthwhile considering that even if a biodegradable mulch film meets the NOP criterion of 90% biodegradation within 2 years, there may be accumulation of mulch residuals in the soil following repeated mulch applications.

Since many manufacturers do not test their products in field studies, or do not include multiple sites with diverse environmental conditions, it should not be presumed that mulches are designed to achieve a specific level of biodegradation in 1 or 2 years, or that a product biodegrades completely under a diversity of field conditions. The impacts of accumulation of mulch residuals on soil quality and productivity have not been well explored; this issue merits continued investigation to understand the functional implications of repeated mulch use, especially for mulches that do not quickly or completely biodegrade. The issue of accumulation of mulch residuals in the soil is one of the key questions regarding the sustainable nature of biodegradable mulches that extends beyond the realm of organic production.

Assessing Mulch Biodegradation in Soil

At this time, there is no standard method for measuring the rate of mulch biodegradation in the field after tillage incorporation. Additionally, few studies have attempted to measure the amount of biodegradable plastic mulch in the soil post-incorporation. The simplest field-based methods for measuring the amount of biodegradable mulch in the soil post-incorporation are to measure the area or weight of the mulch. As noted above, these methods do not measure CO_2 evolution and

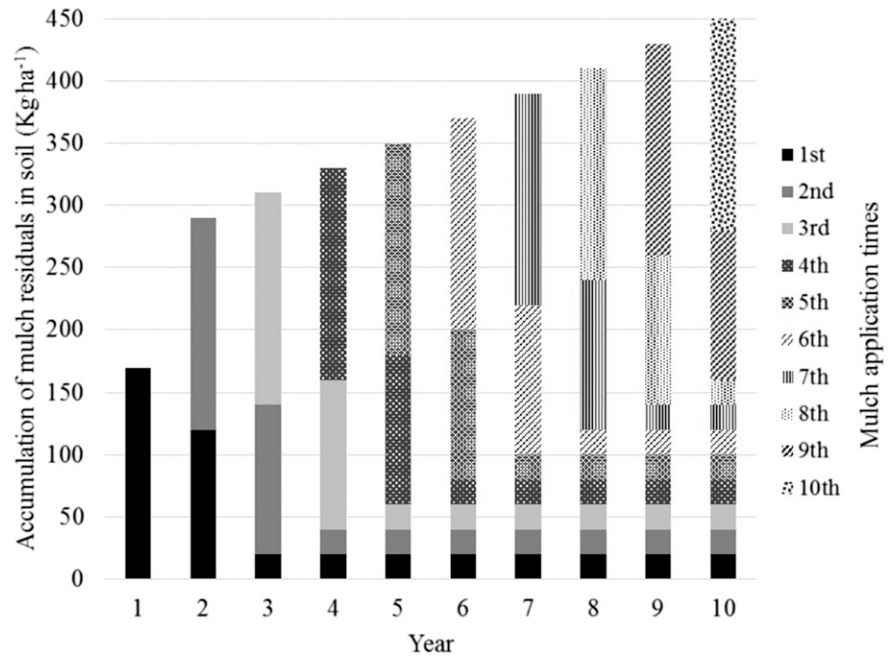


Fig. 1. Estimated accumulation of mulch residuals in soil when mulch is applied at $200 \text{ kg}\cdot\text{ha}^{-1}$ (based on mulch dimensions 1.8 m width and 0.0254 mm thickness, and bed spacing of 1.8 m center to center) per year for 10 years and undergoes a projected 15% degradation during the growing season, an additional 30% biodegradation after 1 year of soil incorporation, and a total of 90% biodegradation 2 years after soil incorporation; 10% of the mulch is assumed to persist due to nondegradable plastic components.

so they are not a direct measure of biodegradation but rather an estimation that biodegradation has or has not occurred based on the presence or absence of mulch fragments. In the study by Li et al. (2014), field-weathered biodegradable plastic mulch samples (10.15 cm by 10.15 cm) were placed in mesh bags ($250\text{-}\mu\text{m}$ nylon mesh, 12.7 cm by 12.7 cm) along with 300 to 400 g of field soil, and bags were placed at 8- to 12-cm depth (the depth of tillage) in agricultural field sites at Knoxville, TN; Lubbock, TX; and Mount Vernon, WA. At each site, one bag was extracted from the soil every 6 months over a 2-year period; the soil and mulch from each bag were sieved ($<4.75 \text{ mm}$), and mulch fragments were removed with forceps, placed on a paper towel and mist-sprayed with deionized water to remove adhering soil. All recovered mulch fragments were placed between two sheets of transparency film and the mulch area was

measured using a LI-3100 Area Meter (LI-COR, Lincoln, NE).

Cowan et al. (2013) used a golf cup cutter (15-cm depth and 10-cm diameter) to sample soil 397 d after biodegradable mulch had been tilled in. Soil samples were wet sieved (1.18 mm), and recovered mulch fragments were cleaned gently in water, laid out on a glass plate, blotted dry, and photographed (digital camera with 18–55 mm lens; Canon USA, Inc., Lake Success, NY). The area of each digital image was calculated using ImageJ software (Rasband, 1997). The authors found that the surface area of SB-PLA-11 (an experimental nonwoven mulch prepared from PLA obtained from NatureWorks LLC, Blair, NE) did not change appreciably, signifying that this mulch product did not biodegrade. In contrast, the surface area of BioAgri[®] mulch (BioBag Americas, Palm Harbor, FL) was 40% of the originally applied

area, and no visible fragments of Crown 1 mulch (currently marketed as Naturecycle; Custom Bioplastics, Burlington, WA) were detected. A study by Wortman et al. (2016) used the same soil sampling method as Cowan et al. (2013) and measured the mass of recovered biodegradable mulch. Almost 1 year after soil incorporation in the open field, $\approx 0\%$ to 5% of the two commercial biodegradable products (Eco Film; Cortec Corp., Saint Paul, MN, and Bio Telo; Dubois Agrinovation, Saint-Remi, QC, Canada) and $\approx 12\%$ to 55% of the four experimental biofabrics (spunbond nonwoven PLA; 3M Co., Saint Paul, MN) included in this study were recovered. More studies are needed to verify the accuracy of these soil sampling and mulch measurement techniques, and to provide simple methods that farmers and inspectors can use to accurately measure the amount of biodegradable plastic mulch remaining in the field following soil incorporation.

Conclusions

Plastic mulch is ubiquitous in agricultural production systems worldwide and provides some key advantages for crop production such as weed control, moisture conservation, and increased crop yield and quality. Due to limited opportunities to recycle plastic mulch, however, this important production tool has become a potential source of environmental pollution. Biodegradable plastic mulch may provide a solution to this dilemma by providing all the crop production benefits of plastic mulch while also reducing the amount of plastic waste that remains after its use. Biodegradable plastic mulches are an emerging sustainable technology, but their use in organic agriculture remains constrained as currently in the United States none of the biodegradable plastic mulches on the market has been approved for use in certified organic production systems. This is because none of the mulches meet the current certification requirement of using only biobased feedstocks, and GMOs are used to manufacture the biobased feedstocks. Organic growers are advised always to check with their certifier before applying a product as some biodegradable mulch manufacturers and marketers erroneously advertise their product as “organic.”

Although the organic standards are designed to protect environmental health and promote sustainability, it is questionable whether excluding products from use based on manufacturing processes meets the overarching goals of sustainability when these processes do not introduce harmful byproducts to the environment. If use of GM feedstocks, bacteria, or yeast was not an issue for organic certification, the overall cost of feedstocks used in the manufacture of biodegradable mulch would likely decrease, and manufacturers would likely be more able to develop products that are completely biobased and biodegradable. The opposition to the use of GMOs in organic agriculture is deeply embedded in the organic movement, and so any changes to this aspect of the organic certification rules would

need to be extensively discussed and agreed upon by stakeholders.

Environmental health and sustainability may, however, be put at risk when plastic mulch does not fully biodegrade and mulch fragments remain in the soil. Questions remain regarding the rate and extent of plastic in-soil biodegradation, and soil-based standards are needed for biodegradable plastic. ASTM International, ISO, and other organizations are well placed to develop a laboratory-based standardized test for biodegradation of plastics in soil as they have extensive experience and knowledge in developing similar standards. Indeed, ASTM International is developing a new standardized laboratory testing method, WK29802 “New specification for virgin plastics that biodegrade in soil under aerobic laboratory conditions.” Such a laboratory test should be carried out with agricultural soil under temperature and moisture conditions that reflect annual field conditions. Data collection equivalent to the standardized test ASTM D6400 would be appropriate (e.g., measures of CO₂ evolution, heavy metals, and minimum particle size).

A laboratory test of the primary feedstocks that are used to make biodegradable plastic is an essential first step to understanding potential biodegradation of the end product. Knowledge of the rate and extent of biodegradation under field conditions will provide additional important information regarding the amount of plastic mulch residuals that have the potential to accumulate in the soil, especially with repeated use. Field trials should be conducted at three to five locations to measure how mulch products perform under a diversity of environmental conditions.

Simple-to-use field sampling methods are also needed to enable growers and other agricultural professionals to assess the amount of mulch remaining in the field post soil-incorporation. As more biodegradable plastic products enter the agricultural marketplace, there is a need for guidelines to assure growers that these products perform similarly in the field as they do in standardized laboratory tests. For example, new biobased biodegradable fabrics are being developed, and though they are not yet commercially available, they show promise for agriculture (e.g., to be used as mulch, landscape fabric, and rowcover) (Li et al., 2014; Wortman et al., 2015; Wortman et al., 2016). The end goal of agricultural and polymer scientists is to provide manufacturers with new information so they can develop fully biodegradable and biobased mulches for potential use in organic and sustainable production systems. Biodegradable plastic mulch has the potential to significantly reduce the amount of plastic entering the waste stream, and this holds promise for agricultural producers and society as a whole.

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